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The Knowledge Domain of an Hierarchical Distributed System Determines its Architecture

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Abstract. The concept of a distributed reasoning system based on semantic schemas organized on three levels was introduced in ([4]). We intend to construct an improved version for this kind of system, in which the number of the system's levels is not restricted to a certain one. Instead, it will depend greatly on the size of the system's knowledge domain. This article presents a method by means of which the architecture for an hierarchical distributed system can be defined based on the system's knowledge domain.

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1. Introduction

Reasoning about knowledge seems to play a fundamental role in distributed systems ([7]). Different kinds of labelled graphs have been used to represent knowledge. In artificial intelligence they are named *semantic networks*. Over the years, many models of this family have been developed ([6]) such as the *existential graph* model of C. Peirce or the related *conceptual graph* model of J. Sowa ([8]).

The *semantic schema* concept was introduced in ([5]) in order to extend that of semantic network.

In ([4]) we presented a distributed knowledge system organized on three levels which uses the semantic schema theory as the knowledge representation and reasoning mechanism.

The architecture of this system does not depend on the volume of information the system has to process. The system uses a fixed number of agents in order to collect the information and a fixed number of managers in order to process them.

In this article we present a new architecture for this kind of system.

In comparison with the architecture for the system presented in ([4]), this new one is also defined on levels but is built based on the system's knowledge domain. As consequence, in this organization the number of levels is not restricted to a certain one. Results that also the number of the used agents and managers is not a priori established. This new method for defining the architecture presents some advantages that will be relieved in the subsequent sections of this paper.

2. Prerequisites

Consider a symbol θ of arity 2 and a finite non-empty set A_0. We denote by $\overline{A}_0$ the Peano θ-algebra generated by A_0, therefore $\overline{A_0} = \bigcup_{n\geq 0} M_n$ where M_n are defined

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recursively as follows ([2]):

$$\begin{cases} M_0 = A_0 \\ M_{n+1} = M_n \cup \{\theta(u,v) \mid u,v \in M_n\} \end{cases} \tag{1}$$

For every $\alpha \in \overline{A_0}$ we define $trace(\alpha)$ as follows:
if $\alpha \in A_0$ then $trace(\alpha) =< \alpha >$
if $\alpha = \theta(u,v)$ then $trace(\alpha) =< p,q >$ for $trace(u) =< p >$ and $trace(v) =< q >$

A semantic schema is an abstract structure, which can represent knowledge by means of an appropriate interpretation. Such a structure is a tuple of four components defined as follows:

Definition 2.1. *([5]) A* **semantic θ-schema** *is a system $\mathcal{S} = (X, A_0, A, R)$ where:*

- *X is a finite non-empty set of object symbols*
- *A_0 is a finite non-empty set of label symbols*
- *$A_0 \subseteq A \subseteq \overline{A}_0$, where $\overline{A}_0$ is the Peano θ-algebra generated by A_0*
- *$R \subseteq X \times A \times X$ is a non-empty set which fulfills the following conditions*
    - *($C1$) If $(x, \theta(u,v), y) \in R$ then $\exists\ z \in X : (x,u,z) \in R$ and $(z,v,y) \in R$*
    - *($C2$) If $\theta(u,v) \in A$, $(x,u,z) \in R$, $(z,v,y) \in R$ then $(x, \theta(u,v), y) \in R$*
    - *($C3$) $pr_2 R = A$*

Such a structure provides a **reasoning environment** for the represented relations by means of:

- some formal computations guided by the elements of the Peano algebra A. These computations are based on the concept of *derivation* ([3]).
- some evaluation aspects based on the interpretations corresponding to the elements of $\mathcal{S}$.

3. The knowledge domain of the system

Starting from the architecture of the previous version, our new proposal for the architecture of an **H**ierarchical **D**istributed **R**easoning System (shortly HDR System) also consists of some agents and some managers by means of which the distributed reasoning of the system is performed.

