

# Autonomous Semantic Link Networking Model for the Knowledge Grid<sup>1</sup>

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**Abstract.** A Semantic Link Network (SLN) consists of nodes (entities, features, concepts, schemas or communities) and semantic links between nodes. This paper proposes an autonomous Semantic Link Network formalism to support intelligent applications on large-scale network. The formalism integrates the SLN logical reasoning with the SLN analogical reasoning and the SLN inductive reasoning as well as existing techniques to form an autonomous semantic overlay. The SLN logical reasoning mechanism derives implicit semantic relations by a semantic matrix and relevant addition operation and multiplication operation based on semantic link rules. The SLN analogical reasoning mechanism proposes conjectures on semantic relations based on structural mapping between nodes. The SLN inductive reasoning mechanism derives general semantics from special semantics. The cooperation of diverse reasoning mechanisms enhances the reasoning ability of each therefore provides powerful semantic ability for the semantic overlay. Self-organizing diverse scales of semantic link network supports intelligent applications of the Knowledge Grid.

**Keywords.** Analogy, Knowledge Grid, Reasoning, Semantic Link Network, Semantic Grid.

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## **1. Introduction**

### **1.1 The Semantic Issue**

The first fundamental issue in developing the Semantic Web [1], the Semantic Grid ([23], [www.semanticgrid.org](http://www.semanticgrid.org)) and the Knowledge Grid [20] is to find an appropriate semantic representation model to codify semantics, which, ideally, is both human-readable and machine-understandable, so that human and machine can understand each other. Previous approaches like various metadata [3], ontologies (e.g., Wordnet, <http://wordnet.princeton.edu>; Framenet, <http://framenet.icsi.berkeley.edu>; GUM, [www.purl.org/net/gum2](http://www.purl.org/net/gum2)) and markup languages (e.g., XML, RDF, Topic Map and OWL, [www.w3.org/TR/](http://www.w3.org/TR/)) are static and passive. DAML+OIL uses some modeling primitives of frame-based languages ([www.w3.org](http://www.w3.org)).

The second fundamental issue is to create an advanced semantic computing model that supports reasoning and resource organization (normal organization, self-organization, or the synergy of normal organization and self-organization) [20, 25]. An ideal solution is an autonomous semantic overlay that supports distributed intelligent applications.

### **1.2 The Semantic Link Network**

The Semantic Link Network SLN was for establishing semantic relationships among various resources (data, image, and various documents) aiming at extending the hyperlink network World Wide Web to a semantic-rich network and establishing the Active Document Framework [19]. However, a Semantic Link Network on entities reflects semantics between individuals. Semantic links between schemas (the definition of the structure of a set of data types and relevant constraints) reflect semantics between groups [25]. Semantic relationships between abstract concepts are knowledge that can be applied to wider applications. So a Semantic Link Network needs two levels: an abstraction level and an entity level.

An SLN consists of semantic nodes and semantic links (relations) between nodes. *A semantic node can be a semantic community, a schema, a concept, a feature, an entity, or an identity. A semantic community is a Semantic Link Network that represents integrated*

semantics. It has no isolated nodes or parts. The normal forms (NF) of Semantic Link Network were proposed in [20]. A 4NF Semantic Link Network is an ideal semantic community. For example, the SLN of graph theory and the SLN of set theory are semantic communities of the SLN of mathematics.

*The original semantics consists of primitive concepts, axioms and feature space.* Primitive concepts and axioms are commonsense. *Feature space* is an  $n$ -dimensional space  $\{ \langle \text{feature: type} \rangle \mid \text{feature belongs to the name set and the type defines the value set of the feature} \}$ , which includes the features of all concepts.

A concept is described by a sub-space of the *feature space* and the relations on features as follows: *Concept*:  $\langle \{ \text{feature: type}; \dots; \text{feature: type} \}, L \rangle$ , where  $L$  can be a null set (for simple concepts) or a set of concepts and axioms representing the semantic relations on features. The subtype relationship between concepts constitutes concept hierarchies, where a low-level subtype concept inherits all features and relations of its super-concept at higher level and can include more features. An entity is a point in the feature space:  $\{ \text{feature: value}; \dots; \text{feature: value} \}$ . Every entity is also called an instance of a concept.

Semantic links and features of semantic nodes could be derived from relevant semantic links and semantic nodes in SLN. Compared with the World Wide Web, the Semantic Link Network has the following advantages:

- (1) Support semantic browsing and reasoning at both the entity (instance) level and the abstraction level. Browsing the entity level, users or agents could foresee the content of the next-hop by checking surrounding semantic links. The semantic linking rules can extend such foresee to multiple hops. Browsing the abstraction level, users or agents can obtain knowledge about the underlying content.
- (2) Provide with not only the answer but also relevant contents that semantically link to the answer.
- (3) Derive out the semantics of a node or propose conjectures by semantic reasoning. For example, the semantics of a node can be fixed if it is a *subtype* of a node with known semantics.

Figure 1 shows a Semantic Link Network with an abstraction level and an instance level.

Both levels support semantic query. A semantic link  $A-l \rightarrow B$  means that there exists a semantic relation  $l$  from  $A$  to  $B$  (the reverse of a semantic link is hold for some semantic relations). Implication relationship exists between semantic links, for example, if  $A$  cooperates with  $B$ , then they might share something (i.e., there exists a share relationship between them). This implication is denoted as a derivation  $A-cooperate \rightarrow B \Rightarrow A-share \rightarrow B$ .

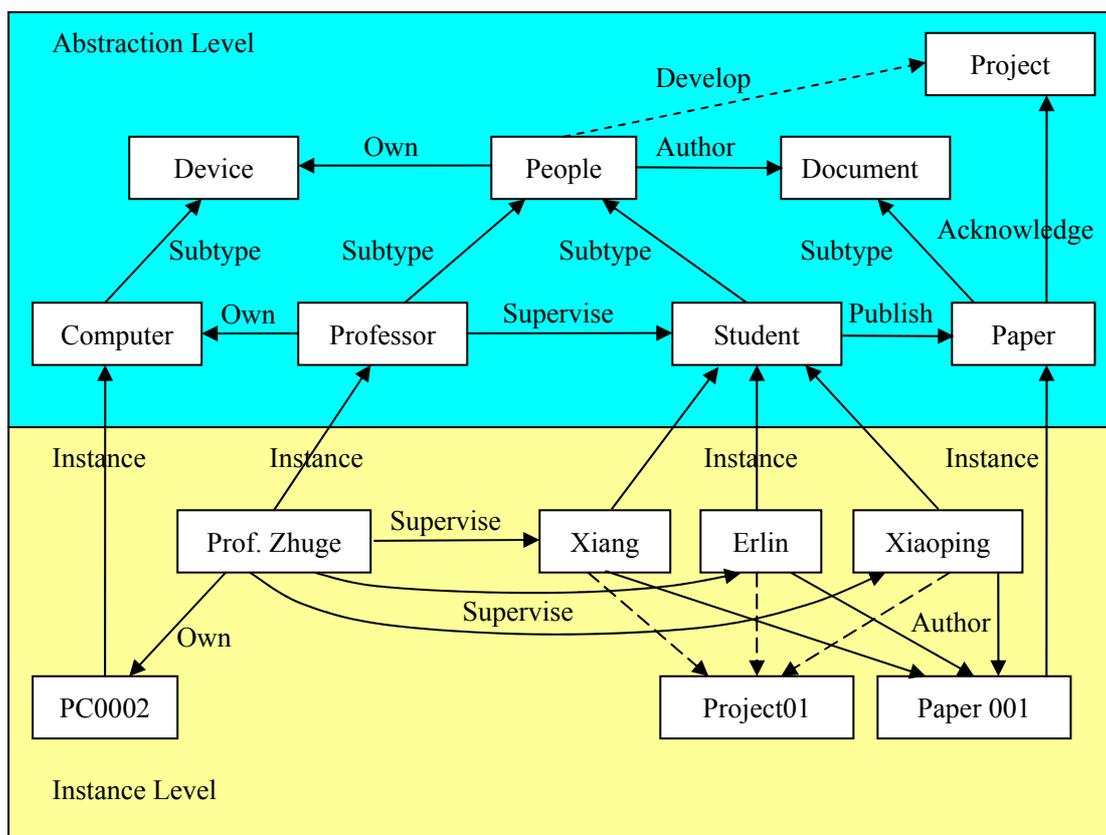


Figure 1. A two-level Semantic Link Network.

