

# Cognitive Stigmergy: A Framework Based on Agents and Artifacts

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**Abstract.** *Stigmergy* has been variously adopted in MASs (multi-agent systems) and in other fields as well—as a technique for realising forms of emergent coordination in societies composed by a large amount of typically simple, ant-like, non-rational agents. In this article we introduce a conceptual and engineering framework for exploring the use of stigmergy in the context of societies composed by cognitive / rational agents, as a means for supporting high-level, knowledge-based social activities. We refer to this kind of stigmergy as *cognitive stigmergy*. Cognitive stigmergy is based on the use of suitable engineered *artifacts* as tools populating the agent working environment, and which agents share and rationally use for their individual goals. Artifacts are first-class entities representing the environment that mediates agent interaction and enables emergent coordination: as such, they encapsulate and enact the stigmergic mechanisms and the shared knowledge upon which emergent coordination processes are based.

In this seminal paper, we introduce an agent-based framework for cognitive stigmergy based on artifacts. After discussing the main conceptual issues—the notion of cognitive stigmergy, the role of artifacts—, we sketch an abstract architecture for cognitive stigmergy, and we consider its implementation upon the TuCSon agent coordination infrastructure.

## 1 Introduction

The study of *stigmergy* has characterised a number of different research fields, including MASs (multiagent systems) in the last years. In general, and in MAS research in particular, stigmergy is mostly used as the source of simple yet effective coordination metaphors and mechanisms for robust and reliable systems in unpredictable settings. The main source of inspiration is obviously represented by the studies on insects and ant societies [7], which have led to a basic meta-model based on (ant-like) *simple* and homogeneous *agents*, with no relevant cognitive abilities, interacting through *local* modifications to the *environment*, thus originating *global* structures, behaviours and system properties [4].

While this stream of research has produced a number of very interesting approaches in MASs (see [17, 20] among the many others), it has also brought on the

two main biases in the field: *(i)* the agent model is very simple—ant-like agents do not exploit any cognitive ability of theirs—and *(ii)* the environment model is often quite elementary—pheromone-like signs/signals, mostly with simple mechanisms modelled upon pheromone diffusion, aggregation and evaporation—at most extended to force fields [11].

By contrast, a number of relevant works in the field of cognitive sciences put in evidence how stigmergy—as the social mechanism of coordination based on interaction through local modifications to a shared environment—is a fundamental mechanism of coordination in the context of human societies and organisations [19, 22]. There,

- modifications to the environment are often amenable of an interpretation in the context of a shared, conventional system of signs
- the interacting agents feature cognitive abilities that can be used in the stigmergy-based interaction
- the environment is articulated, and typically composed of *artifacts*, which build up the social workspace, or field of work.

Along this line, in this paper we explore how the general notion of stigmergy can impact on the structure and organisation of MASs based on cognitive agents—that is, where the notion of agency is strong, and includes high-level knowledge representation capabilities, explicit representation of agent goals, inferential / planning / deliberation abilities, and so on. In particular, we aim at understanding how *cognitive stigmergy*—that is, the generalisation of stigmergic coordination to enable agent cognitive abilities—can impact on the models for interaction and coordination within MASs.

Following the approaches in cognitive sciences, and CSCW (Computer Supported Cooperative Work) in particular [22], our conceptual framework is based on *artifacts*—that is, instruments and tools that make up and constitute the agent environment, which agents can select and use for their own purposes. Artifacts are then the first-class entities that are *(i)* the subject of cognitive agent activity, *(ii)* the enabler and rulers of agent interaction, and *(iii)* the natural *loci* for cognitive stigmergy processes.

The main aim of this line of research is to propose a reference conceptual framework for cognitive stigmergy, and also to define an engineering framework allowing for practical experimentation in the field of MASs. This aim is articulated along at least three different objectives:

- from a scientific-synthetic viewpoint, we aim at constructing a model for stigmergic coordination going beyond ant-like metaphors: agents are not only ants, and signs for stigmergy are not only pheromones. The cognitive abilities of agents, and the articulation of the environment through artifacts are the essential ingredients to generalise from stigmergy to cognitive stigmergy;
- from a scientific-analytic viewpoint, the proposed framework should be combined with agent-based and simulation technologies in order to provide predictive models for systems based on cognitive stigmergy, such as human organisations and societies;

- from an engineering viewpoint, we aim at devising out a framework for the construction of MAS stigmergic mechanisms to coordinate complex activities of any sort within articulated operating contexts. Coordinated MAS behaviour should then emerge as the result of both cognitive and non-cognitive activities by the agents, and by their local interaction mediated by suitably engineered artifacts.

In this paper, we mostly deal with the first issue, and also sketch a possible approach to the third one. In particular, in Section 2 we recapitulate some of the multidisciplinary pillars that a theory of cognitive stigmergy should be based upon, then in Section 3 we first sketch our conceptual background. Then, in Section 4 we provide some remarkable examples of artifacts for cognitive stigmergy, and finally, in Section 5, we shortly outline a possible methodological and technological framework for engineering MAS with cognitive stigmergy based on the TuCSoN infrastructure for MAS coordination, adopting tuple centres as artifacts. Conclusion and future work are provided in Section 6.

