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PAPER

Analyzing Emergence in Complex Adaptive System: A Sign-Based Model of Stigmergy

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SUMMARY The description and analysis of emergence in complex adaptive system has recently become a topic of great interest in the field of systems, and lots of ideas and methods have been proposed. A Sign-based model of Stigmergy is proposed in this paper. Stigmergy is widely used in complex systems. We pick up "Sign" as a key notion to understand it. A definition of "Sign" is given, which reveals the Sign's nature and exploit the significations and relationships carried by the "Sign". Then, a Sign-based model of Stigmergy is consequently developed, which captures the essential characteristics of Stigmergy. The basic architecture of Stigmergy as well as its constituents are presented and then discussed. The syntax and operational semantics of Stigmergy configurations are given. We illustrate the methodology of analyzing emergence in CAS by using our model.

key words: *stigmergy, sign, emergence, complex adaptive system, simulation*

1. Introduction

A number of recent studies have focused on the description and analysis of emergence in complex adaptive system (CAS) [1], but most methods proposed so far are unsuitable for quantitative analysis because of the intrinsic complexity of CAS [2].

The study of emergence in CAS has, up to now, been focused on macroscopic descriptions, the mechanism of microcosmic- macroscopical link and mathematical model till now. The mechanism of microcosmic- macroscopical link is popularly recognized and widely adopted, for example, Stigmergy mechanism, pheromone mechanism, reinforcement mechanism, trust and reputation mechanism etc. [3].

The term "Stigmergy" was coined by biologist Pierre-Paul Grasse to refer to termite behavior [4]. The study of Stigmergy has influenced a number of different research fields. In CAS, Stigmergy mostly serves as a rich source of simple yet effective coordination metaphors and mechanisms [7], [10], [13].

The specific meaning of Stigmergy has not been fully developed yet, even though it is being widely used. In the design taxonomy of multi-agent interactions given by H.V.D. Parunak etc., Stigmergy stands for the indirect communication among peer agents [11]. However, according to C. Castelfranchi, the general definition of Stigmergy, "indirect communication through the environment", is rather weak and unprincipled [12]. He regards Stigmergy as a subcategory of BIC (Behavior Implicit Communication) [12], and defines it as "the process of indirect communication of behavioral messages with implicit signals" [13]. A. Omicini and his colleagues take environment as a key concept to grasp the meaning of Stigmergy, and endeavor to implement it as artifacts [5]–[7].

In this paper, we try to understand Stigmergic by returning to its literal meaning. The word "Stigmergy" is derived from the Greek words "*στίγμα stigma*" (mark, sign) and "*ἔργον ergon*" (work, action) [10], which indicates that an agent's actions leave signs in the environment, thus carrying the sense of "incitement to work by products of work" [12]. Hinted by the related work [7], [9], [10], [12]–[14], we think that the role of "Sign" in Stigmergy is very essential. In a Stigmergic CAS, Sign is the link between all components and the link between all the components and environment. So, Sign is the key to identify and grasp Stigmergy in CAS.

Section 2 proposes a definition of Sign and presents its basic characteristics. And for further understanding, the agent-Sign and environment-Sign relationships are analyzed in detail. Based on Sign, Sect. 3 presents a conceptual model of Stigmergy. Section 4 provides a case study of analyzing the emergence using SBMS model we proposed, and Sect. 5 concludes and discusses open issues at last.

2. Signs in the Stigmergy

2.1 Definition of the Sign

According to the general view of Stigmergy, we define Sign as *the behavior or the product of activities which is given by agents, represented by environment, and sensed by others*. This definition reveals the nature of Signs described below.

(a) The content of Sign is agent's behavior or the product of agents' activities. This implies that Signs are given by agents. Note that the content only denotes the explicit information that Signs carry, while its implicit meanings rely on agent's mental power.

(b) Environment is the carrier of Signs, and represents them by its states and activities. The only "concrete" form of Signs is the *corresponding states and activities of environment*. This indicates that the messages used for direct communication between agents are not Signs and excluded from the mechanisms in Stigmergy.

(c) Signs can be sensed or observed by other agents. In

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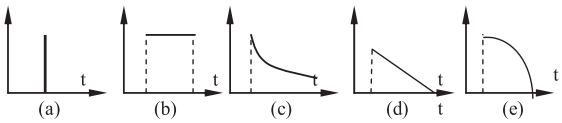

Fig. 1 Examples of the independent dynamics of Signs.

other words, Signs can be traced and interpreted by agents. Therefore, things those are not perceptible can not be Signs. However, agents can not obtain Signs in a straight way, they must get the environmental representations of Signs, then translate them.