Some semantic links sharing a semantic node can derive out a new semantic link. The following are examples of such derivations (semantic link rules):

- (1) " $A-work-for \rightarrow Y, B-work-for \rightarrow Y \Rightarrow A-colleague \rightarrow B$ " means that " $A$  works for  $Y$ " and " $B$  works for  $Y$ " imply " $A$  and  $B$  are colleague". Here the reverse of the colleague relation is still colleague relation.
- (2) " $A-use \rightarrow X, B-use \rightarrow X \Rightarrow A-share \rightarrow B$ " means that " $A$  uses  $X$ " and " $B$  uses  $X$ "

imply “A shares something with B”.

- (3) “ $A\text{---}author\rightarrow P, B\text{---}author\rightarrow P \Rightarrow A\text{---}co\text{---}author\rightarrow B$ ” means that “A is the author of P” and “B is the author of P” imply “A and B are co-author”.
- (4) “ $A\text{---}develop\rightarrow X, B\text{---}develop\rightarrow X \Rightarrow A\text{---}cooperate\rightarrow B$ ” means that “A develops  $X$  (project)” and “B develops  $X$ ” imply “A cooperates with B”.

The general semantic link rules are independent from domain so they can be used as knowledge for reasoning on any Semantic Link Networks. A set of such general semantic link rules was proposed in [19]. The semantic linking rules can be regarded as an operation “.” on semantic factors. For example, the semantic link rule “ $A\text{---}subtype\rightarrow B, B\text{---}instance\rightarrow C \Rightarrow A\text{---}instance\rightarrow C$ ” can be represented as an operation on semantic factors:  $subtype \cdot instance = instance$ .

### 1.3 Autonomous Semantic Link Network and the Knowledge Grid

An autonomous SLN has the following characteristics:

- (1) Autonomously adapt semantic relations with the evolution of the SLN;
- (2) Autonomously establish semantic links between semantic nodes;
- (3) Self-organize diverse scales of SLNs into semantic communities; and,
- (4) Integrate multiple semantic reasoning mechanisms.

A powerful reasoning ability is the basis of intelligent services such as on-demand information provision and decision support. The cooperation of the following reasoning mechanisms can raise the reasoning ability:

- (1) the semantic link reasoning, which can derive implied semantics,
- (2) the SLN analogical reasoning, which can propose conjectures on new semantic relationships that could not be derived out by semantic link reasoning, and
- (3) the SLN inductive reasoning, which can derive abstract semantics according to special semantics.

The Knowledge Grid is an ideal intelligent interconnection environment that enables people or virtual roles to effectively capture, publish, share and manage knowledge resources.

It can provide on-demand services to support innovation, cooperative teamwork, problem-solving and decision making. It concerns three fundamental scientific issues: effective organization model for distributed resources, autonomous semantic networking model, and dynamic clustering of distributed resources [20]. An autonomous semantic overlay provides powerful semantic support for realizing dynamic clustering of resources and knowledge sharing in distributed intelligent applications.

## 2. General Architecture

An autonomous Semantic Link Network not only reflects the static semantic relations between resources but also evolves with the interaction among the following parts: internal formalism, human activities, sharable knowledge, social networks and underlying peer-to-peer networks. Figure 2 describes the general architecture of an autonomous Semantic Link Network, which resolves the following two issues:

- (1) *Autonomous semantic networking*. Using building tools to build a Semantic Link Network is a labor-intensive approach although it is necessary [21]. Autonomous semantic networking means that semantic relations could be created and adapted by reasoning or by automatically discovering in various networks such as hyperlink network, social network and information flow network [7, 16]. Peer-to-peer querying the semantic structures used inside node and matching between structures can establish some semantic relations such as *similar-to* and *inclusion* [25].
- (2) *SLN reasoning*. The SLN logical reasoning can generate the implied semantic relations in existing Semantic Link Networks. The SLN analogical reasoning approach can generate useful conjectures on semantic links or features [18]. The SLN inductive reasoning and statistics-based relation discovery techniques could automatically find semantic links and features, which could inspire new logical and analogical reasoning. The analogical conjectures prompt targets or clues for logical reasoning and inductive reasoning.

The dotted block in Figure 2 shows the core of an autonomous Semantic Link Network. This paper focuses on the SLN logical reasoning, SLN analogical reasoning and SLN inductive reasoning. The analogical reasoning approach herein absorbs the idea of the object analogical reasoning and reflects richer semantics than previous approaches [24].

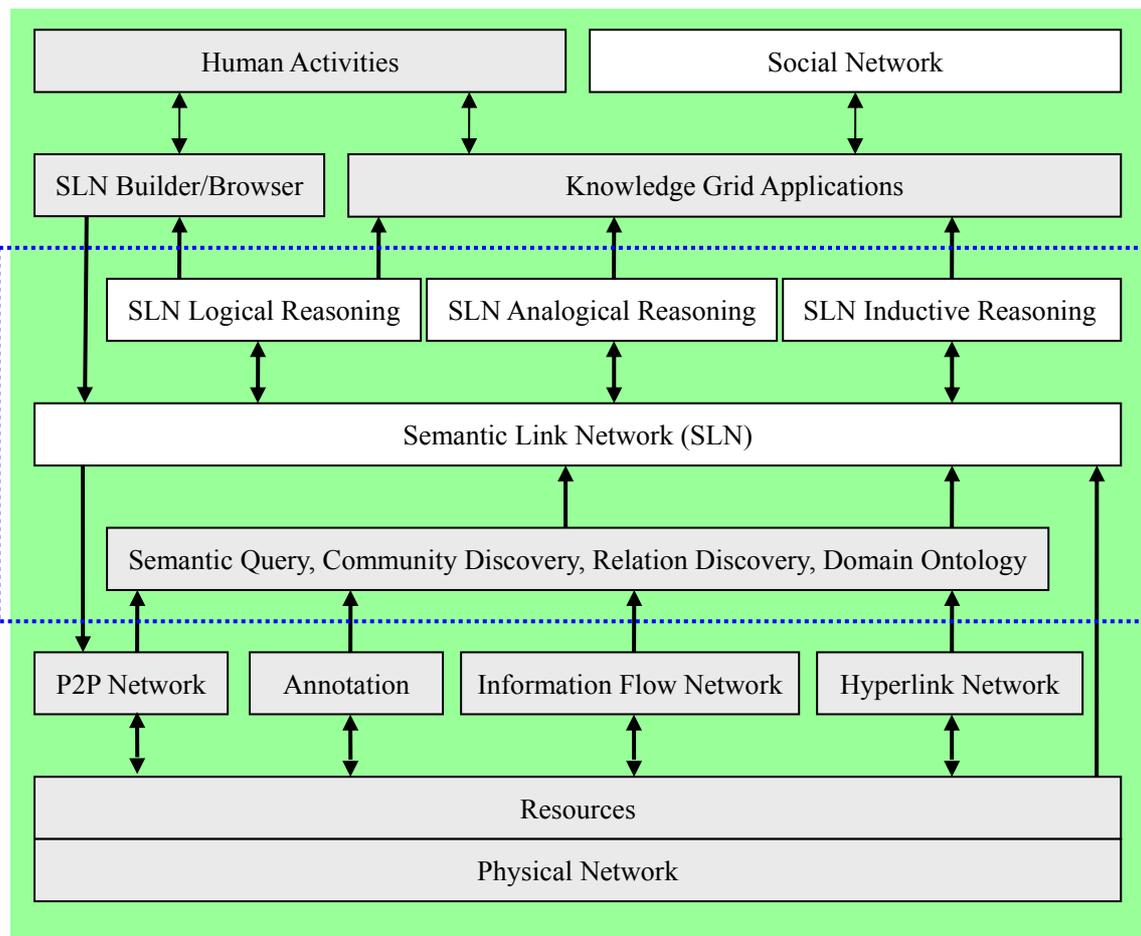


Figure 2. General architecture for autonomous Semantic Link Network.

Figure 3 depicts a self-organized Semantic Link Network. Individual resources are allowed to use diverse semantic representations. For interchange, they need a transformation function ( $\varphi$ ) to transform different individual representations into community semantics that are understandable by all individual resources. With the help of primitive semantics and commonsense knowledge, some semantic links could be established by comparing individual resources under community semantics.