## 2 Trans-disciplinary Background

The notion of stigmergy, its relation with the environment, interaction through artifacts, and the many sorts of structures and behaviours that emerge from stigmergic coordination in complex social bodies: all are strictly inter-related issues that have been the subjects of investigation in a multiplicity of heterogeneous research areas. Adopting a multi-disciplinary view is then more or less mandatory—but in some sense quite usual in the field of MAS, given the generality and expressive power of abstractions like agent, society and environment.

Even more, a trans-disciplinary approach is potentially very fertile: taking examples and definitions of stigmergic coordination from both ethology and social sciences to the MAS field, and building there a general model for cognitive stigmergy, which could in principle be brought back to the original fields to induce novel interpretations, is a fascinating perspective indeed.

### 2.1 Definition and (Mis)Use of the Notion of Stigmergy

The original notion of *stigmergy* was introduced by Grassé in the late 50s while studying and trying to explain the behaviour of social insects. In its first formulation, stigmergy was defined as a “class of mechanisms that mediate animal-animal interactions which is fundamental for achieving emergent forms of coordinated behaviour at the society level”. Originally, the concept of stigmergy was used to build up a coherent explanation of the so-called *coordination paradox* between the individual and the societal level: that is, the fact that while looking at the behaviour of a group of social insects, they seem to be cooperating in an organised, coordinated way; instead, looking at each individual, they seem to be working as if they were (mostly) alone, neither interacting with each other, nor involved in any collective behaviour [7]. The explanation to the coordination

paradox provided by stigmergy is that insects interact *indirectly*: each insect (ants, bees, termites) affects the behaviour of other insects by indirect communication through the use of artifacts, such as building material for the nest, or chemical traces.

From the original formulation of the notion of stigmergy, then, a few things clearly emerge: first of all, the key role of the *environment*, acting not only as a passive landscape against which all the interactions occur, but rather as a mediator and a ruler of interactions. Then, along this line, the fact that stigmergic interaction is always *mediated*: it occurs locally to the interacting entity, and directly affects a portion of the environment. Finally, changes to the environment are confined / bounded to well-defined elements, such as a pheromone or a chunk of material for nest construction: so, objects, tools, instruments, *artifacts* that are both part of the environment, and prominent actors in the process of stigmergic coordination, encapsulating the logic of local interaction.

In the context of computer science, in general, and in the field of MASs, in particular, stigmergy has been widely used as a technique for complex problem solving, as well as (more recently) as an approach to the design and development of systems. This of course was mainly motivated by the need of system reliability and robustness in complex and unpredictable environments, which could in principle be addressed by mechanisms for self-organisation like stigmergy.

However, what actually happened both in computer science in general, and in the MAS field in particular, was that ants and pheromones provided for a simple, easy-to-reproduce mechanism for stigmergy: as a more or less direct consequence, stigmergy was often implicitly reduced to an ant-like phenomenon. This is not to say that ant-based mechanisms, models and technologies do not obtain significant outcomes: instead, a large number of remarkable results were indeed achieved in computer science [6], robotics [8], and MASs [2, 10].

What is missing, instead, is a wide and coherent view on stigmergy which on the one hand would stick to the general principles of the original Grassé's definition of stigmergy, on the other would account for the facts that agents are cognitive entities—agents are not ants—, environments are in general more articulated than a mere pheromone container, and that interaction through the environment is mediated by artifacts. This is exactly what we find in research from cognitive sciences.

## 2.2 Artifacts, Workspaces, and Stigmergic Coordination

Forms of indirect, mediated interaction are pervasive in complex systems, in particular in systemic contexts where systems take the form of structured societies with an explicit organisation, with some cooperative activities enacted for achieving systemic goals. In such contexts, in order to scale with activity complexity, sorts of *mediating artifacts* are shared and exploited to enable and ease interaction among the components. Mediating artifacts of different sorts can be identified easily in human society, designed and exploited to support coordination in social activities, and in particular in the context of cooperative work: well-known examples are blackboards, form sheets, post-it notes, archival tools.

Mediation is well-focused by some theories such as Activity Theory [12] and Distributed Cognition [9] adopted in the context of CSCW and HCI (Human Computer Interaction), exploring how to shape the environment in terms of mediating artifacts in order to better support cooperative work among individuals.

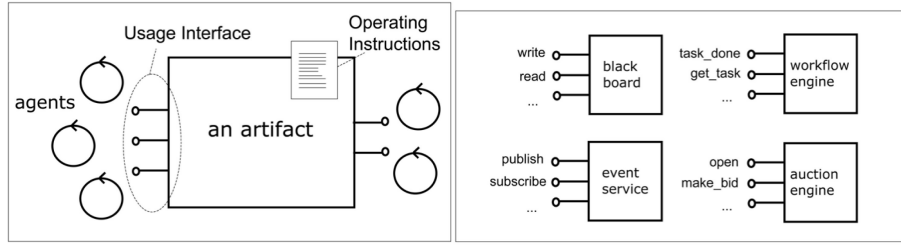
Among the most interesting references, the work by Susi [19] represents one of the most coherent efforts toward a theory of artifacts in social interactions, putting together HCI and cognitive sciences. From there, a picture clearly emerges where the activities within complex (human) organisations occur in the context of structured *workspaces*: workspaces are made of artifacts, which are subjects of the human cognitive activity, work as mediators of interaction, and encapsulate coordinative functions. The notion of workspace (media spaces, virtual rooms, virtual workspaces in CSCW [22]) clearly exemplifies the idea of a non-trivial, non-passive, articulated environment—where artifacts represent the environment articulation. Also, artifacts are mostly cognitive ones, such as triggers, placeholders or entry-points [19]: intelligent activity is required to enact them, make them work, and understand their meaning as coordinating entities.