For this reason, the agents and the managers of an HDR system are called the **reasoning entities** of the system.

Like every other reasoning system, an HDR system is endowed with a specific *domain of knowledge.*

Definition 3.1. *The knowledge domain of an HDR system consists of a set of binary relations that can be represented and processed using the semantic schema representation and reasoning mechanism.*

The input of an HDR system is composed of a text in natural language in which instances of relations from its domain are described. We will call the relations that can appear in inputs as the **initial relations** of the system.

In this version, the chosen domain of knowledge has a special significance in the designing of the system.

Thus, if in the previous version each system's level was dedicated to a certain kind of reasoning entities (the agents compose the first level, the primary managers belong to the second level and the general manager is the single component of the third level) in this version the architecture of the system is determined by the volume of deductions that can be made based on the initial relations of the system.

Definition 3.2. *We say that a* **reasoning entity** *is specialized on some relations of the system's domain if it knows:*

- how to represent them in a semantic schema using the symbolism of the system

- how to process them in the obtained semantic schema's reasoning environment.

Based on this specialization, in an HDR system we have two kinds of reasoning entities: agents and managers.

Definition 3.3. *An agent is the reasoning entity which is specialized on a certain subset of system's initial relations set and which belongs to the first level of the system.*

Definition 3.4. *A manager is the reasoning entity which is specialized on certain relations obtained below in the system architecture by two different reasoning entities.*

4. Internal and external representations of the system's knowledge domain

As we have said, the domain of an HDR system is a set of binary relations. Because the system uses the semantic schema mechanism for knowledge representation and processing, these relations must have two representations:

- **internal representations** for the formal computations
- **external representations** for providing the answers to the interrogations

The internal representation of the system's initial relations is a set of labels (symbols) that is noted with A_0. The external representation of these relations consists of the verbal constructions in natural language corresponding to the abstract elements of A_0. These constructions are returned by a set of algorithms noted with $\{Alg_u\}_{u\in A_0}$.

The set A_0 is divided in n_1 non-empty disjoint subsets: $A_0^1, \ldots, A_0^{n_1}$, $n_1 > 1$, in order to increase the speed of processing the elements of A_0. Based on these subsets the system is endowed with n_1 agents, noted $Ag_1, \ldots, Ag_{n_1}$ such that:

$$\forall i = \overline{1, n_1} \text{ the set } A_0^i \text{ is the specialization of the agent } Ag_i.$$

We have:

- $A_0^1 \cup \ldots \cup A_0^{n_1} = A_0$ such that $\forall i = \overline{1, n_1} : A_0^i \neq \emptyset$
- $A_0^i \cap A_0^j = \emptyset$, $\forall i, j \in \{1, \ldots, n_1\}$, $i \neq j$

Remark 4.1. *The last property of the sets $A_0^1, \ldots, A_0^{n_1}$ tells us that $\forall a \in A_0$, $\exists! i \in \{1, \ldots, n_1\}$ such that $a \in A_0^i$. This means that every initial relation of the system is in the specialization of an unique agent.*

If we note by L_1 the set of the first level's components of an HDR system we have:

$$L_1 = \{Ag_1, \ldots, Ag_{n_1}\}, n_1 > 1$$

Each agent Ag_i, $i = \overline{1, n_1}$ in order to be able to compose the relations from its specialization is endowed with:

- a subset A^i of the Peano θ-algebra generated by A_0^i: $A_0^i \subseteq A^i \subseteq \overline{A_0^i}$ defined as follows:

$$A^i = \{u \in \overline{A_0^i} \mid Alg_u^i \ can\ be\ defined\ and\ has\ meaning\}$$

- the corresponding external representations of the symbols of A^i, that is the set $\{Alg_u^i\}_{u\in A^i}$. Of course, for preserving the symbolism of the system we have:

$$\{Alg_u^i\}_{u\in A_0^i} = \{Alg_u\}_{u\in A_0^i}$$

At the second level we find knowledge managers specialized on the sets generated by some agents of the first level. We note by L_2 the set of these components:

$$L_2 = \{KM_{v_{n_1+1}}, \ldots, KM_{v_{n_2}}\}, n_2 \geq n_1 + 1$$

where $\forall i = \overline{n_1 + 1, n_2}$:

- there are $i_1, i_2 \in \{1, \ldots, n_1\}$, $i_1 \neq i_2$ such that $v_i = (i_1\ i_2)$. This notation represents the fact that the sets A^{i_1} and A^{i_2} are the specialization of KM_{v_i}.
- each manager KM_{v_i} is endowed with a set noted $A^{v_i}_{joint}$ because, as will be detailed in the next section, it is obtained by **joining** the labels of A^{i_1} with the labels of A^{i_2}.
- there is not $j \in \{n_1 + 1, \ldots, n_2\}$ such that $v_i \equiv v_j$

Using the same notations, the set of the components of the l-th level, $l \geq 3$, consists of those managers:

$$L_l = \{KM_{v_{n_{l-1}+1}}, \ldots, KM_{v_{n_l}}\}, n_l \geq n_{l-1} + 1$$

such that $\forall i = \overline{n_{l-1} + 1, n_l}$:

- KM_{v_i} contains in its specialization at least a set of relations' labels obtained at the $(l-1)$-th level. For $v_i \in \{v_{n_{l-1}+1}, \ldots, v_{n_l}\}_{l \geq 3}$ we have two possibilities. If:
  - $v_i = (i_1\ v_{i_2})$ with $i_1 \in \{1, \ldots, n_1\}$ and $i_2 \in \{n_{l-2}+1, \ldots, n_{l-1}\}$ then $A^{v_i}_{joint}$ is obtained by joining A^{i_1} with $A^{v_{i_2}}_{joint}$
  - $v_i = (v_{i_1}\ v_{i_2})$ with $i_1 \in \{n_1 + 1, \ldots, n_{l-1}\}$ and $i_2 \in \{n_{l-2} + 1, \ldots, n_{l-1}\}$ then $A^{v_i}_{joint}$ is obtained by joining $A^{v_{i_1}}_{joint}$ with $A^{v_{i_2}}_{joint}$
- there is not $j \in \{n_{l-1} + 1, \ldots, n_l\}$ such that $v_i \equiv v_j$.

Proposition 4.1. *From the way the sets L_l are defined we have that each manager $KM_{v_i} \in L_l$ has an unique specialization, $l \geq 2$, $i \in \{n_{l-1} + 1, \ldots, n_l\}$.*

Proof. Lets suppose that $\exists KM_{v_i} \in L_{l_1}$ and $\exists KM_{v_j} \in L_{l_2}$ such that $v_i \equiv v_j$, $l_1, l_2 \geq 2$, $i \in \{n_{l_1-1}, \ldots, n_{l_1}\}$, $j \in \{n_{l_2-1}, \ldots, n_{l_2}\}$, $i \neq j$.

Because each manager is specialized on at least one set of labels of the previous level we have that:

- $v_i = (x\ i_1) : i_1 \in \{1, \ldots, n_{l_1-1}\}_{l_1=2} \cup \{v_{n_{l_1-2}+1}, \ldots, v_{n_{l_1-1}}\}_{l_1>2}$ where: $x \in \{1, \ldots, n_{l_1-1}\}_{l_1=2} \cup \{v_{n_1+1}, \ldots, v_{n_{l_1-1}}\}_{l_1>2}$, $x \neq i_1$
- $v_j = (y\ i_2) : i_2 \in \{1, \ldots, n_{l_2-1}\}_{l_2=2} \cup \{v_{n_{l_2-2}+1}, \ldots, v_{n_{l_2-1}}\}_{l_2>2}$ where: $y \in \{1, \ldots, n_{l_2-1}\}_{l_2=2} \cup \{v_{n_1+1}, \ldots, v_{n_{l_2-1}}\}_{l_2>2}$, $y \neq i_2$.

