Utilizing Stigmergy in Support of Autonomic Principles

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Abstract

Learning by nature has always been a source of inspiration for various kinds of developments in different domains. So called bio-inspired mechanisms, such as stigmergy, swarm behavior or heart beat monitoring have been utilized in various systems in order to take advantage of principles that have not only been evolved by nature but have been proven to be effective. Recently, such mechanisms have received a special interest from the area of autonomic computing where they are seen to be highly relevant to support autonomic features such as self-organization and self-adaptation. This paper evaluates the use of stigmergic mechanisms in order to support such autonomic principles. In particular, three distinct use-cases will be evaluated, which use stigmergy to facilitate or optimize their behavior. The concepts proposed will be applied to a new type of knowledge provisioning system, namely Knowledge Networks, which will be used as a running example throughout. Furthermore, relevant concepts of stigmergy are formally defined and a working prototype is outlined.

1 Introduction

There is strong motivation for new perspectives for the utilization of bio-inspired mechanisms in support of new principles in computing in general but in autonomic computing in particular. The promotion of various self* features, such as self-optimization, self-adaptation and self-contextualization, is paramount to the success of autonomous systems as they represent the building blocks to be used to achieve higher degrees of autonomic behavior.

This is of particular interest within the context of next generation knowledge provisioning systems which need to be capable of delivering pre-organized, well-structured and situation specific knowledge to individual services and applications. For that, dedicated services and components have to autonomously
self-organize and self-adapt in order to react to the dynamicity of the underlying data as well as the changing requirements introduced from the user's perspective. In other words new and fundamentally different techniques are required for the management, retrieval and reasoning of knowledge in order to serve situation-specific and contextual-rich knowledge at various levels of granularity.

Bio-inspired mechanisms, which incorporate concepts such as stigmergy, swarm intelligence and heartbeat signals offer new perspectives that are relevant for the optimization and adaptation of structures that are complex in nature, highly distributed and often unrelated with each other or with the domain /situation they are used for. In theory, they enable distinct optimization without the requirement for a intrinsic stimulus, which allows for truly distributed self-mechanisms. Furthermore, introducing autonomous features into systems where selective adaptation and control mechanisms are difficult to implement makes such systems not only more robust and reliable but often they make them usable in the first place.

The main objective for this work is to highlight the importance of such mechanisms in support of autonomic principles. In particular the utilization of stigmergy to enable self-organization, self-optimization and self-contextualization will be discussed and prototypical concepts will be depicted. The use of stigmergic overlay networks will be explored for optimizing knowledge querying, allowing reasoning over knowledge structures and for constructing and utilizing dynamic usage pattern of smart world infrastructures.

The remainder of this paper is organized as follows. Section 2 provides an insight into generic stigmergic principles and defines relevant constructs while Section 3 introduces the concept of Knowledge

Networks which act as a working environment for stigmergic overlay structures. Related work in this area is depicted throughout but in particular in Section 4, where distinct use-cases are depicted validating the utilization of bio-inspired mechanisms before Section 5 concludes this paper.

2 Principles of stigmergy

Self-organization is a biologically-inspired behavior where there is no external organizer [6]. In addition, the underlying facts organization is achieved with may be internal to the system or may be derived or influenced from the outside and may not be related to the system itself. More than this, stigmergy may involve self-organizing without any real knowledge of neither the system itself nor the environment it is used in, but rather by reacting to observable changes that occur. The concept of stigmergy has been first introduced by the Biologist Grassé [2] to describe the mechanism by which termites coordinate their nest building activities. Stigmergy itself occurs if future behavior is determined or influenced by past behavior [14], where the type or the source of the behavior is of no importance to the utilization thereof.

A wildly recognized exploitation of stigmergy is the Ant Colony Optimization, ACO, algorithm presented in [1]. ACO works by copying the actions of ants as they try to find the optimal route from one position to another. They randomly select a number of routes and leave a pheromone behind indicating the route they took. The shortest route will build up the strongest pheromone amounts and so eventually all ants will choose this route as it represents the most optimum solution. The ants do not know what the optimal route is, but rather discover it through the experience of all the routes that they take. Moreover, their reasoning does not require any knowledge of the environment, but to be able to read the pheromone trail, which effectively reflects a change in the environment which is a key principle of stigmergic sensing.