From a psychologist perspective, the work by Castelfranchi [3, 15] points out another key issue: independently of the intentions motivating activities on artifacts (intention to communicate or not, for instance), any behaviour in a workspace is anyway amenable to an interpretation by the observers, which could bring meaningful information, and affect their subsequent behaviour. For instance, when I take one of the two glasses on the table to drink, I am not explicitly communicating with my friend on the other side of the table “take the other glass”—I am just taking my glass plain and simple. However, my friend will interpret my action on the shared workspace (the table with the glasses) as an implicit communication from mine, and take the other glass anyway.

This is also quite apparent in some of the most well-known examples of shared knowledge-based human-oriented artifacts: the platforms for cooperative work, systems like Wiki (and the Wikipedia [21]), and even platforms for e-commerce (which are also huge sources of information) like Amazon [1]. For instance, one of the most obvious but effective ways of interaction in the Wikipedia is annotating a page. When looked from an ant-like perspectives, this resembles the release of a pheromone on a shared environment—here made of pages: more (pheromones-)annotations “deposited” on the same page may “aggregate” to indicate a higher level of interest, then attract the interest of other (ants-)readers.

However, the cognitive nature of both the page artifacts and the annotations, along with the cognitive abilities of the human agents, allows for less trivial forms of “stigmergic” processes. For instance, ranking a page based on its perceived utility enables more articulated forms of aggregation (like global average ranking), and may consequently lead to different evolution histories of the whole knowledge base.

Even mediated implicit communication is easy to be observed, for instance in Amazon. For instance, I do not buy book A and then book B to say anything to anyone—just to have them both. However, logging and aggregating this sort of actions allow Amazon to say someone else buying book B that “customers



**Fig. 1.** An abstract representation of an artifact, along with some specific instances.

who bought this book also bought book A”—which quite often turns to be very informative in practice, and tends to influence both the individual and the global behaviours. In other terms, individual cognitive actions (read a book presentation, decide to buy that book) in a local context (the view from the browser) upon a cognitive artifact (the purchase page) in shared environment (the Amazon web site) change the state of the environment, and then the behaviour of other individuals, such that in the overall the global behaviour of the system is affected.

Evidence of stigmergic processes involving cognitive features could not be clearer around us—in the scientific arena, as well as in our everyday life. The point is now how to use this evidence in MASs, so that both traditional results from the ant-biased interpretation of stigmergy, and the cognitive interpretation drawn from CSCW, HCI, Activity Theory and cognitive sciences could be subsumed, coherently modelled, and then be used to build complex, robust and intelligent MAS.

### 3 Cognitive Stigmergy in MAS

Our objective in this work is the investigation of stigmergy principles in the context of cognitive MAS, i.e. societies of goal/task-oriented/driven agents interacting at the *cognitive level*. Such agents are therefore not necessarily simple and reactive ones, as in the ant case, but can typically be rational, heterogeneous, with adapting and learning capabilities. We adopt the term *cognitive stigmergy* to denote this approach, so as to remark the differences with respect to existing approaches to stigmergy in MAS, which are typically based on societies of agents whose capabilities and behaviour resemble those of insect-like entities.

As in the case of classic stigmergy, the environment is a central concept for cognitive stigmergy, as an enabler and mediator of the agent work and interaction. The general picture—reflecting a certain complexity in the corresponding engineering of applications—is given by a (possibly open) set of agents with their own specific tasks and goals, which perform their individual as well as social activities in the same working environment, sharing the same *field of work*. The interaction among the agents is indirect, uncoupled in time and space. From a

modelling and engineering point of view, it is natural to model such a working environment as a first-class entity: agents are aware (i) of their field of work, (ii) of it being shared with other agents, and (iii) of its functionalities and opportunities to be possibly exploited to achieve their objectives (*affordance* of the environment). Such opportunities are exploited by properly *using* the working environment, that is, by executing the operations that the environment makes available to agents and by observing its state.

As in the case of classic stigmergy, a main point here is that the environment is not a mere passive “container”, but it embeds mechanisms and (reactive) processes that promote the emergence of local and global coordinated behaviours. It has not only a state that can be observed and modified by agents, but it encapsulates some laws that can be triggered by agent actions (or, by events such as a change in location, or the passing of time), and that alter the environment state independently of the agent intentions.

Under a cognitive perspective, the working environment in cognitive stigmergy can be framed as a set of shared stateful tools providing specific functionalities that are useful for agents performing their *individual* work. At the same time, such tools are designed to be collectively shared and used by agents, and are generally implemented so as to effectively and efficiently support their shared functionalities, thus largely impacting on the *social* level.

In the rest of this section, we focus on the answer to the following key question: how to model this kind of working environment as first-class issue in MAS? To this end, we use the notion of *artifacts*, as the means to explicitly and directly design and build such a working environment.

### 3.1 Exploiting the Notion of Artifact

The notion of artifact (and the related conceptual framework) has been introduced recently in MAS as a first-class abstraction representing tools or objects (devices) that agents can either individually or collectively *use* to support their activities, and that can be designed to encapsulate and provide different kinds of functionalities or services [18, 14]. If agents are meant to be first-class abstractions to model goal/task-oriented/driven pro-active entities, artifacts are those entities modelling systems (or parts of a system) that are better characterised as resources or tools *used* by agents for their own aims. In particular, and differently from agents, artifacts have neither internal goals nor a pro-active behaviour, but more simply provide some kind of functionality that can be suitably exploited, as a service—in other words, while agents *communicate with* other agents, agents *use* artifacts.