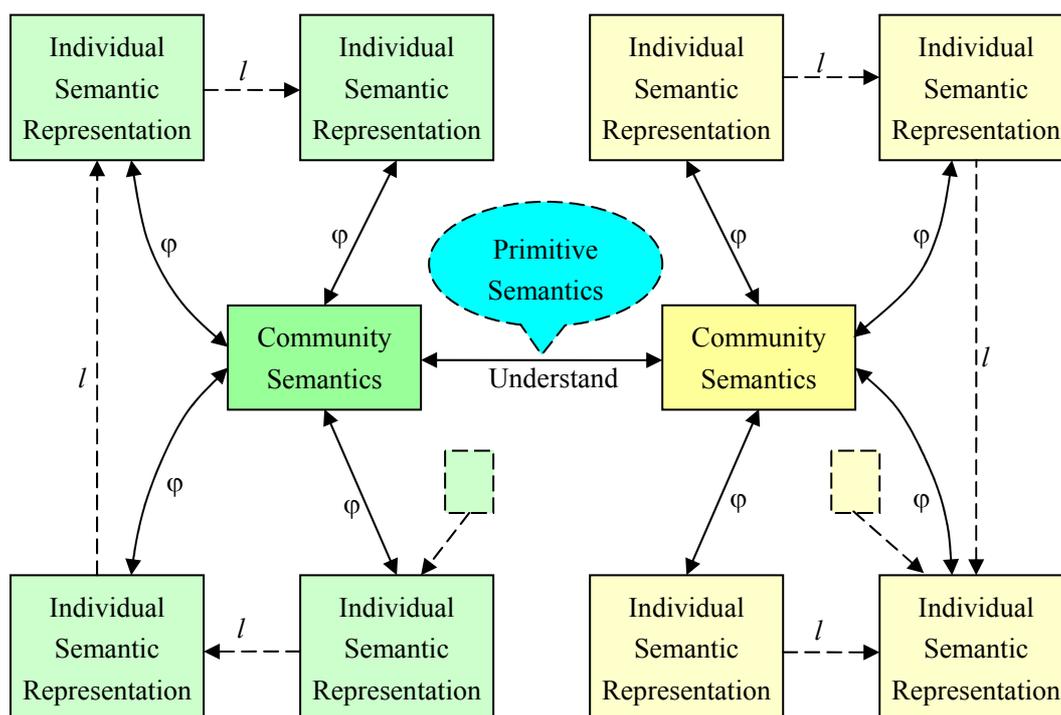


Figure 3. Self-organization of Semantic Link Network.

Different from the growth of the hyperlink network, a new node tends to establish a semantic link with the semantically relevant community or node. The addition of one semantic link could lead to the generation of another new semantic link due to semantic reasoning.

### 3. Semantic Link Networking Formalism

A semantic link from one semantic node  $S$  to another  $S'$  can be represented as  $S \xrightarrow{\langle l, cd \rangle} S'$ , where  $l$  is a semantic factor, and  $cd$  ( $cd \in [0, 1]$ ) measures its uncertainty and incompleteness. Primitive semantic factors reflect a kind of domain-independent knowledge. A primitive semantic factor set (PSF) includes the following semantic factors: *ce* (cause-effect), *imp* (implication), *st* (subtype), *part* (part-of), *att* (attribute-of), *sim* (similar-to), *ins* (instance), *seq* (sequential), *ref* (reference), *e* (equal-to), *N* (unknown), *feature* and *opp* (opposite) [18-22]. The *unknown* link means that the semantic relationship is unknown so

far. To avoid repeat statement, here we do not explain the meaning of each primitive semantic factor one by one, and focus on the semantic link networking mechanism.

More semantic factors can be added to extend the semantic ability of SLN in applications. For example, the following semantic factors are employed for describing the layout relationships between wall-painting pieces in Dunhuang Culture Grid ([www.culturegrid.net](http://www.culturegrid.net)): *is-north-of*, *is-west-of*, *is-south-of*, *is-east-of*, *is-above*, *is-below*, *is-right-of*, and *is-left-of*.

Operations on semantic factors include:

- 1) *Reversion* “ $\neg$ ”. The reversion of a semantic link  $l$  from  $S_1$  to  $S_2$  is a semantic link from  $S_2$  to  $S_1$  that has the same semantics as  $l$ , denoted as  $l^R$ . For example, the reversion of a cause-effective link  $ce$  from  $S_1$  to  $S_2$  is a relation from  $S_2$  to  $S_1$  denoted as  $ce^R$ .
- 2) *Addition* “ $+$ ”. The addition of two given semantic links  $l_1$  and  $l_2$  from  $S_1$  to  $S_2$  results in one semantic link  $l_1 + l_2$  from  $S_1$  to  $S_2$ .
- 3) *Multiplication* “ $\cdot$ ”. The multiplication of two semantic links  $l_1$  (from  $S_1$  to  $S_2$ ) and  $l_2$  (from  $S_2$  to  $S_3$ ) results in a semantic link  $l_3$  from  $S_1$  to  $S_3$ , satisfying the semantic link reasoning rule [19, 20].

**Definition 1.** Let  $V$  be the set of semantic factors, “ $\cdot$ ” be the connection operation between semantic factors. For any two semantic factors  $\alpha$  and  $\beta$  in  $V$ , if  $\neg\alpha$ ,  $\alpha\beta$ , and  $\alpha+\beta$  also belong to  $V$ , then  $\langle V, \neg, \cdot, + \rangle$  is a semantic algebra. The primitive semantic factor set  $PSF$  is a subset of  $V$ , and for any semantic factor  $\alpha$  in  $V$ , either  $\alpha$  belongs to  $PSF$  or there exists  $\delta$  and  $\gamma$  in  $PSF$  such that  $\alpha = \neg\delta$ ,  $\alpha = \delta\gamma$ , or  $\alpha = \delta + \gamma$ .

A Semantic Link Network can be represented as a semantic matrix  $M = [m_{ij}]_{n \times n}$  satisfying:

- (1)  $m_{ii} = \{ \langle e, 1 \rangle \}$ ;
- (2) If  $i \neq j$  and there exist  $S_i \xrightarrow{\langle l_1, cd_1 \rangle} S_j$ ,  $S_i \xrightarrow{\langle l_2, cd_2 \rangle} S_j, \dots, S_i \xrightarrow{\langle l_m, cd_m \rangle} S_j$  and  $S_j \xrightarrow{\langle l_1', cd_1' \rangle} S_i$ ,  $S_j \xrightarrow{\langle l_2', cd_2' \rangle} S_i, \dots, S_j \xrightarrow{\langle l_n', cd_n' \rangle} S_i$ , then  $m_{ij} = \{ \langle l_1, cd_1 \rangle, \langle l_2, cd_2 \rangle, \dots, \langle l_m, cd_m \rangle, \langle l_1^R, cd_1^R \rangle, \langle l_2^R, cd_2^R \rangle, \dots, \langle l_n^R, cd_n^R \rangle \}$ .
- (3) Otherwise,  $m_{ij} = \{ \langle null, 1 \rangle \}$ .

A set of semantic linking rules such as  $S \xrightarrow{ce} S'$ ,  $S' \xrightarrow{ce} S'' \Rightarrow S \xrightarrow{ce} S''$  was introduced to support semantic reasoning in [19].

**Definition 2.** Let  $M$  be a semantic matrix,  $Rules$  be a set of semantic linking rules and reasoning rules,  $OP$  be operation set, and  $n$  be the number of semantic nodes in the Semantic Link Network. The semantic link networking model is defined by the following items:

- (1)  $\zeta: N \rightarrow \{ \langle id, description \rangle \mid id \in Identity-Set \}$ , a mapping from the integer set  $N = \{1, 2, \dots, n\}$  into the set of identity-description pairs to sequentially identify semantic nodes in the semantic matrix. Each identity in the *Identity-Set* is a string that uniquely represents a description in the feature space or an *SLN*.
- (2)  $SLN = \langle \{M, Rules\}, OP \rangle$  such that for operation  $\neg$  in  $OP$ ,  $\neg M$  updates  $M$  by reversing all semantic factors, for semantic matrix multiplication operation  $\times$ ,  $M \times M$  updates  $M$  according to the addition and multiplication operations on semantic links and the rules in  $Rules$ , and for analogical reasoning operation  $\oplus$ ,  $M \oplus Rules$  updates  $M$  by applying analogical reasoning and inductive reasoning. The special cases are:  $M \oplus M = M$ , and  $M \oplus Rules = M$ . Binary operations include self-multiplication, union ( $\cup$ ), intersection ( $\cap$ ) and minus ( $-$ ) [22]. *Add-Node*( $n, M$ ) adds node  $n$  to  $M$ .
- (3) The element  $m_{ij}$  at the  $i$ th row and  $j$ th column of  $M$  is a semantic factor set, in which every factor represents a semantic link between  $\zeta(i)$  and  $\zeta(j)$ .