As no additional knowledge is required, stigmergy can be considered as a very lightweight communication and even reasoning mechanism between any number of entities. It can typically be implemented through the use of weights and thresholds to reflect links between different components that interact with each other either directly or by means of additional features. In the case of the ants, the links represent connections between different areas of the optimal route as reflected by the strength of the sensed pheromone. In the case of artificial networks, the links can again connect nodes to define an optimal route. A link can simply be a reference in one node to another, with the importance being increased or decreased based on positive or negative feedback mechanisms. For a network that supports sensors, this lightweight way to organize is particularly attractive because it can reduce the amount of memory required and due to its independency from individual components it can be realized in a truly distributed fashion. Moreover, in many cases stigmergy is used for optimizations and as such implemented mechanisms exist in the form of overlays which may also act as a failsafe mechanisms as the underlying structure of e.g. a communication network doesn't need to be altered to be optimized.

In order to model such stigmergic overlays the concept of a stigmergic link is introduced next. Conceptually, a stigmergic link L is defined to have an edge on either side reflecting the two components it intends to establish a relationship with. In addition it incorporates the concept of potency in a way that the link may be strengthened or weakened depending on the stimuli that supervises the relationship of the components. Thus $L(E_1, E_2, \alpha)$, where E reflect the two edges respectively and α, representing the potency, is defined to be between 0 … 1. Furthermore, depending on a given threshold β, α may deteriorate over time in order to weaken the relationship between the two components and to, ultimately, eliminate it in the case that no negative feedback mechanism exist. For instance, α of a given L may be strengthened if the link represented by its edges is traversed. Since there is no such thing as a "non traversal" event L may be weakened over time, thus modeling the disuse of established relations as a negative feedback signal.

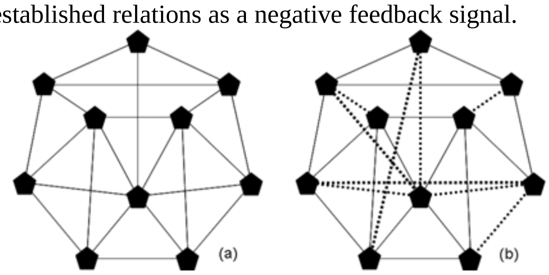

Figure 1: Stigmergic network; (a) Underlying data network; (b) Stigmergic overlay network

Considering that multiple stigmergic links can be constructed over individual components, a generic overlay network may be composed that, as depicted in Figure 1, reflects either relations between any two nodes that have a direct relation (solid lines), e.g. neighboring nodes within a sensor network. Or it establishes new relations between nodes that did not have a relationship beforehand. Obviously, the rationale for establishing stigmergic overlays does depend on how services intend to exploit them. Nonetheless, and as mentioned earlier, the rationale for establishing single stigmergic links is indifferent to the services that intend to utilize them. Thus, stigmergic links stemming from different underlying concepts may be shared among different overlay networks in a shared fashion. For instance, if a stigmergic link represents e.g. a shorter distance between any two nodes then it may be used by services that deal with path optimizations but it will probably be worthless to a service that deals with content correlation. Whereas a link that reflect similar content may also be relevant for path optimization mechanisms. In any case and as further discussed in Section 4.3, for some services only the fact that a relation is present is relevant while the rationale behind a stigmergic link is often irrelevant.

3 Knowledge networks

In a nutshell, the high level objective of knowledge networks, KN, can be summarized as the provision of a vehicle capable of creating, storing, propagating and discovering information in a light-weight, scale free and multi-view environment. In particular the organization and the provisioning of knowledge at different levels of granularity is of particular importance as it allows pre-organization of available knowledge based on different principles. Moreover, KNs must be able to self-organize themselves in the sense that it autonomously monitors available context within the virtual space it is operating in and provides the required context and any other relevant knowledge as well as operational support to the requesting services, and, finally, self-adapts when context changes.