Thus we obtain:

$$v_i \equiv v_j \Leftrightarrow (x\ i_1) \equiv (y\ i_2) \Leftrightarrow i_1 = i_2$$

The last double implication if true only if $l_1 = l_2$ or equivalently if KM_{v_i} is at the same level with KM_{v_j}.

Resuming, two managers KM_{v_i} and KM_{v_j} can have identical specializations if they belong to the same level. We write this as follows:

$$v_i \equiv v_j \Rightarrow KM_{v_i}, KM_{v_j} \in L_l, l \geq 2 \tag{2}$$

Obviously, from the way the levels of an HDR system are defined results that $\nexists KM_{v_i}, KM_{v_j} \in L_l, l \geq 2$ such that $v_i \equiv v_j$.

Thus we have proved that each manager of an HDR system has an unique specialization.■

At this point we can summarize the representations used in an HDR system:

Definition 4.1. *For an HDR system with k levels, $k > 1$ and the set A_0 of initial relations:*

- *the internal representation of the system's knowledge domain consists of the following n_k sets of relations' labels:*
$$\{A^1, \ldots, A^{n_1}, A_{joint}^{v_{n_1+1}}, \ldots, A_{joint}^{v_{n_2}}, \ldots, A_{joint}^{v_{n_{k-1}+1}}, \ldots, A_{joint}^{v_{n_k}}\}$$
where: $A^1, \ldots, A^{n_1}$ form the reasoning environment for the system's agents and $A_{joint}^{v_{n_1+1}}$, ..., $A_{joint}^{v_{n_k}}$ form the reasoning environment for the system's managers.
- *the corresponding external representation of these labels of relations from the system's knowledge domain consists of the following n_k sets of algorithms:*
$$\{\{Alg_u^1\}_{u\in A^1}, \ldots, \{Alg_u^{n_1}\}_{u\in A^{n_1}}, \{Alg_u^{v_{n_1+1}}\}_{u\in A_{joint}^{v_{n_1+1}}}, \ldots, \{Alg_u^{v_{n_k}}\}_{u\in A_{joint}^{v_{n_k}}}\}$$

4.1. The joining operation of two sets of labels. As we have said, each manager of an HDR system is endowed with a set of relations' labels obtained by joining two sets of the same type. In ([1]) we presented a method that links two semantic schemas in a bigger structure based on a joining operation between the relations' labels sets of the considered schemas. This structure will include both schemas and moreover we proved that the obtained construction is also a semantic schema.

Shortly, the operation that joins the elements of two sets of labels is defined as follows:

Definition 4.2. *Let us consider two Peano θ-algebras V and W. We note by $\bowtie$ the joining operation that composes the symbols of V with the symbols of W using the same binary algebraic operation θ. We have:*
$$\bowtie : V \times W \to \overline{V \cup W}$$
$$V \bowtie W = \{u \mid trace(u) =< u_1, \ldots, u_r >, r \geq 2 : \begin{array}{l}\{u_1, \ldots, u_r\} \subseteq V \cup W \\ \{u_1, \ldots, u_r\} \cap V \neq \emptyset \\ \{u_1, \ldots, u_r\} \cap W \neq \emptyset\}\end{array}$$
We note by $\overline{V \cup W}$ the Peano θ-algebra generated by $V \cup W$.