2.2 Sign in Itself

Concerning Sign in itself, there are two important issues that deserve discussing.

(a) The significations of Sign

Three facets of Sign's meaning must be distinguished, namely, representation, denotation and connotation. The representation of Sign is given by environment as discussed before. Environment behaves Signs by its states and dynamics. Sign's denotation denotes its content mentioned above. Usually, when talking of Sign, it means its denotation. The connotation of Sign is developed and exploited by agents. Consequently, it may vary with different agents. Agents decide Sign's connotation by Sign's content as well as the mental power and metal states of themselves.

(b) The independent dynamics of Sign

Another important aspect of Sign is its dynamics, which governs the evolution of Sign's attributes. Especially, the independent dynamics refer the dynamic behaviors of Sign's own, which is independent of the activity of agents once Sign is produced.

Several examples are shown in Fig. 1. If agent's current behavior or state is designed as Sign, the Sign is transient (Fig. 1 (a)); if agent set a symbol as Sign, it is unvaried before erased (Fig. 1 (b)); if pheromone is taken as a lot of applications do, it trails off as time passed (Fig. 1 (c), (d), (e)).

2.3 Relationships with Environment

Generally speaking, the relationship between environment and Sign is similar to that between form and content. Deriving from this relationship, there are two pair notions that must be pointed out.

(a) Forms and contents

Sign is represented or expressed mainly in two forms: *environment states and the changes of them*. Commonly, these two forms correspond to the two kind of Sign's content: *the product of agents' activities and agent's behavior*.

(b) Representation and interpretation

To imprint Signs on environment, we demand the representation configuration of Signs. It provides the "dictionary" and "grammar" for translating Signs into environment. That is, representation configuration gives the mappings which are from Signs to environment. Contrarily, interpretation configuration provides the mappings from environment to Signs. Using it, we can retrieve Signs from environment. Therefore, representation and interpretation configurations are closely correlated to each other. They are relatively independent and respectively serve for different goals.

2.4 Relationships with Agent

It is producing-produced and sensing-sensed relationship which exists between agent and Sign.

(a) Producing and sensing

In Stigmergic CAS, agent gives Signs mainly in two ways: active way and passive way. Correspondingly, Signs can be gotten by two means: pulled and pushed, which bring two sensing modes: pulling mode and pushing mode. In pulling mode, agent touches or feels Signs actively, and gets what he wants. Yet, in pushing mode, agent presents its interested Signs and the qualifications of the Signs beforehand; then the relevant Signs are delivered to it once they appear or meet the conditions. These producing and sensing ways can be associated with the perspectives on interaction in [15].

(b) Discrimination and identification

Agents discriminate and identify Signs by their relevant attributes. These attributes may involve every aspect of Sign, for example, the producer, the time it is produced, the location it is situated and so on. They are given by agents when Sign is created or modified. By Signs' attributes, according to their interests and ability, the sensing agents decide which Signs to perceive.

(c) Influence and effectiveness

When agent gets Sign and interprets it to change its mental states, to reinforce its abilities, or to make decision, Signs then has influence on agent. The effectiveness that Sign has on agent is relevant to the connotation of Sign. As discussed before, the connotation of Sign is determined by Sign's content as well as the mental power and metal states of agent. So, the effectiveness of Sign is not unilateral; it is decided by both sides: Sign and agent.

3. SBMS: A Sign-Based Model

Based on the understanding of Sign above, we obtain a Sign-Based Model of Stigmergy (SBMS), which captures the essential characteristics of Stigmergy

3.1 The Basic Architecture

In [10], H.V.D. Parunak has already presented a basic architecture of Stigmergy (Fig. 2 (a)). However, it is only an abstract architecture of MAS in [16]. Figure 2 (b) shows our architecture which employs the Sign.

The architecture shown in Fig. 2 (a) only indicates that Stigmergy is an indirect communication between agents via the environment they are sharing. It seems too simple to

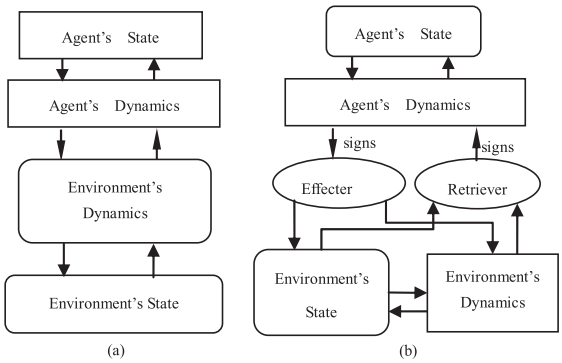

Fig. 2 The basic architectures of Stigmergy.