According to the abstract model defined [18], artifacts in cognitive MAS can be characterised by (see Fig.2): a *function*, as its intended purpose, i.e. the purpose established by the designer / programmer of the artifact—in other words what are the intended functionalities the artifact provides; a *usage interface*, as the set of the operations which agents can invoke to use the artifact and exploit its functionality; some kind of *operating instructions*, as a description of how to use the artifact to get its functionality; a *structure and behaviour*, concerning

the internal aspects of the artifact, that is, how the artifact is implemented in order to provide its function.

Differently from agents, artifacts are not meant to be autonomous or exhibit a pro-active behaviour, neither to have social capabilities. Among the main properties that are useful according to artifact purpose and nature, one could list [14]: (i) *inspectability and controllability*, i.e. the capability of observing and controlling artifact structure, state and behaviour at runtime, and of supporting their on-line management, in terms of diagnosing, debugging, testing; (ii) *malleability*, i.e. the capability of changing / adapting artifact function at runtime (on-the-fly) according to new requirements or unpredictable events occurring in the open environment,<sup>1</sup> and (iii) *linkability*, i.e. the capability of linking together at runtime distinct artifacts as a form of composition, as a means to scale up with complexity of the function to provide, and also to support dynamic reuse. It is worth to be remarked that these artifact features are not agent features: typically, agents are not inspectable, do not provide means for malleability, do not provide operations for their change, and do not compose with each other through operational links.

Also, artifacts can have a *spatial extension*, i.e. given a MAS with a topology, the same artifact could cover different nodes: in other words, a single artifact can be both conceptually and physically distributed. For instance, a blackboard artifact can cover different Internet nodes, where agents may use it by exploiting a local interface. Technically, also agents could be distributed—for instance having the knowledge base in some node and the core realising the deliberation process in some other node: most often, an agent is situated within a specific location, at least by considering the agent models and architectures that are most diffused (an example is FIPA model).

Given this notion of artifact, we can reformulate the context of cognitive stigmergy in terms of a set of agents sharing a set of artifacts representing their working environment. This set can be split along two different levels:

- a *domain level*, with artifacts that represent the target of the agent work, or an *objectification* of such a target.
- a *tool level*, with artifacts that represent the working tools which can help agents in doing their work.

Our objective is to instrument the tool level with a web of linked artifacts which can be used to improve the work of the collectivity of agents sharing the same working environment. At the systemic level, these artifacts are meant to be used both to improve the knowledge about the *practices* in using the artifacts at the domain level, and to possibly support *social construction* and *evolution / adaptation* of such artifacts, toward directions which are useful for the collectivity of agents in the overall. In order to support this functionality, the artifacts belonging to the tool level should encapsulate stigmergic mechanisms partially similar to the mechanisms found in ant-based systems and pheromone infrastructures: such mechanisms are described in Section 4.

<sup>1</sup> Such adaptation is not meant to be realised autonomously by the artifacts themselves, but by agents acting on the artifacts.

### 3.2 Reframing the Notion of Locality: Workspaces

In classic approaches to stigmergy the notion of topology (and related notion of locality) is mostly physical, defining from the viewpoint of agents—which are typically mobile—the portion of the environment which can be directly affected by their actions or can be perceived. In the case of cognitive stigmergy, this crucial notion can be formulated in a natural way with the notion of *workspace*, as the set of artifacts directly available (usable) for an agent. Workspaces would play the role of “open sets” in the mathematical concept topology, with agents and artifacts playing the role of points belonging to that sets. Workspaces can cross each other sharing agents and artifacts, can be nested, and so on: in synthesis they are a way to define the topology in a rigorous way.

Actually, the topology induced by this characterisation is more abstract and could be articulated along different dimensions. An important one is for instance organisation: the same artifacts could be accessible and usable in different ways according to the roles and the permissions assigned to agents by the organisation they belong to.

It is worth noting that the nature and functionality of the artifacts could bring in situation where—to some extent—the principle of physical locality is violated. This is evident in our society, where artifacts (for humans) such as cell phones, televisions, or the Internet itself can be used to observe and interact in a direct way with entities—e.g. humans—located at completely different places of the world. Conceptually, the action of an agent executing an operation on an artifact of its workspace (its locality) can have “instant” effects on a completely different workspace. This happens because artifacts can be either shared among workspaces or linked together across workspaces.<sup>2</sup> Actually, the principle of locality still holds, since agents can still use only the artifacts belonging to their workspaces.

### 3.3 From Pheromones to Annotations

In every stigmergic system, the effects of agent actions on the environment are understood as signs. Once created, signs persist independently of their creator and are observable by the other agents, and are subject of manipulation by the environment itself according to the laws which characterise the stigmergic processes—e.g. diffusion and evaporation. Differently from pheromones in the case of ant-based stigmergy, in the case of cognitive stigmergy signs typically hold a *symbolic* value, embodying information of some sort, with a formal or informal semantics, referring to some ontology. We refer to such a symbolic information in cognitive stigmergy as *annotations*.