Proposition 4.2. *Let us consider two Peano θ-algebras V and W. For every subsets $V_1 \neq \emptyset$, $W_1 \neq \emptyset$ such that $V_1 \subseteq V$ and $W_1 \subseteq W$ we have:*
$$V_1 \bowtie W_1 \subseteq V \bowtie W$$

Proof. We verify that $V_1 \bowtie W_1 \subseteq V \bowtie W$ by proving the following relation:
$$(\forall u) : u \in V_1 \bowtie W_1 \Rightarrow u \in V \bowtie W$$
Indeed, from $u \in V_1 \bowtie W_1$ with $trace(u) =< u_1, \ldots, u_r >$ we have:
$\{u_1, \ldots, u_r\} \subseteq V_1 \cup W_1 \Rightarrow \{u_1, \ldots, u_r\} \subseteq V \cup W$ because $V_1 \cup W_1 \subseteq V \cup W$
$\{u_1, \ldots, u_r\} \cap V_1 \neq \emptyset \Rightarrow \{u_1, \ldots, u_r\} \cap V \neq \emptyset$ because $V_1 \subseteq V$
$\{u_1, \ldots, u_r\} \cap W_1 \neq \emptyset \Rightarrow \{u_1, \ldots, u_r\} \cap W \neq \emptyset$ because $W_1 \subseteq W$
and thus we obtain that $u \in V \bowtie W$.■

Thus, the sets that are used to construct the reasoning environment for the managers of the system, noted by $A_{joint}^{v_i}$, $i = \overline{n_1 + 1, n_k}$ can be defined as subsets of the joining operation's result between the sets of their specialization.

Definition 4.3. *The sets used to endowed the managers of an HDR system with the general architecture $HDRS_{A_0}$ are defined as follows:*

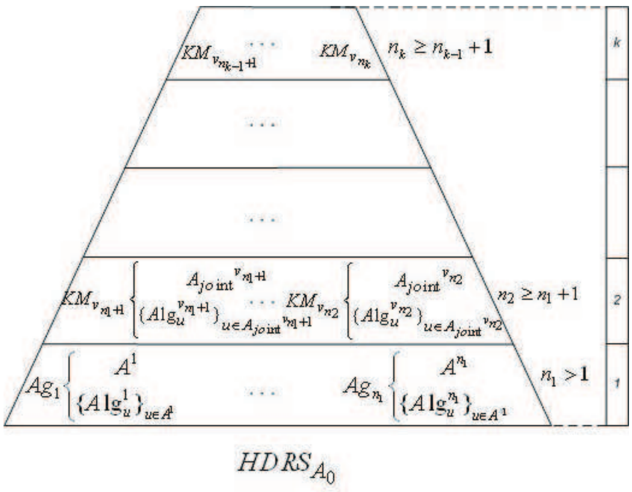

FIGURE 1. The general architecture of an HDR system

- *The sets used to endowed the managers of the second level of* $HDRS_{A_0}$*, that is, the sets* $A_{joint}^{v_{n_1+1}}, \ldots, A_{joint}^{v_{n_2}}$ *are defined as follows:*
  $\forall v_i = (i_1\ i_2), i = \overline{n_1+1, n_2}$ *and* $i_1, i_2 \in \{1, \ldots, n_1\}, i_1 \neq i_2$:
  $$A_{joint}^{v_i} = \{u \in A^{i_1} \bowtie A^{i_2} \mid Alg_u^{v_i} \text{ can be defined and has meaning}\}$$
- *The sets used to endowed the managers of the l-th level of* $HDRS_{A_0}$*,* $l \geq 3$*, that is, the sets* $A_{joint}^{v_{n_{l-1}+1}}, \ldots, A_{joint}^{v_{n_l}}$ *are defined as follows:*
  $\forall i = \overline{n_{l-1}+1, n_l}$*, if:*
  - $v_i = (i_1\ v_{i_2})$ *for* $1 \leq i_1 \leq n_1$ *and* $n_{l-2}+1 \leq i_2 \leq n_{l-1}$ *then*
  $$A_{joint}^{v_i} = \{u \in A^{i_1} \bowtie A_{joint}^{v_{i_2}} \mid Alg_u^{v_i} \text{ can be defined and has meaning}\}$$
  - $v_i = (v_{i_1}\ v_{i_2})$ *for* $n_1+1 \leq i_1 \leq n_{l-1}$ *and* $n_{l-2}+1 \leq i_2 \leq n_{l-1}, i_1 \neq i_2$ *then*
  $$A_{joint}^{v_i} = \{u \in A_{joint}^{v i_1} \bowtie A_{joint}^{v_{i_2}} \mid Alg_u^{v_i} \text{ can be defined and has meaning}\}$$

5. The general architecture of an HDR system

Based on the presented notations, we can define the architecture of an HDR system corresponding to the set A_0 of its initial relations.