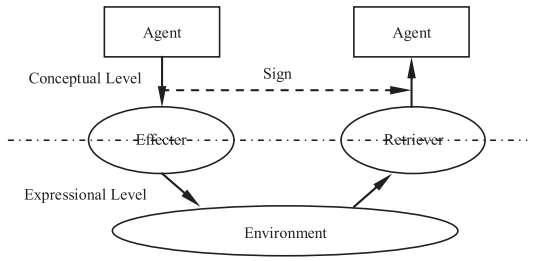

Fig. 3 The two levels of the basic architecture.

help understanding Stigmergy.

In our architecture (Fig. 2 (b)), the notion of Sign is explicitly illustrated. Signs are produced by agent. Then, according to the representation configurations, the *effecter* represents Signs by the state and dynamics of environment. The *retriever* captures the state of environment and uses the interpretation configurations to interpret it to get Signs. Then the obtained Signs are delivered to the requiring agent.

The most prominent dissimilarity between architectures shown in Fig. 2 (a) and Fig. 2 (b) is that the module of Sign is introduced in our architecture. As discussed in Sect. 2, Sign is represented or expressed mainly in two forms: environment states and the changes of them (i.e. environment's dynamics). So, agent can retrieve or leave information via both environment's state and environment's dynamics in our model, which is different from [10].

In fact, in the basic architecture of Stigmergy, there are two levels: *conceptual level* and *expressional level* as Figure 3 shows. Figure 3 depicts that the basic architecture admits the modularity and separation of concerns principles.

In the conceptual level, the coordination between agents only relates to the content of Sign, and does not involve the environmental representation of it. But Signs can be sensed only if they are represented by environment. In the expressional level, the representation of Signs is independent of agent architecture; it just refers to Signs and the realization of environment. The interface of the two levels is *effecter* and *retriever*.

So, the basic architecture of Stigmergy well admits the modularity and separation of concerns principles. And it provides a useful perspective for analyzing and designing Stigmergy.

3.2 Definitions of the Constituents in the Architecture

Some formal definitions are given is this section, such as Sign, environment, agent, etc.

Definition 1. A Sign is a structure: $Sign = (C_S, D_S)$
where

- $C_S = \langle c_{s1}, c_{s2}, \ldots, c_{sn} \rangle$ is the content of Sign. And each c_{si} is an attribute of its content.
- D_S is the independent dynamics of Sign. It gives the laws that govern the evolution of every c_{si}.

Definition 2. An *environment* for representing Signs is a structure: $E = (S_E, D_E)$
where

- S_E is the finite set of the environment temporal states. Every state includes several component statuses and a number of relations between them. That is, $S_E \subset S_{E1} \times S_{E2} \times \cdots \times S_{En} \times R_{ES}$, where $S_{Ei} = \{s_{i1}, s_{i2}, \cdots s_{ij}\}$ and R_{ES} is a set of relations on $\cup S_{Ei}$.
- D_E is the set of dynamics of environment. It governs the independent evolution of environment state.

Definition 3. A *representation configuration* of Signs is a structure: $F_{SR} = (Sg, E, R_S, R_D)$
where

- Sg is the set of Signs to represent.
- E is the representing environment.
- $R_S : C_S \times S_E$ is the set of mapping relations between Sign content and environment state. C_S is the set of Signs' (in Sg) content, and S_E is the set of states of the environment E.
  $R_D : D_S \times D_E$ is the set of mapping relations between Sign dynamics and environment dynamics. D_S is the set of Signs' (in Sg) dynamics, and D_E is the set of the dynamics of environment E.

Definition 4. A *interpretation configuration* of Signs is a structure: $F_{SI} = (S_{ER}, C_{SE}, I_S)$
where

- $S_{ER} \subset S_E$ is a set of environment states to interpret.
- C_{SE} is the content set of Signs that can be retrieved from S_{ER}.
- $I_S : S_{ER} \times C_{SE}$ is the set of mapping relations between environment state and Sign content.