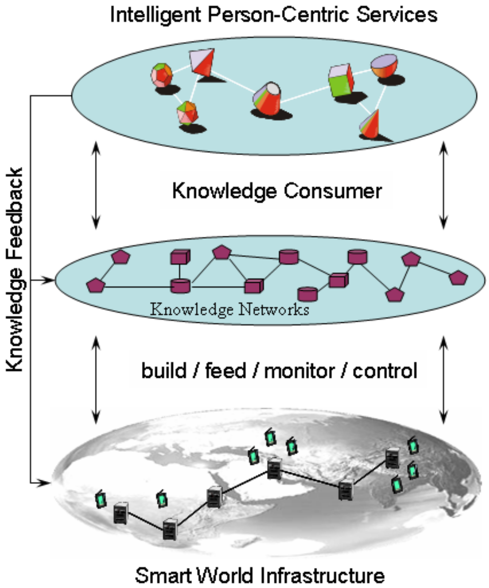

Figure 2: Knowledge network framework

The general the concept of KNs is centered on three key principles: situation-awareness, self-optimization, and semantic self-organization. While each of the mentioned principles is seen to be equally important to the overall concept of knowledge networks, this paper concentrates on aspects that are particular relevant for self-optimization and self-reasoning.

From a more operational perspective, knowledge networks may be positioned as a sort of middle layer where they connect to some sort of data layer as well as to a dedicated consumer layer. As depicted in Figure 2, the data layer exists, from a knowledge provisioning point of view, below the knowledge network and, within the drawing, is represented by a smart world infrastructure that may comprise a multitude of different sensors or other information sources. The conceptually higher oriented consumer layer may utilize the knowledge that is embraced by the knowledge network and may be represented by a set of dedicated pervasive services and applications.

As such a knowledge network represents a network like reference structure containing any number of nodes that (a) allow direct access to knowledge as provided or sensed by their underlying concepts; and (b) provide for the hierarchical organization of knowledge nodes in order to provide hierarchical knowledge structures at different levels of granularity. Thus, as depicted in Figure 3, the construction of large scale networks of networks may be facilitated by organizing both of the above mentioned node types into a single architectural framework. This allows constructing super networks of virtually any size and complexity that comprise any type of knowledge at various levels of granularity.

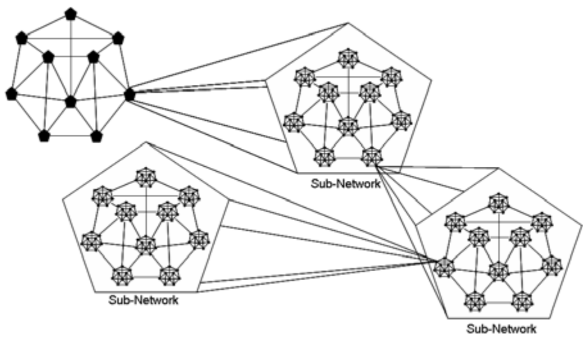

Figure 3: Network of networks

Naturally, such a network like structure, independent of its type but with respect to the number of nodes it comprises and to its structure, can potentially be very large, querying or reasoning therein may be very difficult and needs to be aided by some form of dynamic optimization mechanisms, in order to reduce the time required to produce an answer. Such query optimizations are an important issue for large networks as otherwise the sheer size of the network or its complex relations often makes the traversal of the overall network, in search of an answer, impractical.

Stigmergic principles offer a unique mechanism to introduce optimization at different levels of interest and for different purposes without altering the underlying concepts or data structure of existing networks. In particular, overlaying stigmergic links, allows for the construction of virtual networks that are optimized for a specific purposes, e.g. a specific domain, business goal or even environment specifics. Moreover, the fact that the underlying structure does not need to be altered in any way enables (a) the construction of multiple overlay networks at the same time; (b) the evaluation of optimization procedures before they are committed to the underlying network and (c) a failsafe mechanisms as individual services may work either on the overlay or on the underlying "real" network. For the latter, if either one becomes temporary unavailable the other one may be used to guarantee continues quality of service.

Obviously, in order to exploit stigmergy for various optimizations, stimuli for the construction of relevant stigmergic patterns have to be, firstly, observed and, secondly, overlaid onto the network. In general, the fact holds that whatever concept has been employed for the modeling of the overlay network is also the beneficiary thereof. That is, the concept used to create the overlay network may also utilize it, instead of the original network, in order to self-optimize itself. Nonetheless, it does not prevent the overlay network to be used by other services.