Normal forms of SLN are defined for the simplicity, correctness and connectivity [20].

SLN logical reasoning is realized by self-multiplication of semantic matrix. SLN Analogical reasoning and inductive reasoning are realized by operations on semantic matrix and analogical reasoning rules, which will be introduced in section 6.

A Semantic Link Network can be ranked to differentiate the importance of its semantic nodes so as to raise the efficiency and effectiveness of browsing and searching the network. Traditional Web search engines employ hyperlink analysis and ranking algorithms such as the *PageRank* algorithm to enhance the effectiveness of Web page retrieval by sorting the retrieval results according to their ranks [8, 12]. Similar to the *PageRank*, ranking SLN is to rank the semantic nodes according to semantic link structure analysis [20]. Search on a ranked SLN can return results according to the rank order.

## 4. SLN Logical Reasoning

SLN logical reasoning is to derive the implied semantics from existing semantic links.

The reasoning depends on a set of reasoning rules.

### 4.1 Reasoning on Feature

The following general reasoning rules are on feature.

- (1) **Rule:**  $S_2$  is a subtype of  $S_1$  (i.e.,  $S_1 \text{---}st \rightarrow S_2$ ) and  $S_1$  has feature A (i.e.,  $S_1 \text{---}feature \rightarrow A$ )  $\Rightarrow S_2 \text{---}feature \rightarrow A$ . This rule implies that a subtype node inherits features from its ancestor (super type).
- (2) **Rule:**  $S_2$  is an instance of  $S_1$  (i.e.,  $S_1 \text{---}ins \rightarrow S_2$ )  $\Rightarrow S_1$  and  $S_2$  share the same feature set.
- (3) **Rule:**  $S_2$  is equal to  $S_1$  (i.e.,  $S_1 \text{---}e \rightarrow S_2$ )  $\Rightarrow S_1$  and  $S_2$  share common features.
- (4) **Rule:**  $S_2$  is similar to  $S_1$  (i.e.,  $S_1 \text{---}sim \rightarrow S_2$ )  $\Rightarrow S_1$  and  $S_2$  share some features according to different similarity.
- (5) **Rule:**  $S_1$  and  $S_2$  are subtypes of  $S \Rightarrow S_1$  and  $S_2$  share some features.
- (6) **Rule:**  $S_1$  and  $S_2$  are subtypes of  $S \Rightarrow S_2$  is similar to  $S_1$  (Derived from Rule 4-5).

### 4.2 Generalization of Semantic Link Rules

Semantic link rules can be generalized according to the rule of semantic factors used.

For example, the following semantic link rules can be generalized as  $SLR_{ins} = \{l \bullet ins = ins \mid l \in \{e, st, imp\}\}$ .

- $S \text{---}e \rightarrow S', S' \text{---}ins \rightarrow S'' \Rightarrow S \text{---}ins \rightarrow S''$  (i.e.,  $S$  is semantic-equivalent to  $S'$ , and  $S''$  is the instance of  $S'$ , then  $S''$  is the instance of  $S$ ).
- $S \text{---}st \rightarrow S', S' \text{---}ins \rightarrow S'' \Rightarrow S \text{---}ins \rightarrow S''$  (i.e.,  $S'$  is a subtype of  $S$ , and  $S''$  is the instance of  $S'$ , then  $S''$  is the instance of  $S$ ).
- $S \text{---}imp \rightarrow S', S' \text{---}ins \rightarrow S'' \Rightarrow S \text{---}ins \rightarrow S''$ . (i.e., if  $S$  semantically implies  $S'$ , and  $S''$  is the instance of  $S'$ , then  $S''$  is the instance of  $S$ ).

Other semantic link rules can also be generalized in the same way. For example, semantic link rules introduced in [19] can be generalized as follows:

- (1)  $SLR_{st} = \{st \bullet st = st\}$ .

$$(2) SLR_{imp} = \{imp \bullet l = imp \mid l \in \{imp, st\}\} \cup \{l \bullet imp = imp \mid l \in \{st, ins\}\}.$$

$$(3) SLR_{ref} = \{l \bullet ref = ref \mid l \in \{ref, ins, st, imp\}\}.$$

$$(4) SLR_{ce} = \{ce \bullet l = ce \mid l \in \{ce, imp, st, sim, ins\}\} \cup \{l \bullet ce = ce \mid l \in \{ce, imp, st, ins\}\}.$$

$$(5) SLR_{seq} = \{seq \bullet seq = seq\}.$$

An inexact reasoning rule:  $l(cd) \bullet l'(cd') = l''(cd'')$  means that a semantic link  $S_1 \xrightarrow{\langle l'' \rangle} S_3$  can be derived from semantic links  $S_1 \xrightarrow{\langle l, cd \rangle} S_2$  and  $S_2 \xrightarrow{\langle l', cd' \rangle} S_3$ , where  $cd'' = f(cd, cd')$ ,  $f$  is a function determined in applications, for example, it can be defined as  $f(cd, cd') = \text{Min}(cd, cd')$  or  $f(cd, cd') = cd \times cd'$ . Sometimes, a rule can be represented as  $S_1 \xrightarrow{\langle l, cd \rangle} S_2, S_2 \xrightarrow{\langle l', cd' \rangle} S_3 \Rightarrow S_1 \xrightarrow{\langle l'', f(cd, cd') \rangle} S_3$ . A semantic link reasoning can form a reasoning path:  $\langle l_1, cd_1 \rangle \bullet \langle l_2, cd_2 \rangle \bullet \dots \bullet \langle l_n, cd_n \rangle \Rightarrow \langle l_k, f(cd_1, cd_2, \dots, cd_n) \rangle$ ,  $1 \leq k \leq n$ , or denoted as  $l_1 \bullet l_2 \bullet \dots \bullet l_n = l_k$  in simple.

The addition of two inexact semantic factors is denoted as  $\langle l, cd \rangle + \langle l', cd' \rangle$ . If they describe the same link and  $l=l'$ , then the two semantic links can be regarded as an enhancement of the same semantic relationship, so to select the maximum of the two certainty degrees as the final certainty degree is reasonable, i.e.,  $\langle l, cd \rangle + \langle l, cd' \rangle = \langle l, \max(cd, cd') \rangle$ .

### 4.3 Reasoning on Semantic Link

For a *semantic matrix* with  $n$  semantic nodes  $M$ , its full semantic matrix  $FSRM$  can be got by  $n-1$  times of self-multiplication denoted as  $M^{n-1}$  [20, 22]. All semantic relationships between components can be found in  $FSRM$ . However, for a large-scale SLN, it is time-consuming to compute  $M^{n-1}$ . In most cases, users' querying on an SLN only cares about some specific semantic relationships, such as "What is the cause or what does it lead to?" (*cause-effect* relationship) and "I want to know more about this." (*reference* relationship). Therefore, we can get the views of the semantic matrix  $M$  about some semantic factors. According to the generalization of connection rules, a relationship can be retrieved by considering only several specific relationships rather than all. For example, the reference relationship can be retrieved only by the equivalence (*e*), reference (*ref*), instance (*ins*), subtype (*st*) and implication (*imp*) semantic links. That is, only these five relationships should be taken into account while looking for *ref* relationships.