Because this architecture contains reasoning entities that can process every relation symbolized by the elements of A_0 we will call it the **general architecture** of the system.

Definition 5.1. *The general architecture of an HDR system corresponding to the set* A_0 *of the system's initial relations labels is the tuple:*
$$HDRS_{A_0} = (L_1, L_2, \ldots, L_k)_{k>1}$$
where:
- $L_1 = \{Ag_1, \ldots, Ag_{n_1}\}_{n_1>1}$
- $L_2 = \{KM_{v_{n_1+1}}, \ldots, KM_{v_{n_2}}\}_{n_2 \geq n_1+1}$
  $\forall i = \overline{n_1+1, n_2}, \exists i_1 \neq i_2 : i_1, i_2 \in \{1, \ldots, n_1\}$ *such that* $v_i = (i_1\ i_2)$
- $(\forall l) 3 \leq l \leq k$:

$L_l = \{KM_{v_{n_{l-1}+1}}, \ldots, KM_{v_{n_l}}\}_{n_l \geq n_{l-1}+1}$
$\forall i = \overline{n_{l-1}+1, n_l}, \exists i_1 \in \{1, \ldots, n_1\}(i_1 \in \{n_1+1, \ldots, n_{l-1}\})$ *and*
$\exists i_2 \in \{n_{l-2}+1, \ldots, n_{l-1}\} : v_i = (i_1\ v_{i_2})(v_i = (v_{i_1}\ v_{i_2}))$

such that:

- $A_0 = A_0^1 \cup \ldots \cup A_0^{n_1}$
  - **(S1)** $\forall i = \overline{1, n_1}$ *the set* $A_0^i \neq \emptyset$ *is the specialization of the agent* Ag_i
  - **(S2)** $A_0^i \cap A_0^j = \emptyset$, $\forall i, j \in \{1, \ldots, n_1\}$, $i \neq j$
- **(S3)** $\forall i \in \{n_1+1, \ldots, n_k\}$:
  - $A_{joint}^{v_i} \neq \emptyset$
  - $\forall j \in \{n_1+1, \ldots, n_k\}$, $j \neq i$ *we have* $v_i \neq v_j$

The conditions (**S1**) $\div$ (**S3**) regard the specializations of the reasoning entities of $HDRS_{A_0} = (L_1, L_2, \ldots, L_k)_{k>1}$. Thus, these components must fulfill the following three conditions:

- (**S1**) each agent Ag_i is specialized on a non-empty subset A_0^i of A_0; $1 \leq i \leq n_1$.
- (**S2**) there are no two agents specialized on a same initial relation of the system domain
- (**S3**) each manager of the system has an unique non-empty specialization

6. Conclusions and Future work

It is obviously that the inputs of an HDR system do not necessarily contain all the initial relations of the system's domain. Because of this, using the general architecture to process only a subset of the system's initial relations set is not very efficient.

Thus it will be helpful if we could easily construct architectures specialized on each input's relations based on the general one. For this reason we intend to define a method by means of which restrictions of the general architecture to any non-empty subsets of the system's initial relations set can be constructed.

And also we intend to present how the semantic schema's reasoning mechanism is implemented in HDR systems organized in the presented manner in order to make deductions and answer to interrogations.

This new method for defining the architecture of an HDR system based on the system's knowledge domain has several advantages:

- the obtained architecture contains as many levels as the system needs for processing the relations from its domain of knowledge
- new architectures for every sub-domain of the system's knowledge domain can be defined based on the general architecture
- any modification of the system's domain will be reflecting only on some components easily to be identified because of the used notations

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