Coming back to the two levels previously introduced, annotations are useful first of all for expressing some kind of comment or knowledge about the artifacts (and about the practice of use of artifacts) belonging to the domain level, which

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<sup>2</sup> One should remember that from a physical point of view, an artifact could be distributed across multiple sites.

are targets of the agent work. Then, annotations are useful to objectify also comments or reflections that do not concern a specific artifact, but more generally a working practice, and can possibly refer to multiple artifacts. Finally, annotations can be used for expressing a comment on the annotations themselves, typically concerning their utility, effectiveness, and so on.

Knowledge provided by an annotation is both explicit—the content of the annotation—and implicit—the “shape” and the context of the annotation, including for instance the possible intention of the agent or group of agents that created the annotation. The concept of shape for annotations can be considered analogous to the concept of force in the case of speech acts: it modulates annotation content according to the information that could be of some use when reasoning and exploiting annotations.

Some of the artifacts defining the working space in cognitive stigmergy are possibly devoted to the management of annotations, providing agents with operations for creating and observing annotations, and embedding mechanisms for automatically manipulating such annotations (with form of aggregation, diffusion, selection, ordering) in order to implement the functionality required for cognitive stigmergy. Accordingly, we deal with two basic kinds of annotations:

- annotations explicitly and intentionally created by agents. These include, for instance, agent feedback (evaluation) about a specific artifact belonging to the domain level, agent feedback about a specific annotation on one such artifact, agent annotations about a set of artifacts or a usage practice during a working session.
- annotations automatically created by the artifacts supporting their working activities. Examples include annotations reporting about how much an artifact has been used, how many agents exploited an artifact for their purposes, how many agents considered an annotation useful for their purposes, which other artifacts have been used (and how) by agents using a given artifact.

## 4 Artifacts for Cognitive Stigmergy

Generally speaking, artifacts in cognitive stigmergy should first of all promote *awareness*, that is, making agents seamlessly aware of the work and practices of other agents, which could in turn be effective to drive or improve their own activities. Awareness is a key aspect to support emergent forms of coordination, where there is no pre-established plan defining exactly which are the dependencies and interactions among ongoing activities (involving agents and artifacts) and how to manage them—instead, such a plan emerges along with the activities themselves.

A simple but effective example of stigmergic mechanism promoting awareness can be found—for instance—in Amazon: a user consulting the page of a book is provided with a list of other books, bought by users that purchased the same book. This kind of mechanism in Wikipedia could be realised through a page annotation of the kind: “people consulting this page have also consulted the pages X, Y, Z”. In our framework, such a mechanism can be generalised by supporting

the automatic creation of annotations on artifacts of the domain level, reporting information about which other artifacts have been used by agents using the same artifact.

In the remainder of the section we describe a basic set of artifacts which could constitute a simple example of an architecture supporting some form of awareness and other features characterising cognitive stigmergy. On the background of this architecture there is the notion of *working session*, as a temporal scope for an agent activities. An agent starts a working session with an objective in mind, which is supposed to persist for all the duration of the session. Knowing the (either explicit or implicit) objective of an agent during a working session is important to provide a context—in terms of the problem to be solved, the goal to be achieved, the task to be executed—to the annotations (evaluations, comments,...) made by the agents, and to the practice of the agents using the artifact of the domain level. For instance, in Wikipedia, feedbacks that an agent can provide about the utility of a page could be better evaluated by considering the problem the agent is facing (i.e. what is it looking for).

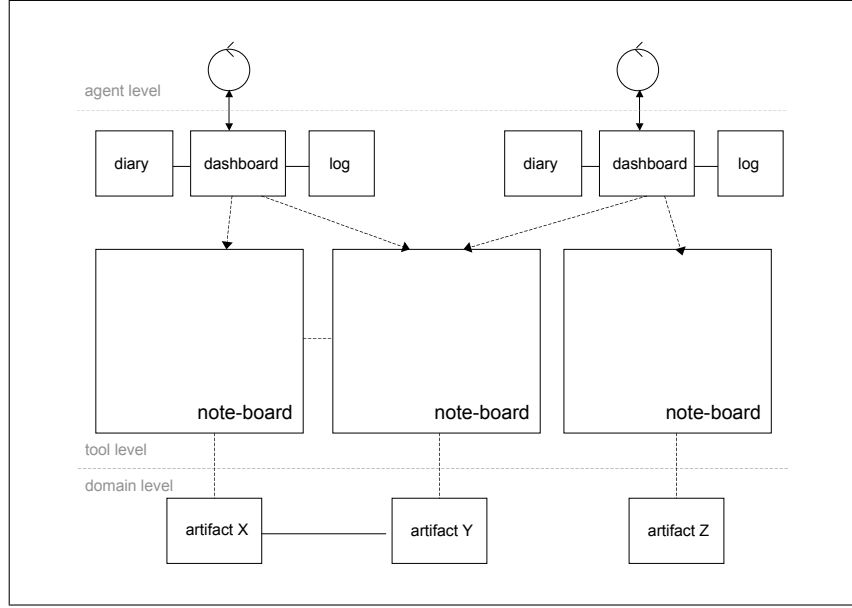
#### 4.1 Promoting Awareness: Dashboards, Logs, Diaries and Note-Boards

A first and necessary step toward awareness is to keep track of both the actions and the annotations made by individual agents during a working session. For this purpose, we identified three basic kinds of artifacts, corresponding to three different kinds of functionalities: dashboards, logs and diaries (see Fig.2):

- A *dashboard* provides the functionalities of a panel (interface) used to *focus* on a specific artifact (or a set of artifacts belonging to the domain level) to interact with the artifact and to take / observe / manage annotations. The concept of focusing aims at representing the intention of using an artifact.
- A *log* is used to keep track of events, providing operation for their inspections and ordering.
- A *diary* is an artifact used to keep track of intentionally annotations made by an agent. The diary typically keeps the annotations organised by working sessions.