The *semantic matrix view* on semantic link set  $\{l_1, l_2, \dots, l_k\}$  can be defined as  $[w_{ij}]_{n \times n}$ ,

such that:

- (1)  $w_{ii} = m_{ii} = \langle e, 1 \rangle$ ;
- (2) If  $i \neq j$  and  $m_{ij} = \langle null, 1 \rangle$ , then  $w_{ij} = m_{ij}$ ;
- (3) Otherwise,  $w_{ij} = \sum_l \langle l, cd \rangle$ , where  $\langle l, cd \rangle$  is involved in  $m_{ij}$  and  $l \in \{l_1, l_2, \dots, l_k\}$ . If no  $\langle l, cd \rangle$  is involved in  $m_{ij}$  satisfying  $l \in \{l_1, l_2, \dots, l_k\}$ , then  $w_{ij} = \langle null, 1 \rangle$ .

A view on semantic matrix about the currently interested semantic link set  $\{l_1, l_2, \dots, l_k\}$  can be represented as  $\partial_{\{l_1, l_2, \dots, l_k\}} M$ , such that:

- (1)  $\partial_{\{l_1^R, l_2^R, \dots, l_k^R\}} M = \left( \partial_{\{l_1, l_2, \dots, l_k\}} M \right)^T$ , the transpose of  $\partial_{\{l_1, l_2, \dots, l_k\}} M$ .
- (2)  $M^{n-1} = \sum_{l_i \in SL} \partial_{l_i} (M^{n-1})$ .

According to the generalized semantic link rules *SLR*, we have the following reasoning forms [20, 22]:

- (1) Reasoning on *subtype* link:

$$\partial_{\{st\}} (M^{n-1}) = \left( \partial_{\{st\}} M \right)^{n-1}.$$

- (2) Reasoning on *instance* link:

$$\partial_{\{ins\}} (M^{n-1}) = \partial_{\{ins\}} \left( \left( \partial_{\{st, imp, ins\}} M \right)^{n-1} \right).$$

- (3) Reasoning on *implication* link:

$$\partial_{\{imp\}} (M^{n-1}) = \partial_{\{imp\}} \left( \left( \partial_{\{st, imp, ins\}} M \right)^{n-1} \right).$$

- (4) Reasoning on *reference* link:

$$\partial_{\{ref\}} (M^{n-1}) = \partial_{\{ref\}} \left( \left( \partial_{\{ref, st, imp, ins\}} M \right)^{n-1} \right) = \partial_{\{ref\}} \left( \left( \partial_{\{st, imp, ins\}} M \right)^{n-1} \left( \partial_{\{ref\}} M \right)^{n-1} \right).$$

- (5) Reasoning on *cause-effect* link:

$$\begin{aligned} \partial_{\{ce\}} (M^{n-1}) &= \partial_{\{ce\}} \left( \left( \partial_{\{ce, sim, st, imp, ins\}} M \right)^{n-1} \right) \\ &= \partial_{\{ce\}} \left( \left( \partial_{\{st, imp, ins\}} M \right)^{n-1} \left( \partial_{\{ce\}} M \right)^{n-1} \left( \partial_{\{sim\}} M \right)^{n-1} \left( \partial_{\{st, imp, ins\}} M \right)^{n-1} \right). \end{aligned}$$

(6) Reasoning on *sequential* link:

$$\underset{\{seq\}}{\partial} (M^{N-1}) = (\underset{\{seq\}}{\partial} M)^{N-1}$$

## 5. SLN Structural Isomorphism

A semantic node is a two-tuple:  $S = \langle C, L \rangle$ , where  $C$  is a set of semantic nodes or concepts,  $L$  can be a null set or a set containing semantic links between the nodes, that is,  $L$  can be a *null* set or  $\{c_i \langle l, cd \rangle c_j \mid c_i, c_j \in C\}$ . If  $L$  is a *null* set, then  $S$  is a set of isolated semantic nodes. Assume  $U$  is the set of all semantic nodes in an SLN. The semantic inclusion, structure isomorphic, and partial structure isomorphic relations can be defined on  $U$ . In [20], we define the notion of *orthogonal semantic links*, the *implication* relationship between Semantic Link Networks, *semantic equivalence* and the *semantic inclusion* relationship ( $\supseteq$  or  $\subseteq$ , e.g., the SLN of discrete-mathematics semantically includes the SLN of graph-theory). To avoid redundancy, we do not explain here in detail.

**Definition 3.** (Semantic Inclusion Degree) Let  $S = \langle C, L \rangle$  and  $S' = \langle C', L' \rangle$  be two semantic nodes, if  $S'$  semantically includes  $S$ , i.e.,  $S \subseteq S'$  or  $S' \supseteq S$ . The inclusion degree can be measured according to the scale of  $C$  and  $C'$  as well as the scale of  $L$  and  $L'$ :

$$\text{IncD}(S, S') = \left( \frac{|C|}{|C'|} + \frac{|L|}{|L'|} \right) / 2, \text{ obviously, } \text{IncD}(S, S') \in [0, 1] \text{ because of } |C| \leq |C'| \text{ and } |L| \leq |L'|.$$

Figure 4 depicts the semantic inclusion relationship ( $S \subseteq S'$ ), where  $S'$  includes two semantic communities. The semantic inclusion relation  $R_{\subseteq}$  between semantic nodes in  $U$  is reflexive, anti-symmetric and transitive, thus  $R_{\subseteq}$  is a partial order on  $U$ .

The semantic inclusion relation can be used to define the semantic equivalence relationship:  $A \xrightarrow{e} B$  if and only if  $A \subseteq B$  and  $B \subseteq A$ .

The semantic inclusion relationship is useful in applications, for example, if  $S_i$  represents the content of a research area, then  $S_1 \subseteq S_2 \subseteq \dots \subseteq S_n$  indicates the development of the area. For two semantic communities  $S$  and  $S'$ , if  $S \subseteq S'$  and the solution/answer cannot be found in  $S'$ , then it might not exist in  $S$ . Consequently, if we know  $S_1 \subseteq S_2 \subseteq \dots \subseteq S_n$  and the answer cannot be found in  $S_n$ , then we don't need to search in  $S_k$  ( $k=1, \dots, n-1$ ). Reversely, if an

answer can be found in  $S_1$ , then it can also be found in  $S_n$ .

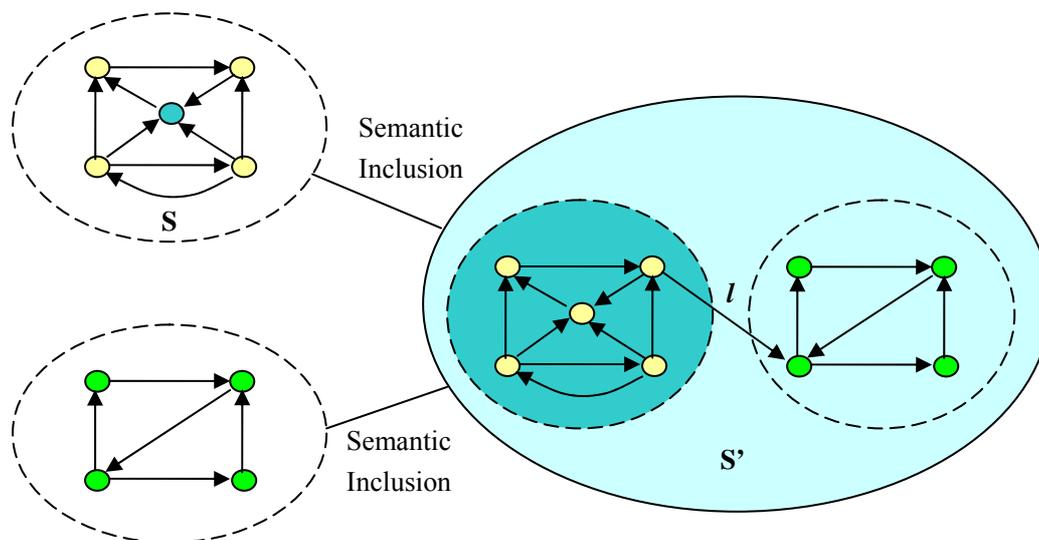


Figure 4. Example of semantic inclusion.

**Definition 4.** (Structure Isomorphism) For any two semantic nodes  $S = \langle C, L \rangle$  and  $S' = \langle C', L' \rangle$ ,  $|C| = |C'|$ ,  $|L| = |L'|$ ,  $S$  is isomorphic to  $S'$  (denoted as  $S \cong S'$ ) if

- 1) there exists a 1-1 and onto mapping  $\theta: C \rightarrow C'$ ; and,
- 2) there exists a 1-1 and onto mapping  $g: L \rightarrow L'$ , and for any semantic link  $c_i \rightarrow c_j$  in  $L$ , there exists a corresponding semantic link  $c_i' \rightarrow c_j'$  in  $L'$ , where  $c_i' = \theta(c_i)$  and  $c_j' = \theta(c_j)$ .