Definition 5. An *effecter* of Signs a tuple of functions: $Effecter = \langle eff_S, eff_D \rangle$
where

- $eff_S : C_S \times F_{SR} \rightarrow S_E$ is a expressing function of Sign's content that translate Sign contents (in contents set C_S) into environment states (in states set S_E) according to the representation configuration (F_{SR}).
- $eff_D : D_S \times F_{SR} \rightarrow D_E$ is a transforming function of Signs' dynamics that translate Sign dynamics (in the D_S) into environment dynamics (in the set D_E) according to

STS	:: = 0 | Env | Ag | Eff | Sen | ST||ST	Configuration of Stigmergic CAS
Env	:: = 0	the Configuration of Environment
	| AllowE (eff, e)	allow the Effecter 'eff' to modify the state 'e'
	| AllowS (sen, e)	allow the Retriever 'sen' to sense the state 'e'
	| Env || Env	combination
Ag	:: = 0	the Configuration of Agent
	| Produce (a, s)	Agent 'a' produces sign 's'
	| Actable (a, s)	Produce (a, s) can be true
	| SenseA (a, b, s)	Agent 'a' sensed the sign 's', which is belong to Agent 'b'
	| ObservableS (a, s)	Agent 'a' can observe the sign 's'
	| ObservableA (a, b, s)	ObservableS (a, s), and s belongs to the Agent 'b'
	| Coordinate (a, b, s)	Agent 'a' coordinates agent 'b' through the sign 's'
	| Ag || Ag	combination
Eff	:: = 0	the Configuration of the Effecter
	| Represent (eff, s, e)	Effecter 'eff' represents sing 's' by using environment 'e'
	| Represent_able (eff, s, e)	Represent (eff, s, e) can be true
	| Have_FR (eff, s, fr)	Effecter 'eff' has the description frame 'fr' of sign 's'
	| Eff || Eff	combination
Sen	:: = 0	the Configuration of Retriever
	| Retrieve (sen, s, e)	Retriever 'sen' retrieves sign 's' from the environment 's'
	| Retrieve_able (sen, s, e)	Retrieve (sen, s, e) can be true
	| Have_FI (sen, s, fi)	Retriever 'sen' has explanation frame 'fi' of the sign 's'
	| Sen || Sen	combination

Fig. 4 Syntax of Stigmergy Configurations in SBMS.

the representation configuration (F_{SR}).

Definition 6. A *retriever* of Signs is a tuple:
$Retriever = \langle retrieve \rangle$
where

- $retrieve : S_E \times F_{SI} \rightarrow C_S$ is a interpreting function that translate environment states (in states set S_E) into Sign contents (in contents set C_S) according to the interpretation configuration (F_{SI}).

Definition 7. A *agent* in Stigmergies is a structure:
$Agent = (S_A, act_A, sen_A, D_A)$
where

- S_A is the internal state of agent, which can not be directly seen by others.
- $act_A : S_A \rightarrow Sg$ is the function that produces Signs (in Sg) according to agent's internal state (in S_A).
- $sen_A : Sg \times S_A \rightarrow S'_A$ is the procedure that develops a new internal state (in SA')according to the retrieved Signs (in Sg) and current internal state (in SA).

$D_A : S_A \rightarrow S'_A$ is the internal dynamics of agent which transforms current state (in SA) to a new state (in SA'). This dynamics is independent of outside world and can be regarded as the "introspection" of agent.

3.3 Operational Semantics of Stigmergy Configurations in SBMS

(a) Syntax of Stigmergy Configuration

$$\frac{\text{AllowE (eff, e)} \in \text{STS}}{\text{Have\_FR (eff, s, fr)}||\text{STS} \rightarrow \text{Represent\_able (eff, s, e)}||\text{STS}} \quad [\text{REP}]$$

$$\frac{-}{\neg\text{AllowE (eff, e)} \vee \neg\text{Have\_FR (eff, s, fr)}||\text{STS} \rightarrow \neg\text{Represent\_able (eff, s, e)}||\text{STS}} \quad [\text{N-REP}]$$

$$\frac{\text{AllowS (sen, e)} \in \text{STS}}{\text{Have\_FI (sen, s, fi)}||\text{STS} \rightarrow \text{Retrieve\_able (sen, s, e)}||\text{STS}} \quad [\text{RET}]$$

$$\frac{-}{\neg\text{AllowS (sen, e)} \vee \neg\text{Have\_FI (sen, s, fi)}|| \text{STS} \rightarrow \neg\text{Retrieve\_able (sen, s, e)}||\text{STS}} \quad [\text{N-RET}]$$