The dashboard is linked to the log so as to trace all the operations executed by the agent during a working session. Actually, the log of the operations executed by an agent is interesting also for analysing paths as sequences of executed operations, which can be important to identify and evaluate practices in using one or a set of artifacts belonging to the domain level. The stigmergic system could be instrumented so as to make agents aware of such practices and of the possibility to provide an evaluation, so as to augment the common awareness about good (and bad) practices.

Besides tracing individual agent actions and annotations, it is necessary to introduce artifacts that actually make it possible to effectively share annotations about specific artifacts of the domain level. For this purpose, the *note-board*



**Fig. 2.** An abstract representation of an architecture for cognitive stigmergy based on dashboard, log, diary and note-board artifacts.

artifact is introduced. A note-board is useful for keeping and managing all the annotations about a specific artifact (or set of artifacts) of the domain level. For instance, in the Wikipedia example we can have a note-board for each page (or group of pages) of the system.

A note-board is meant to contain both the annotations intentionally made by agents on the specific artifact, and the annotations automatically created by the artifact itself or by other artifacts by virtue of the stigmergic mechanisms and processes. A simple example can be an annotation reporting how many different kinds of agents used a specific artifact. Such a functionality can be obtained by properly combining the dashboard and note-board: for instance, each time a dashboard focuses for the first time on an artifact *X*, an annotation about this fact can be made on the note-board of the artifact *X*. The note-board can then transform the set of such annotations in a single annotation (by means of *aggregation* mechanisms, described in next subsection), reporting the number of agents that used the artifact. Another example could be an annotation reporting information about which other artifacts have been used by agents using this artifact. In this case, when the focus of an agent switches from an artifact *X* of the domain level to an artifact *Y*, a suitable annotation can be automatically created on the note-board of the artifact *X* reporting the fact that an agent using the artifact *X* has then used the artifact *Y*, and on the note-board of the artifact *Y* with the dual information.

The above examples suggest how the combined use of artifacts with relatively simple functionalities could be effective enough to improve agent awareness about their working practices. Functionalities provided by the artifact are instrumental to realise the forms of reinforcement and positive feedback that typically characterise stigmergic systems as dynamic non-linear systems: the more agents are aware of the usefulness of an artifact, the more they use it, augmenting the global awareness about the utility of the artifact.

## 4.2 Some Basic Stigmergic Mechanisms

Analogously to the case of ant-based stigmergy, also in the context of cognitive stigmergy it is possible to identify some basic and recurrent mechanisms which can be embedded in artifacts in order to support stigmergic processes:

**Diffusion** — Diffusion is one of the basic mechanism in ant-based stigmergy.

In the context of cognitive stigmergy, an analogous principle could be exploited to improve awareness, according to the simple rule that annotations that concern a specific artifact could be useful also for artifacts that are directly linked to such an artifact according to some kind of relation explicitly established at the domain level. For instance, in the case of Wikipedia, annotations concerning a specific page could be useful also for pages that are directly linked to or directly link such a page.

Note-boards could be designed to suitably support diffusion capabilities: annotations intentionally made by agents about an artifact could be automatically propagated from the related note-board to all the note-boards of the linked artifacts. Then, among the information that gives shape to an annotation, a *diffusion level* could also be included, indicating whether the annotation has been made directly by an agent or it has been propagated from other artifacts. Different kinds of diffusion policies are possible: for instance, note-boards could support either diffusion of direct annotations only, or propagation of annotations, too, possibly specifying a sort of propagation radius in terms on maximum diffusion level.

**Aggregation** — In our framework, aggregation mechanism accounts for automatically transforming a set of annotations—related by some criteria—into a single annotation, typically containing an explicit information describing the aggregation in the overall (for instance, a quantity). Note-boards have the fundamental role of aggregators of the annotations concerning a specific artifact of the domain level. For instance, note-boards could automatically aggregate annotations containing agents’ feedback (evaluation) on an artifact or on an annotation made on the artifact.

**Selection and Ordering** — Annotations may have a different relevance according to the different kinds of criteria / dimensions, which can be either subjective or objective. Consequently, such annotations could be automatically ordered by artifacts managing them in order to reflect their relevance. An example of ordering criteria is freshness, measuring relevance of an annotation according to its age. Another one is pertinence, measuring the rel-

evance of a propagated annotation according to its diffusion level, as defined previously. A selection mechanism accounts for keeping and making available only a limited set of annotations—typically the most relevant ones according to the selected criteria / dimensions. Selection is often combined with ordering. To some extent, selection and ordering mechanisms could be considered a generalisation—in the context of cognitive stigmergy—of the evaporation mechanism, as found in ant-based system. Also *dissipation*—a frequent mechanism in stigmergy system—could be considered a specific case of selection, where all annotations not selected according some criteria are forgotten.