The structure isomorphic relation  $R_{\cong}$  between semantic nodes is an equivalence relation on  $U$ . The equivalent class generated by node  $c$  is denoted as  $[c]_{\cong}$ . According to the definition of semantic inclusion, we have the following characteristic.

**Characteristic 1.** (Characteristic of inclusion degree) Let  $\lambda$  be relation  $>$ ,  $=$ , or  $<$ .  $S_1$  and  $S_2$  are two components of  $S$ .  $S_1'$  and  $S_2'$  are two components of  $S'$ , that is,  $S_1 \subseteq S$ ,  $S_2 \subseteq S$ ,  $S_1' \subseteq S'$ , and  $S_2' \subseteq S'$ . If  $S_1 \cong S_1'$ ,  $S_2 \cong S_2'$ , and  $IncD(S_1, S) \lambda IncD(S_2, S)$ , then we have  $IncD(S_1', S') \lambda IncD(S_2', S')$ .

**Definition 5.** (Partial Structure-Isomorphic relation). Let  $SD(S, S')$  be the similar degree between  $S$  and  $S'$ . Two semantic nodes  $S$  and  $S'$  are called partial structure-isomorphism denoted as  $S \approx S'$  if there exist two semantic nodes such that  $S_1 \subseteq S$ ,  $S_1' \subseteq S'$  and  $S_1 \cong S_1'$ .

The inclusion degree reflects the semantic closeness between a semantic node and its

component, that is, if  $S \subseteq S'$  then  $SD(S, S') = IncD(S, S')$ .

The partial structure isomorphic relation  $R_{\approx}$  between semantic nodes is a compatibility relation on  $U$ . The maximal compatibility block including node  $c$  is denoted as  $[c]_{\approx}$ .

According to Characteristic 1, we have the following lemma.

**Lemma 1.** If  $S$  semantically includes  $S_1, \dots, S_n$ , and  $S'$  semantically includes  $S_1', \dots, S_n'$  such that  $S_1 \cong S_1', S_2 \cong S_2', \dots, S_n \cong S_n'$  and  $IncD(S_k, S) = \max(IncD(S_1, S), IncD(S_2, S), \dots, IncD(S_n, S))$ , where  $1 \leq k \leq n$ , then we have:  $IncD(S_k', S') = \max(IncD(S_1', S'), IncD(S_2', S'), \dots, IncD(S_n', S'))$ .

The similarity degree between  $S$  and  $S'$  can be measured by  $SD(S, S') = IncD(S_k, S) \times IncD(S_k', S')$ . The bigger  $SD(S, S')$ , the more similarity between  $S$  and  $S'$ .

**Characteristic 2.** The following characteristics hold:

- (1)  $SD(S, S') = SD(S', S)$ ;
- (2)  $SD(S, S') \in [0, 1]$ ;
- (3)  $SD(S, S) = 1$ ;
- (4) If  $S \cong S'$ , then  $SD(S, S') = 1$ ;
- (5) If  $S \subseteq S'$ , then  $SD(S, S') = IncD(S, S')$ ; and,
- (6) If there is no isomorphic component between  $S$  and  $S'$  then  $SD(S, S') = 0$ .

**Lemma 2.** The structure isomorphic relation and the partial structure isomorphic relation satisfies:  $R_{\subseteq} \subseteq R_{\approx}$ .

**Lemma 3.** A structure isomorphic relation  $R_{\cong}$  on  $U$  generates a unique partition of  $U$ . The quotient set of  $U$  by  $R_{\cong}$  is denoted as  $U/R_{\cong}$ .

Semantic link reasoning rule set  $RS$  is a subset of  $U \times U$ . For a given semantic node  $S_1$  and a reasoning rule  $S_1 \xrightarrow{\langle l, cd \rangle} S_2 \Rightarrow S_2$ ,  $S_2$  is a solution to the problem of finding out all resources that relate  $S_1$  with semantic link  $l$ .

The reasoning rules on the quotient set are at higher abstraction level. A reasoning mechanism could raise its effect by selecting the rules at appropriate abstraction level to participate reasoning.



**Analogical reasoning mode-1.**

The following analogical reasoning model is about feature.

Premise:  $S_1 \cong S_2, S_1$  has feature A

---

Conjecture:  $S_2$  has feature A

Similarly, we have:

Premise:  $S_1 \approx S_2, S_1$  has feature A

---

Conjecture:  $S_2$  has feature A,  $cd = SD(S_1, S_2)$

**Analogical reasoning mode-2:**

The following analogical reasoning is about semantic links.

Premise:  $S_1 \xrightarrow{\langle l, cd \rangle} S_2$  and  $S_1' \subseteq S_1$

---

Conjecture:  $S_1' \xrightarrow{\langle l, cd' \rangle} S_2, cd' = f(IncD(S_1', S_1), cd)$

Premise:  $S_1 \xrightarrow{\langle l, cd \rangle} S_2$  and  $S_2' \subseteq S_2$

---

Conjecture:  $S_1 \xrightarrow{\langle l, cd' \rangle} S_2', cd' = f(IncD(S_2, S_2'), cd)$

**Analogical reasoning mode-3:**

Premise:  $S_1 \xrightarrow{\langle l, cd \rangle} S_2, S_1' \cong S_1, S_2' \cong S_2$

---

Conjecture:  $S_1' \xrightarrow{\langle l, \sim cd \rangle} S_2'$ .

Sometimes it is difficult to determine  $S_1' \cong S_1$ . But if we can find a transformation  $\varphi$  (e.g., semantic node reconstruction by adding, deleting, splitting or merging components) such that  $\varphi(S_1') \cong S_1$ , then we have the following analogical reasoning as depicted in Figure 6 ( $\varphi$  and  $\varphi'$  reflects the invariability of semantics):

Premise:  $S_1 \xrightarrow{\langle l, cd \rangle} S_2, \varphi(S_1') \cong S_1, \varphi'(S_2') = S_2$

---

Conjecture:  $S_1' \xrightarrow{\langle l, \sim cd \rangle} S_2'$ .

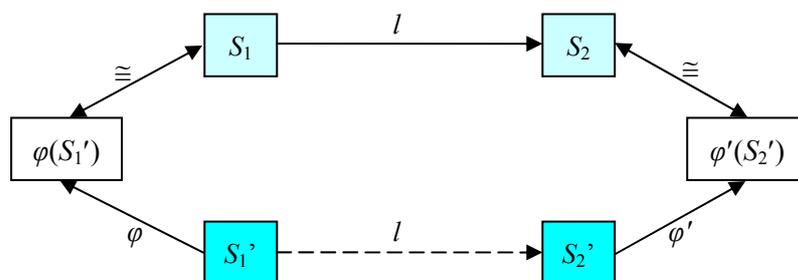


Figure 6. Analogical reasoning via transformation.

**Analogical reasoning mode-4:**

Premise:  $S_1 \text{---} \langle l, cd \rangle \rightarrow S_2, S_1' \approx S_1, S_2' \approx S_2$

---

Conjecture:  $S_1' \text{---} \langle l, \sim cd' \rangle \rightarrow S_2'$ , where  $\sim cd' = cd \times f(SD(S_1, S_1'), SD(S_2, S_2'))$ .

Sometimes we need two transformation functions  $\varphi$  and  $\varphi'$ :

Premise:  $S_1 \text{---} \langle l, cd \rangle \rightarrow S_2, \varphi(S_1') \approx S_1, \varphi'(S_2') \approx S_2$

---

Conjecture:  $S_1' \text{---} \langle l, \sim cd' \rangle \rightarrow S_2'$ , where  $\sim cd' = cd \times f(SD(S_1, \varphi(S_1')), SD(S_2, \varphi'(S_2')))$

**Analogical reasoning mode-5:**

For two semantic nodes  $S = \langle C, L \rangle$  and  $S' = \langle C', L' \rangle$ , the union of  $S$  and  $S'$  is  $S \cup S' = \langle C \cup C', L \Delta L' \rangle$ , where  $L \Delta L'$  is the set of refined semantic links by removing redundant links from  $L \cup L'$  ( $L \cup L'$  would create redundant semantic links). Multiple analogies between parts could lead to a global analogy.