With respect to the utilization of knowledge networks, stimuli for the generation of stigmergic links may come from three different directions.

- **The Consumer Layer:** Stigmergic patterns may be overlaid, in an attempt to optimize the way KNs are used, queried that is. From the consumer layer knowledge may be requested in the form of queries, analyzing them and evaluating the results they produce allows constructing stigmergic patterns that reflect similarities among different queries on an atomic level, which in turn can be used to optimize future queries.

- **The Data Layer:** Being the layer where actual data is sensed and accessed, this layer provides the possibility to generate what has largely been termed usage patterns. Simplified, usage patterns reflect the way any two or more data sources have been used together or in association with each other. For instance, observing the movement of a car on a "smart" motorway. While traveling from A to B it may trigger a multitude of sensors in between indicating that either a car has passed or, more interestingly, indicating that the same car or a distinct car has passed through. Thus the stigmergic strength for this "motorway" link and any sub-parts thereof directly correspond to the amount of traffic that has passed through over time. Being employed on the overall traffic system, specific areas that are e.g. congested could easily be detected and traffic flow could be optimized via state of the art navigation systems.

- **The Organizational Layer:** Finally the organizational layer of the KN itself offers potential stimuli for the generation of stigmergic patterns. The organization layer could be seen as a central yet distributed information sink which contains all the knowledge generated by the lower data level in a properly represented form. Once data is introduced into the "organizational space" of the knowledge network, the goal is to organize it based on different characteristics, such as time, space, purpose, semantic etc. For that, stigmergic principles may be employed in a way that if a data source provides specific organizational characteristics relevant links may be strengthened or weakened respectively. Thus a multitude of specialized overlay networks may be generated, maintained and if no longer desired simply removed without jeopardizing the overall organizational layer.

The three layers described above clearly represent different origins from which stigmergic patterns can be generated from. In essence, the first concept reflects a top to bottom principle where optimizations may take place based on the users that utilize the network. Vice versa, the second concept allows for optimization to be facilitated from the bottom upwards in a way that patterns are derived from the data sources itself rather from the services utilizing them. Finally, the last concept reflects an embedded approach where stigmergy is utilized for initial organizational purposes.

Once stigmergic patterns have been established, optimization and reasoning may be facilitated which is discussed next.

4 Utilizing stigmergy

For knowledge networks, stigmergy provides the means to support several autonomic principles. In particular it provides a mechanism to (a) self-organize the network in support for dynamic query execution and self-optimization; (b) it enables the modeling of usage patterns that are overlaid over the KN and as such support the self-adaptation thereof; (c) it provides a lightweight reasoning mechanism to be implemented that utilizes stigmergy by means of modeling dependency patterns that, eventually, could lead to self-contextualization capabilities that may aid the provision of situation specific knowledge. Each of these mechanisms is addressed individually within the next three sub-sections and specifics are highlighted.

4.1 Stigmergic query optimization

The stigmergic linkage of network nodes as discussed in this section may allows a system to self-optimize itself, thus making it more efficient over time. Some kind of hierarchical structure of the underlying network is assumed to initially guide the search. While this is not compulsory for the optimization process it does provide a certain degree of optimization right from the beginning.

Simplified, a stigmergic overlay network may be constructed based on the evaluation of answers that have been produced for individual queries. In turn, the resulting overlay network and the stigmergic links it embraces are used for the execution of new queries in a quest to exploit similarities among queries over time. In this case the concept of stigmergy is utilized from a user perspective of the KN. That is that overlays are constructed on the KN based on the interaction with the consumer level, in particular based on the knowledge request by individual applications and services.