Actually diffusion, aggregation, selection and ordering are general kinds of mechanisms which can be considered useful for a wide range of artifacts. In the examples we mainly considered note-boards, however it is easy to identify their utility also in diaries, where annotations are typically organised (aggregated) according to working sessions, ordered according to temporal criteria, and possibly also diffused to note-boards, in case they concern specific artifacts.

## 5 Building MAS with Cognitive Stigmergy

### 5.1 Toward an Agent Infrastructure for Cognitive Stigmergy

As mentioned in Section 1, the conceptual framework of cognitive stigmergy is meant to be useful both for modelling / simulating complex social systems—so as to analyse emergent social behaviours of societies working in some specific workspaces—and for engineering complex agent applications, aiming at achieving some sort of fruitful social behaviour in spite of the independent working activities of the individual agents and / or the absence of a global coordination plan to follow. In both cases, in particular for the latter one, it is of primary importance to have models / infrastructures that make it possible to represent in the most direct and seamless way the main concepts of the framework, in particular artifacts of the kind discussed in the paper. Accordingly, such a middleware would provide a support for cognitive stigmergy as a service, which MAS applications could customise and exploit according to the need.

### 5.2 An Example: TuCSoN as a Middleware for Cognitive Stigmergy

As an example, TuCSoN<sup>3</sup> coordination infrastructure [16] can be used as a middleware to experiment cognitive stigmergy, since it provides on the one side a direct support for cognitive and generative communication, based on the generation and consumption of *tuples* as kind of annotations; on the other side, it provides a natural way to model artifacts as first-class abstractions, with the possibility to define their specific behaviour.

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<sup>3</sup> The TuCSoN technology is available as an open source project at the TuCSoN web site <http://tucson.sourceforge.net>.

TuCSon provides *tuple centres* as first-class abstractions that agents can use to support their communication and coordination. Technically, tuple centres are *programmable tuple spaces*—sort of reactive blackboards that agents access associatively by writing, reading, and consuming *tuples*—ordered collections of heterogeneous information chunks—via simple communication operations (*out*, *rd*, *in*, *inp*, *rdp*) [13]. While the behaviour of a tuple space in response to communication events is fixed, the behaviour of a tuple centre can be tailored to the application needs by defining a set of specification tuples expressed in the ReSpecT language, which define how a tuple centre should react to incoming / outgoing communication events. Basically, ReSpecT primitives make it possible to manipulate the tuples inside the tuple centre and also to establish a link between the tuple centre with other tuple centres, for instance making it possible to insert tuples in other tuple centres directly via reactions. ReSpecT is Turing-equivalent, so in principle any kind of tuple manipulation is possible. From the topology point of view, tuple centres are collected in TuCSon nodes, distributed over the network, organised into articulated domains. A node can contain any number of tuple centres, denoted by a specific name (the full name of a tuple centre consists in its local name plus the Internet address of the hosting TuCSon node).

Then, it is natural to use TuCSon tuple centres as general-purpose artifacts that can be programmed according to the need, in order to provide specific functionalities. Annotations can be easily implemented as logic tuples. Interaction between agents and artifacts can be modelled on top of tuple centre basic communication primitives (*out*, *rd*, *in*, etc), by choosing a specific format for both tuples and tuple templates. Artifact behaviour can be implemented as a set of ReSpecT reactions implementing the basic stigmergic mechanisms discussed in the paper, by virtue of the Turing-equivalence of ReSpecT. In particular:

- aggregation mechanisms can be implemented as ReSpecT reactions consuming a specific set of tuples and producing a single tuple, according to some specific criteria;
- selection and ordering mechanisms can be implemented as reactions which create and maintain tuples containing a list of other tuples, imposing an order among them;
- both diffusion and artifact composition can be implemented by using the linkability property of tuple centres, with reactions that propagate tuples from a tuple centre to the others.

The basic set of artifacts identified in previous section—dashboards, diaries, logs and note-boards—can then be implemented as suitably programmed tuple centres. Due to lack of space, it is not possible to provide here further details about design and implementation of such artifacts: such details are to be presented in a future work along with an evaluation of the system performance in supporting cognitive stigmergy.

## 6 Conclusion and future works

Stigmergy is a simple and powerful mechanism around which complex coordination patterns can be organised and built. Despite the generality of the original definition by Grassé [7], the full potential of stigmergy has yet to be developed in the area of MAS, as both a modelling and a constructive principle for complex agent-based systems.

In this paper, we proposed an extended interpretation of stigmergy, which we termed as *cognitive stigmergy*, which could on the one hand preserve the benefits of the ant-biased acceptance usually adopted in the MAS field, on the other hand promote the full exploitation of the cognitive abilities of agents and of the environment articulation in artifacts in the stigmergic process. After summarising our main sources of inspiration from a number of different research areas and technology contexts, we proposed a conceptual framework for cognitive stigmergy in MAS, and then sketched a possible engineering approach based on the TuCSon infrastructure for agent coordination, using tuple centres as artifacts.

Future work will be devoted to further explore both the theoretical framework and the practical perspectives opened by this paper, focusing in particular on scenarios like e-learning systems, and implicit organisations based on over-hearing / over-sensing.