Suppose  $S_{1i} \subseteq S_1, S_{2i} \subseteq S_2, S_{1i}' \subseteq S_1',$  and  $S_{2i}' \subseteq S_2'$  for  $i = 1, 2, \dots, k$ , if the following analogical reasoning is true for all  $i$ :

Premise:  $S_{1i} \text{---} \langle l, cd \rangle \rightarrow S_{2i}, S_{1i}' \cong S_{1i}, S_{2i}' \cong S_{2i}$

---

Conjecture:  $S_{1i}' \text{---} \langle l, \sim cd' \rangle \rightarrow S_{2i}'$ .

Then, we have:

Premise:  $S_1 \text{---} \langle l, cd \rangle \rightarrow S_2$

---

Conjecture:  $S_1' \text{---} \langle l, \sim cd' \rangle \rightarrow S_2'$ , where  $\sim cd' = f(cd,$

$$\left( \left| \bigcup_{i=1}^k C_{1i} \right| / |C_1| + \left| \bigtriangleup_{i=1}^k L_{1i} \right| / |L_1| \right) / 2, \left( \left| \bigcup_{i=1}^k C_{2i} \right| / |C_2| + \left| \bigtriangleup_{i=1}^k L_{2i} \right| / |L_2| \right) / 2, \left( \left| \bigcup_{i=1}^k C_{1i}' \right| / |C_1'| + \left| \bigtriangleup_{i=1}^k L_{1i}' \right| / |L_1'| \right) / 2, \left( \left| \bigcup_{i=1}^k C_{2i}' \right| / |C_2'| + \left| \bigtriangleup_{i=1}^k L_{2i}' \right| / |L_2'| \right) / 2$$

**Analogical reasoning mode-6:**

Premise:  $S_1 \text{---} \langle l, cd \rangle \rightarrow S_2, S_1' \subseteq S_1, S_2' \subseteq S_2, IncD(S_1', S_1) > \sigma, IncD(S_2', S_2) > \sigma,$

$\sigma$  is the low bound of inclusion degree

---

Conjecture:  $S_1' \text{---} \langle l, \sim cd' \rangle \rightarrow S_2'$ , where  $\sim cd' = cd \times f(IncD(S_1', S_1), IncD(S_2', S_2))$ .

Sometimes we need a transformation  $\varphi$ :

Premise:  $S_1 \text{---} \langle l, cd \rangle \rightarrow S_2, \varphi(S_1') \subseteq S_1, S_2' = \varphi'(S_2''), S_2'' \subseteq S_2,$

$IncD(\varphi(S_1'), S_1) > \sigma, IncD(\varphi(S_2''), S_2) > \sigma$

---

Conjecture:  $S_1' \text{---} \langle l, \sim cd' \rangle \rightarrow S_2'$ , where  $\sim cd' = cd \times f(IncD(\varphi(S_1'), S_1), IncD(S_2'', S_2))$ .

## 7. SLN Inductive Reasoning

SLN inductive reasoning carries out from special to general. Here gives two SLN inductive reasoning modes:

(1) *From entity to concept*

$E_i \xrightarrow{l} E_i'$ ,  $i=1, \dots, n$  are semantic links between entities

$S \xrightarrow{\text{instance}} E_i$  ( $E_i$  is an instance of  $S$ )

$S' \xrightarrow{\text{instance}} E_i'$  ( $E_i'$  is an instance of  $S'$ )

---

$S \xrightarrow{\langle l, cd \rangle} S'$ ,  $cd=f(n,m)$ ,  $m$  is the number of other instances of  $S$  and  $S'$

(2) *From subtype to super-type*

The following reasoning is about feature.

$S_i \xrightarrow{\text{feature}} F_i$  ( $S_i$  has feature set  $F_i$ ,  $i=1, \dots, n$ )

$S \xrightarrow{\text{subtype}} S_i$  ( $S_i$  is a subtype of  $S$ )

---

$S \xrightarrow{\text{feature}} F_1 \cap \dots \cap F_n$  ( $S$  has feature set  $F_1 \cap \dots \cap F_n$ )

The following reasoning is about semantic link.

$S_i \xrightarrow{l} S_i'$  ( $i=1, \dots, n$ )

$S \xrightarrow{\text{subtype}} S_i$  ( $S_i$  is a subtype of  $S$ )

$S' \xrightarrow{\text{subtype}} S_i'$  ( $S_i'$  is a subtype of  $S'$ )

---

$S \xrightarrow{\langle l, cd \rangle} S'$ ,  $cd=f(n,m)$ ,  $m$  is the number of other subtypes of  $S$  and  $S'$ .

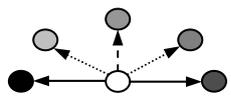
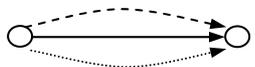
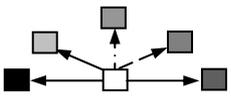
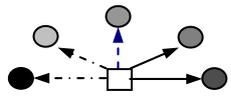
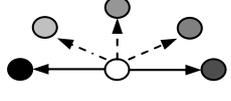
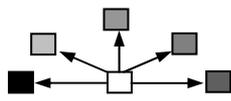
## 8. Application Perspective

### 8.1 Semantic-based Search

The proposed autonomous SLN supports semantic search. Table 1 shows a set of basic functions of this SLN-based semantic search, where different types of arrows represent different semantic factors. Given a concept, the search mechanism can easily find and list its entities (e.g., web pages) according to the instance link. Semantically relevant concepts can also be easily found and graphically displayed according to the surrounding links. A radius can be used to control the length of the semantic chains connected to a central concept. Given an entity, the search mechanism can easily find semantically relevant entities according

to surrounding semantic links, and find the semantically relevant concepts according to the instance link. Given two concepts or entities, all relations between them can be easily found. Given an SLN, the search mechanism can find a view or a larger SLN about some semantic factors for localizing or extending the search scope.

Table 1. Some basic functions of semantic search

Input	Output	Output Form
Concept	Instances	A list of entities
Concept ○	Semantically relevant concepts and links ●	
Two Concepts	Semantic links between them	
Entity □	Semantically relevant entities ■	
Entity □	Semantically relevant concepts ●	
$S-\alpha \rightarrow ?$ ○ →	$S-\alpha \rightarrow X_1, \dots, S-\alpha \rightarrow X_n$	
$E-\alpha \rightarrow ?$	$E-\alpha \rightarrow X_1, \dots, E-\alpha \rightarrow X_n$	
$SLN \supseteq ?$	$SLN \supseteq X$	X is a graphical SLN
$? \subseteq SLN$	$X \subseteq SLN$	SLN can be at abstraction level or entity level

## 8.2 Self-Organization of Diverse Scale of SLN for On-Demand Information Service

The autonomous SLN can further extend into the society. Figure 7 shows an autonomous SLN incorporating four overlays: the global SLN, SLN views, user profile SLNs and search SLNs. The user profiles are SLNs reflecting users' interests. The search SLNs are small temporal SLNs for precise search. A long-term collection of the search SLNs reflects long-term user interest. A person's profile SLN semantically includes the search SLNs. The social network itself is an autonomous SLN, where every community clusters

relevant people and profiles. Using these SLNs, people only need to search within an SLN view. With the profile SLNs, information can be accurately pushed to appropriate persons. Semantic relations between user profiles self-organize an SLN overlay. With such overlays, an information service system does not need to establish and maintain profile for every user. Instead, the system can organize a profile hierarchy for a community from low-level specific profiles to abstract SLNs of higher levels. SLNs of diverse scales adapt according to the evolution of the profile SLN and the global SLN caused by human operations or reasoning mechanism.