$$\frac{\text{Produce (x, s)} \wedge \text{Represent (eff}_x\text{, s, e)} \in \text{STS}}{\text{Retrieve (sen}_a\text{, s, e)} \,||\, \text{STS} \rightarrow \text{SenceS (a, s)} \,||\, \text{STS}} \quad [\text{SEN-S}]$$

$$\frac{-}{\text{Produce (b, s)} \,||\, \text{Represent (eff}_b\text{, s, e)}|| \text{Retrieve (sen}_a\text{, s, e)}||\text{STS} \rightarrow \text{SenceA (a, b, s)} \,||\, \text{STS}} \quad [\text{SEN-A}]$$

$$\frac{\text{Actable (x, s)} \wedge \text{Represent\_able (eff}_x\text{, s, e)} \in \text{STS}}{\text{Retrieve\_able (sen}_a\text{, s, e)} \,||\, \text{STS} \rightarrow \text{ObservableS (a, s)} \,||\, \text{STS}} \quad [\text{OBS-S}]$$

$$\frac{-}{\text{Actable (b, s)} \,||\, ||\text{Represent\_able (eff}_b\text{, s, e)}|| \text{Retrieve\_able (sen}_a\text{, s, e)}||\text{STS} \rightarrow \text{ObservableA (a, b, s)} \,||\, \text{STS}} \quad [\text{OBS-A}]$$

$$\frac{-}{\text{Produce (a, s)} \,||\, \text{SenseA (b, a, s)}||\text{STS} \rightarrow \text{Coordinate (a, b, s)} \,||\, \text{STS}} \quad [\text{COOD}]$$

Fig. 5 Operational semantics of Stigmergy configurations in SBMS.

According to the representation method in [17], and considering the conception model above, we propose the syntax of Stigmergy configuration in SBMS (Fig. 4).

According to the abstraction level introduced in this paper, the capability configuration of Stigmergy CAS is the combination of environment configuration (Env), Agent configuration (Ag), Sign effecter (Eff), and Sign retriever (Sen), as the figure 4 shows.

The configuration of environment indicates the restriction of Sign effecter and Sign retriever from environment, and points out that the modification and apperceiving privilege of effecter and retriever.

The configuration of Agent is the combination of exterior behavior ability, such as the ability of generating Sign, the ability of apperceiving the Sign, the ability of coordination through Sign.

Besides the ability of representation (apperceiving) of the Sign, the configuration of retriever also include the ability of taking the possession (explanation) of the representation structure.

(b) Operational semantics of Stigmergy configurations

On the basis of the syntax of Stigmergy configuration discussed above, the operational semantics is given as to describe the effective pattern of evolvement of these configurations, as Fig. 5 shows [16].

The left of the rules are the conditions of generating

behavior or possession of ability, while the right is behaviors or conditions generated under left conditions. On top of the rules are conditions of using these rules.

The rule [REP] indicates that, under the permission of environment, if effecter has the corresponding representation structure of Sign, then it has the ability of representation. Correspondingly, [N-REP] elucidates the circumstance that effecter does not have the ability of representation. Similarly, rule [RET] and [N-RET] prescribes the behavior ability of retriever.

The rule [SEN-S] indicates that when the Sign s generated and represented, if Retriever of Agent retrieves the corresponding Sign from environment, well then, the Agent will apperceive the Sign s. Similarly, the rule [SEN-A], [OBS-S], [OBS-A] and [COOD] are not hard to understand.

4. Case Study: Analyzing the Emergence

Two examples which is using SBMS model is illustrated in this section.

4.1 Ant Colony

Stigmergy was first observed and studied in social insects. Furthermore, social ant colony is regarded as typical and universally CAS [20]. So, we introduce an experiment in ant colony firstly. A basic architecture of Stigmergy in ant colony using SBMS model is shown in Fig. 6.

The internal state of ant is invisible to other ants. They do not communicate to each other, and their moving directions will not influence others directly. So, ants exchange information by emitting pheromones [18]–[21]. In this situation, the pheromone is regarded as one particular form of "Sign". There are several objects can't be regarded as Signs, even though they influence ant's behaviors too, for example, stones, grass, sand, etc. Because according to our definition, the content of Sign is agent's behavior or the product of agents' activities. Stones, grass and sand etc. should be considered to be parts of environment or the topology of environment. By the way, these objects do not (at least, not remarkably) improve ants' efficiency in real ant colony either.