## References

1. Amazon. <http://www.amazon.com>.
2. Sven A. Brueckner and H. Van Dyke Parunak. Self-organizing MANET management. In Di Marzo Serugendo et al. [5], pages 20–35.
3. Cristiano Castelfranchi. When doing is saying: implicit communication before and without language and gestures. In *International Workshop “Evolving Communication: From Action to Language”*, Siena, Italy, 13–14 May 2004. Communication.
4. Giovanna Di Marzo Serugendo, Noria Foukia, Salima Hassas, Anthony Karageorgos, Soraya Kouadri Mostéfaoui, Omer F. Rana, Mihaela Ulieru, Paul Valckenaers, and Chris Van Aart. Self-organisation: Paradigms and applications. In Di Marzo Serugendo et al. [5], pages 1–19.
5. Giovanna Di Marzo Serugendo, Anthony Karageorgos, Omer F. Rana, and Franco Zambonelli, editors. *Engineering Self-Organising Systems: Nature-Inspired Approaches to Software Engineering*, volume 2977 of *LNAI*. Springer, May 2004.
6. Luca Maria Gambardella, Marco Dorigo, Martin Middendorf, and Thomas Stützle. Special section on ant colony optimization. *IEEE Transactions on Evolutionary Computation*, 6(4):317–365, 2002.
7. Pierre-Paul Grassé. La reconstruction du nid et les coordinations inter-individuelles chez *bellicositermes natalensis* et *cubitermes* sp. la theorie de la stigmergie: essai d’interpretation des termites constructeurs. *Insectes Sociaux*, 6:41–83, 1959.
8. Owen Holland and Chris Melhuus. Stigmergy, self-organization, and sorting in collective robotics. *Artificial Life*, 5(2):173–202, 1999.
9. Edwin Hutchins. *Cognition in the Wild*. MIT Press, Cambridge, MA, 1995.

10. Marco Mamei and Franco Zambonelli. Programming stigmergic coordination with the tota middleware. In *4th ACM International Joint Conference on Autonomous Agents and Multiagent Systems*, pages 415–422, New York, USA, July 2005. ACM.
11. Marco Mamei, Franco Zambonelli, and Letizia Leonardi. Co-Fields: Towards a unifying approach to the engineering of swarm intelligent systems. In Paolo Petta, Robert Tolksdorf, and Franco Zambonelli, editors, *Engineering Societies in the Agents World III*, volume 2577 of *LNCS*, pages 68–81. Springer-Verlag, April 2003.
12. Bonnie Nardi, editor. *Context and Consciousness: Activity Theory and Human Computer Interaction*. MIT Press, Cambridge, MA, 1996.
13. Andrea Omicini and Enrico Denti. From tuple spaces to tuple centres. *Science of Computer Programming*, 41(3):277–294, November 2001.
14. Andrea Omicini, Alessandro Ricci, and Mirko Viroli. *Agens Faber: Toward a theory of artefacts for MAS*. *Electronic Notes in Theoretical Computer Sciences*, 2005. 1st International Workshop “Coordination and Organization” (CoOrg 2005), COORDINATION 2005, Namur, Belgium, 22 April 2005. Post-proceedings.
15. Andrea Omicini, Alessandro Ricci, Mirko Viroli, Cristiano Castelfranchi, and Luca Tummolini. Coordination artifacts: Environment-based coordination for intelligent agents. In Nicholas R. Jennings, Carles Sierra, Liz Sonenberg, and Milind Tambe, editors, *3rd international Joint Conference on Autonomous Agents and Multiagent Systems (AAMAS 2004)*, volume 1, pages 286–293, New York, USA, 19–23 July 2004. ACM.
16. Andrea Omicini and Franco Zambonelli. Coordination for Internet application development. *Autonomous Agents and Multi-Agent Systems*, 2(3):251–269, September 1999.
17. H. Van Dyke Parunak, Sven Brueckner, and John Sauter. Digital pheromone mechanisms for coordination of unmanned vehicles. In *1st International Joint Conference on Autonomous Agents and Multiagent Systems AAMAS’02*, pages 449–450. ACM Press, 2002.
18. Alessandro Ricci, Mirko Viroli, and Andrea Omicini. Programming MAS with artifacts. In Rafael P. Bordini, Mehdi Dastani, Jürgen Dix, and Amal El Fallah Seghrouchni, editors, *Programming Multi-Agent Systems III*, volume 3862 of *LNAI*, pages 206–221. Springer, January 2006. 3rd International Workshop (PRO-MAS 2005), AAMAS 2005, Utrecht, The Netherlands, 26 July 2005. Revised and Selected Papers.
19. Tarja Susi and Tom Ziemke. Social cognition, artefacts, and stigmergy: A comparative analysis of theoretical frameworks for the understanding of artefact-mediated collaborative activity. *Cognitive Systems Research*, 2(4):273–290, December 2001.
20. Paul Valckenears, Hendrik Van Brussel, Martin Kollingbaum, and Olaf Bochmann. Multi-agent coordination and control using stigmergy applied to manufacturing control. In Michael Luck, Vladimír Mařík, Olga Štěpánková, and Robert Trappl, editors, *Multi-Agent Systems and Applications*, volume 2086 of *Lecture Notes in Computer Science*, pages 317–334. Springer, 2001. 9th ECCAI Advanced Course ACAI 2001 and Agent Link’s 3rd European Agent Systems Summer School (EASSS 2001), Prague, Czech Republic, 2–13 July 2001, Selected Tutorial Papers.
21. Wikipedia, the free Encyclopedia. <http://www.wikipedia.org>.
22. Kjeld Schmidt and Ina Wagner. Ordering systems: Coordinative practices and artifacts in architectural design and planning. *Computer Supported Cooperative Work*, 13(5-6):349–408, December 2004.