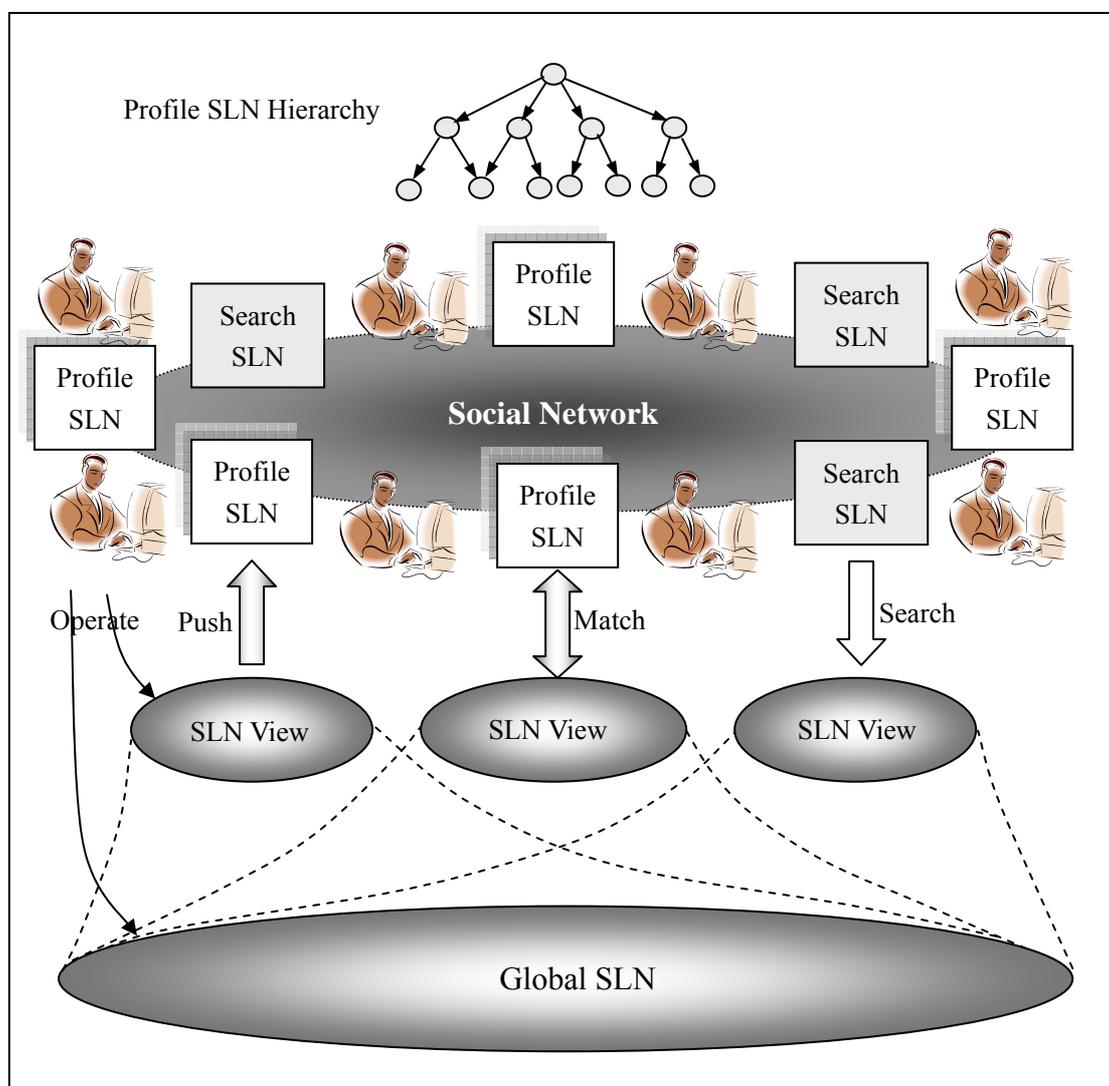


Figure 7. Autonomous semantic overlay incorporating the Global SLN, SLN views, user profile SLNs and search SLNs.

## 9. Related Work and Discussion

Analogy is a kind of human innovative thinking and problem-solving mode. In Gentner's structure-mapping theory [5], analogy is a mapping from one domain (called base) into another (called target), which indicates some common relational structures between the base and the target [6]. Analogy can be used to guide reasoning, to generate conjectures in an unfamiliar domain, and to generalize experiences into abstract schemas [5]. Various computational frameworks have been established for detecting analogies and structural equivalencies [4, 9, 10]. The object analogical reasoning model makes use of object model and the abstraction relationship between objects to enhance analogical reasoning ability [24]. An implementation process of analogical reasoning modes was suggested in [20]. The development of the Semantic Web and the Semantic Link Network provide an opportunity for research and application on analogical reasoning.

The Semantic Link Network, Web, Databases, traditional Semantic Network and Cognitive Map can all be generalized as a directed relational graph composed of nodes and arcs reflecting relationships between nodes, but their intention and semantic expression ability are different.

Databases pursue efficient management of data via various data models. The hierarchical data model organizes data in a tree structure. The network model can model many-to-many relationships in data. The relational data model is based on the functional dependence relationship on attributes. The object-oriented model is based on the uniform abstraction on objects and the inheritance relationship between classes. These data models adopt the simplicity in semantics to obtain efficiency in data management, but the semantics of these models is not enough to support reasoning in distributed intelligent applications.

The World Wide Web uses hyperlink to connect Web pages for human to browse easily from one page to another. Its characteristic is that anything can link to anything. The hyperlink does not represent any semantics between web pages, so it is unable to support efficient resource management and reasoning. The Semantic Web is to overcome this shortcoming by developing markup languages and ontology [1]. Current research and development on the Semantic Web still lack the formalism for automatically generating

semantics and semantic reasoning, especially the analogical reasoning mechanism.

Traditional Semantic Network is a graph in which nodes are concepts and arcs are relations between concepts [14]. Semantic network uses multiple relations to connect concepts to represent knowledge [13]. Six types of semantic networks are: 1) Definitional Network, which emphasizes the *subtype* and *is-a* relationships to organize concepts into hierarchy; 2) Assertional Network, which can assert propositions and represent conceptual structures in natural languages; 3) Implicational Network, which emphasizes the *causal* relationship between concepts; 4) Executable Network, which includes executive mechanisms for inference, searching, etc; 5) Learning Network, which can acquire knowledge from examples by modifying network; and 6) Hybrid Networks, which combine two (or more) of the above [15].

Cognitive Map is also a graph of nodes and arcs, in which nodes represent concepts, and arcs between concepts represent direct or indirect dynamic causal relationships [2, 11]. However, cognitive maps only reflect causal relation, it is unable to support various semantic-rich reasoning.

The Semantic Link Network SLN can describe rich and flexible semantic relations. It has the ability of differentiating the importance of nodes as well as the ability of semantic link reasoning and analogical reasoning. Semantic nodes in an SLN are connected by various semantic relationships. A semantic link builder was developed to support users to build small-scale Semantic Link Networks, which can be connected one another by semantic links to form a large and even global SLN [21]. The partitioned semantic matrix was used to improve the efficiency of large SLN computing [22]. The Semantic Link Network was used to describe the semantic relationship between images to realize semantic-based image retrieval [26].

The self-organization characteristic of the hyperlink-based World Wide Web leads to scale-free phenomenon. A node (a human readable page but not machine understandable) can be ranked according to the number of its links and the ranks of the linked nodes. The nodes with higher ranks are more powerful to attract new nodes. However, for a Semantic Link Network, a new node tends to link to a semantically relevant nodes. For example, a researcher usually submits his papers to conferences and journals according to relevancy and

the match of academic levels, and reviewers are selected according to their areas and workload rather than their ranks. So the evolution of an SLN is the process of forming semantic communities.

A semantic community can be discovered in a large Semantic Link Network by removing those semantic links that could not reason with neighbor links. The semantic community discovery approach is different from the approach for discovering community in semantic-poor networks [17], due to implicit semantic links could be derived out.

## 10. Conclusion

The Semantic Link Network consists of an entity level representing semantics between entities and an abstraction level representing semantics between concepts (schemas or semantic communities). The synergy of the two levels enables users to understand and share not only domain-specific contents at the entity level but also knowledge at the abstraction level. The SLN logical reasoning can derive out implied semantic relationships based on semantic link rules. The SLN analogical reasoning can propose conjectures on semantic links by structural mapping between components. The SLN inductive reasoning can derive abstract semantics according to special semantics. The cooperation of diverse reasoning modes enhances the reasoning ability of each. Incorporating with relevant techniques such as the semantic link building tools, the semantic querying and routing mechanism, the community discovery and the statistics-based relation discovery, the proposed semantic link networking model is powerful to establish an autonomous semantic overlay for supporting intelligent applications of the Knowledge Grid.

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