In principle, it is possible to generate stigmergic links between nodes in the network that typically answer the same types of query. These links can be constructed incorporating stigmergic features strengthening or weakening them based on the number of times they are traversed. When the links reach a certain threshold they can be used as part of the querying process, where the query engine can look at linked sources only rather than having to consider the whole network. This essentially, limits the search space of a query without actually limiting the result space thereof. The links are created by feeding the results of the query answers back through the network, where the nodes used can then form links between themselves. This process is purely a reaction to the environment as the nodes are not aware of the whole query or evaluation process. Instead they overlay the links generated as the answer to a particular query as stigmergic links over the existing network. For this type of linking to be effective it is assumed that the querying process skews the requests towards certain types of queries, where certain source types will typically be queried together. This means that nodes will be able to build up associations as they are typically associated with a much smaller subset of nodes from the whole network. The stigmergic overlay itself is intended to store related sources for similar queries. Although, conceptually similar to some caching approaches it differs significantly in a way that it does not stores the whole query with the sources used but instead it memorizes similarities of any sub-aspect of a query individually. Essentially, each query is fully decomposed and analyzed in a fine grained fashion. This allows later queries to take advantage thereof even if only partially similar.

In [3] an initial prototype has been presented and a series of tests are described that evaluate the performance of linking source nodes only. It finds that there are a multitude of variables that affect the performance of the linking, e.g. query complexity, node distribution, content matching, etc., However it also shows that provided that the queries are sufficiently skewed it represents an effective way to optimize the overall query process over time.

It is also possible to build up views of the whole network through the use of stigmergic links. In this case and application may build up a local view of all nodes in the network that it typically visits. Then the view can be used to reduce search time by specifying a subset of nodes to visit to answer certain queries. One example of using such links in networks can be found in [5], where nodes are clustered in a peer-to-peer network based on query workloads. They measure how similar a node's content is to a type of query, which will mean that it is more likely to return an answer to that type of query. It is then tried to cluster nodes with similar workloads together in workload-aware overlay networks. This will maximize the number of relevant nodes that can be visited in a time period to answer a particular query, by having them just a few links apart. Other examples can be found in [9] and [12]. Simplified, they apply linking to the problem of finding routes through web resources in the area of Life Sciences. In this set of resources, there are known to be different routes to different resources that may answer the same query. They create a directed acyclic graph to describe the possible routes and then adjust weights in transition matrices to produce a ranking of sources to investigate next.

4.2 Stigmergic usage patterns

The previous section discussed generating stigmergic links through the experience of the users querying the system. An alternative approach would be to build up links through feedback from sensors distributed through an environment. As sensors monitor actions they could send this information to other sensors which, if they also record the action could form links between each other. In this way the sensors could self-organize into distinct clusters, which could produce usage patterns of the resources they represent. E.g. [7] discusses context recognition in mobile devices by measuring usage patterns through integrated sensors. An alternative approach is that the observed patterns directly reflect a concept that can be used for optimization as mentioned earlier in the traffic example. Usage patterns have already been proven beneficial in other domains such as web mining (click stream or browsing patterns as discussed e.g. in [13]). In fact [8] has utilized an ant-based clustering algorithm to organize web usage patterns providing clusters of similar behavior. Furthermore, usability and performance based research have utilized observed patterns in order to optimize systems and services. However, linking the observation of usage patterns to a real time system, as envisioned via the concept of knowledge networks, in order to evaluate and maybe even reason about them instantaneously will form new challenges in this area. In particular, the propagation and correlation of stimuli's among distributed sensors forms a current obstacle which may be overcome in due time by improving connectivity of smart devices.

4.3 Stigmergic reasoning

As will be discussed within this section, stigmergic links that are derived from e.g. the query optimization mechanism discussed earlier may also be used as part of a reasoning engine (as discussed e.g. in [4]). In this way more complex queries can be executed over the network, while the network itself remains relatively lightweight. Moreover, results thereof may be integrated into the network in an introspective fashion facilitating the contextual linkage of, before independent knowledge sources and as such supporting the self-contextualization of knowledge structures within the network itself.

To increase the potential use of the network and turn it into a knowledge-base rather than simply for information retrieval, some form of reasoning would be highly desirable. For example, the stigmergic links represent the knowledge of the users that queried the network and as a result associated certain node types with each other. If we assume that the users, over time, generate reasonably sensible queries, then this will actually build up some form of knowledge in the network that correctly associates previously unrelated knowledge components. These associations can then be used to reason through the addition of simple mathematical operations like average, or percentage. In support of the query engine, the sort of reasoning that may be performed could be for the requests such as:

- "What is the best value of one value based on other values?"
- "Is a certain value (or action) possible based on other values?"