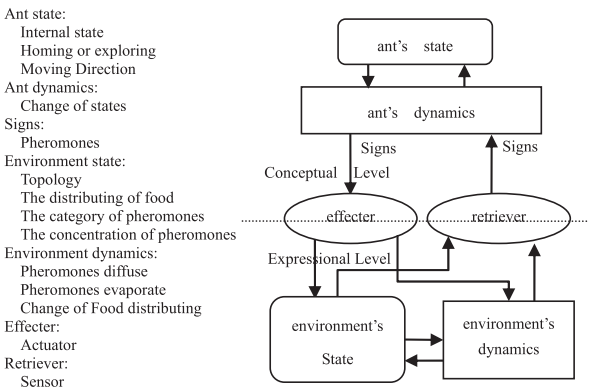

Fig. 6 The basic architectures of Stigmergy in ant colony.

Several facts also can be illustrated from Fig. 6, such as, 1) the pheromones in the conceptual level does not involve the environmental representation of it in expressional level; 2) in the expressional level, the representation of pheromones is independent of ant agent architecture, it just refers to the environment, and 3) the interface of the two levels is effecter and retriever.

So, as discussed above, by contrast with the Stigmergy architecture in [10], our model is helpful for understanding Stigmergy better; furthermore, it well manifests the modularity and separation of concerns principles as well as provides a useful perspective for analyzing and designing Stigmergy.

4.2 Trail Formation

The second example is from human's society. Human have always drawn on Stigmergic mechanisms both to form the trails along which they travel and to choose among alternate existing trails [10].

Figure 7 gives a basic architecture of Stigmergy in trail formation. The flow chart is omitted because it's similar to Fig. 6. The environment is a ground on which can leave trails, such as vegetated terrain, sandy ground. Agents are people, includes pedestrians and people in vehicles. Agents wear down the vegetation (or leave behind footprints) on frequently traveled routes. On the other hand, grass regrows (or footprints are covered up by sand blown by wind) if an old path is not used. So, vegetation covers or footprints are regarded as Signs in this model.

The markers set by travelers, such as road signs, can be helpful to guide others to find valid ways or even shortcuts.

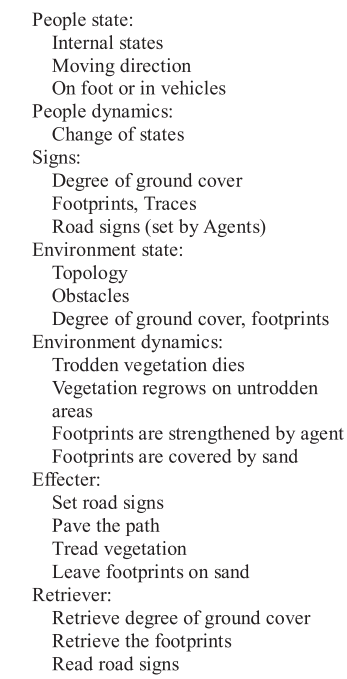

Fig. 7 The basic architectures of Stigmergy in trail formation.

They are in accord with our definition of Sign, but those set by road workers or others are not Signs.

As two examples discussed above show, we can get a better understanding of Stigmergy by distinguishing an object is a Sign or not. For example, the stones and grass in 4.1 and road signs set by road workers in 4.2 are not Signs. They are excluded from the mechanisms in Stigmergy even though they are helpful to agents.

On the other hand, our SBMS model illustrates a fact that both environment states and dynamics can interact on agents' states via effecting Signs by effecters or retrieving Signs by retriever. By the way, because of involving in implementing details, the syntax and operational semantics of Stigmergy of these examples are not expatiated in this section.

5. Conclusions and Future Work

In this paper, we take "Sign" as a key concept to grasp Stigmergy. By the definition that reveals the nature of Signs, we exploit the significations and relationships carried by the notion of Sign. As a result, a conceptual model of Stigmergy, SBMS, is developed, which captures the essential characteristics of Stigmergy.

We illustrate the methodology which analyzing emergence in CAS using SBMS model, and several experiments are provided.

The notion of Sign not merely offers a novel perspective and a general model of Stigmergy, but rather provides a methodology for analyzing, designing and implementing stigmergic CAS which is a very significant direction of Stigmergy research. Moreover, based on Information Theory, SBMS can be used in studying the emergent behavior of Stigmergy which is a very important aspect of it, such as investigating flows of Sign information in Stigmergy, analyzing emergence of CAS quantitatively, and interpreting the emergence mechanism thereinto. This is the work we are just doing.

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