For example, consider a query such as "What is a good temperature for wearing tea-shirts?", which is based on a network with weather and clothes information, where any number of sources in the network exist that relate to clothes (e.g. tea-shirts) but also to weather (e.g. temperature) information and maybe others. Retrieving the sources related to tea-shirts and analyzing them if they have any weather related links represents the first step of the reasoning process. Secondly, if weather links exist, then these sources are accessed and their values are retrieved. The temperature values are then averaged to produce the best value, which should represent the average temperature people wear tea-shirts. This may even be further specified incorporating other aspects such as location, sex, age, etc.

The format for a query like this might look like "Select avg. weather.temp From weather, clothes Where clothes.item EQ tea-shirt". If there are different relevant links, then the individual values can be averaged and percentages may be calculated to describe the amount of confidence in each answer. Thus through the addition of some simple mathematical operators and a few extra keywords, basic reasoning can be performed. Moreover, the underlying data as well as the knowledge exploited for reasoning exist independently and possibly distributed over the whole network, thus ensuring that it stays lightweight, robust and manageable.

Currently there does not seem to be a lot of work focused on stigmergic reasoning. However the general area of artificial intelligence and data mining provides interesting relations as e.g. the links generated would form new clusters of data from the existing information. In [9] a stigmergic method is discussed that self-organizes by generating clusters through data mining techniques. Two examples of directly related work seem to be [11] or [10]. In [11] the use of stigmergy to produce collective intelligence in robots is discussed, whereas [10] describes a process and framework for producing cognitive stigmergy. In their paper they suggest doing this through the use of artifacts, where such artifacts are seen as first-class entities representing the environment that mediate agent interaction and enable emergent cooperation. The stigmergic process itself is not changed, but artifacts are stored in the agents using the stigmergy or in the environment and they can trigger certain events. They can be combined and as such, can individually or collectively produce cognitive behavior in the network as a whole.

5 Conclusions

This work has dealt with various approaches and concepts that are related to the utilization of stigmergic principles in support for autonomic features. In the first part, generic concepts around stigmergy have been introduced and put into perspective to be used for a new type of knowledge provisioning system. It has been argued that stigmergy can be induced from various directions thus incorporating a multitude of different stimuli which support various aspects of self-organization, self-optimization and ultimately self-reasoning. The second part has concentrated on specific use-cases that underline the relevance of stigmergic mechanisms in this area.

Firstly, a querying system has been depicted that takes direct advantage of the knowledge network's hierarchical, lightweight and autonomous structure. The resulting stigmergic overlay network directly reflects a domain specific repository that guarantees long term scalability based on previous knowledge utilization. The querying process itself suggests two initial stages (a) traversing the network and (b) querying the sources. While the search will largely be guided by the underlying hierarchical structure of the data, the search can also be guided by distinct similarity measures that e.g. identify directly nodes that are of interest. Because the main navigation through the network is accounted for, the query process tries to improve the network performance through experience by directly linking semantically unrelated sources for certain query types, either on the overlay network or directly on the underlying data network. Essentially, this can be seen as another step of self-optimization as any update in effect also updates the relations that have been created initially for the source nodes. This in turn may changes the knowledge stored in the network. However if performed on a personal and temporary level (that is on the overlay network only), it does not affect the overall general organizational structure.

Secondly, the modeling of distinct stigmergic based usage patterns has been proposed in an attempt to establish relations between atomic data sources in order to aid self-contextualization. Generating and maintaining any such relations in an autonomous fashion would help paving the way towards semantic oriented smart world infrastructures.

Thirdly, it has been shown that stigmergic overlays gathered through various concepts may be used for reasoning in an effort to answer more complex questions and also to introduce new, more valuable knowledge into the scope of a knowledge network. Initial tests have shown that it is possible to reason over a concept by analyzing its relations to other concepts. Stigmergy may provide the means to successfully generate and maintain such relations within globally orientated and fully distributed environments.

Acknowledgments: Work supported by the project CASCADAS (IST-027807) funded by the FET Program of the European Commission.

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