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Autonomous semantic link networking model for the Knowledge Grid

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SUMMARY

A semantic link network (SLN) consists of nodes (entities, features, concepts, schemas or communities) and semantic links between nodes. This paper proposes an autonomous SLN formalism to support intelligent applications on large-scale networks. 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 overly. The SLN logical reasoning mechanism derives implicit semantic relations by a semantic matrix and relevant addition and multiplication operations 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 providing a powerful semantic ability for the semantic overlay. The self-organizing diverse scales of the SLN support the intelligent applications of the Knowledge Grid. Copyright © 2006 John Wiley & Sons, Ltd.

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1. INTRODUCTION

1.1. The semantic issue

The first fundamental issue in developing the Semantic Web [1], the Semantic Grid [2] (http://www.semanticgrid.org) and the Knowledge Grid [3] is to find an appropriate semantic

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representation model to codify semantics, which, ideally, is both human-readable and machine-understandable, so that the human and machine can understand each other. Previous approaches such as various metadata [4], ontologies (e.g. Wordnet, http://wordnet.princeton.edu; Framenet, http://framenet.icsi.berkeley.edu; GUM, http://www.purl.org/net/gum2) and markup languages (e.g. XML, RDF, Topic Map and OWL, http://www.w3.org/TR/) are static and passive. DAML + OIL uses some modeling primitives of frame-based languages (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) [3,5]. 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 designed to establish 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 [6]. However, a SLN 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 [5]. Semantic relationships between abstract concepts are knowledge that can be applied to wider applications. So a SLN needs two levels: an abstraction level and an entity level.

A 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 SLN that represents integrated semantics. It has no isolated nodes or parts. The normal forms (NF) of a SLN were proposed in [3]. A 4NF SLN 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 {<*feature* : *type*> | *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 subspace of the *feature space* and the relations on features as follows: *Concept*: <{*feature* : *type*; ... ; *feature* : *type*}, L>, 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 the features and relations of its super-concept at a higher level and can include more features. An entity is a point in the feature space: {*feature*: *value*; ... ; *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 a SLN. Compared with the World Wide Web, the SLN has the following advantages.

(1) Supports semantic browsing and reasoning at both the entity (instance) level and the abstraction level. Browsing at 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 foresight to multiple hops. Browsing at the abstraction level, users or agents can obtain knowledge about the underlying content.

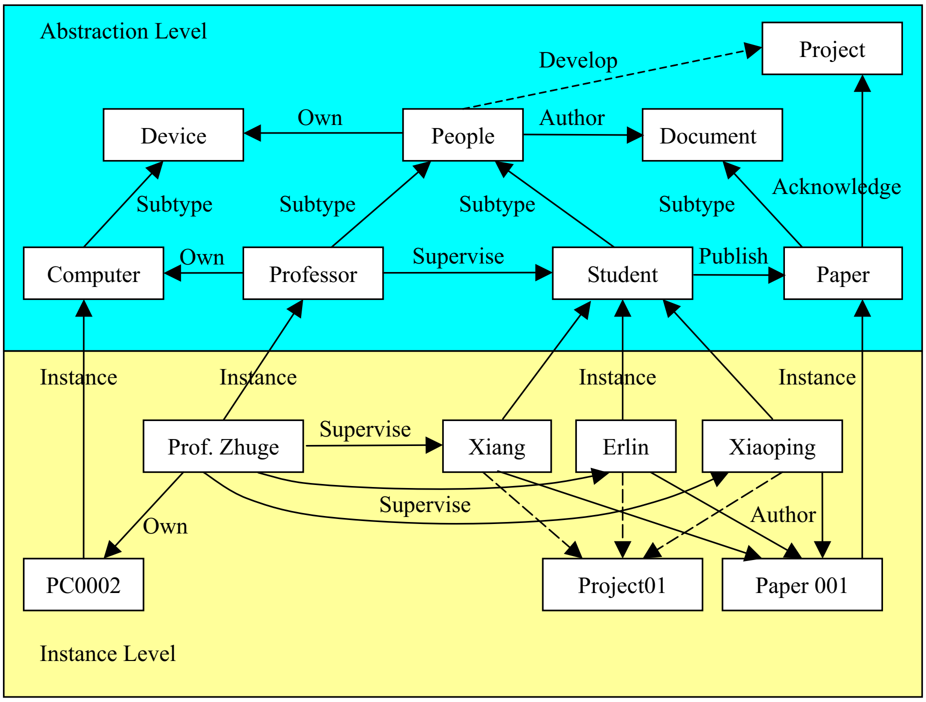

Figure 1. A two-level SLN.

(2) Provides not only the answer, but also relevant content that semantically links to the answer.
(3) Derives the semantics of a node or proposes 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 SLN with an abstraction level and an instance level. Both levels support semantic query. A semantic link $A \xrightarrow{l} B$ 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 relationships exist 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 $A \xrightarrow{cooperate} B \Rightarrow A \xrightarrow{share} B$.

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

(1) '$A \xrightarrow{work\ for} Y$, $B \xrightarrow{work\ for} Y \Rightarrow A \xrightarrow{colleague} B$' means that '$A$ works for Y' and 'B works for Y' imply 'A and B are colleagues'. Here the reverse of the colleague relation is still a colleague relation.

(2) '$A \xrightarrow{use} X$, $B \xrightarrow{use} X \Rightarrow A \xrightarrow{share} B$' means that '$A$ uses X' and 'B uses X' imply 'A shares something with B'.
(3) '$A \xrightarrow{author} P$, $B \xrightarrow{author} P \Rightarrow A \xrightarrow{co\text{-}author} B$' means that '$A$ is the author of P' and 'B is the author of P' imply 'A and B are co-authors'.
(4) '$A \xrightarrow{develop} X$, $B \xrightarrow{develop} X \Rightarrow A \xrightarrow{cooperate} B$' means that '$A$ develops X (project)' and 'B develops X' imply 'A cooperates with B'.

The general semantic link rules are independent of the 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 [6]. The semantic linking rules can be regarded as an operation '·' on semantic factors. For example, the semantic link rule '$A \xrightarrow{subtype} B$, $B \xrightarrow{instance} C \Rightarrow A \xrightarrow{instance} C$' can be represented as an operation on semantic factors: $subtype \cdot instance = instance$.

1.3. Autonomous SLN and the Knowledge Grid

An autonomous SLN has the following characteristics:

(1) autonomously adapts semantic relations with the evolution of the SLN;
(2) autonomously establishes semantic links between semantic nodes;
(3) self-organizes diverse scales of SLNs into semantic communities; and
(4) integrates 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 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 [3]. 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 SLN 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 SLN, which resolves the following two issues.

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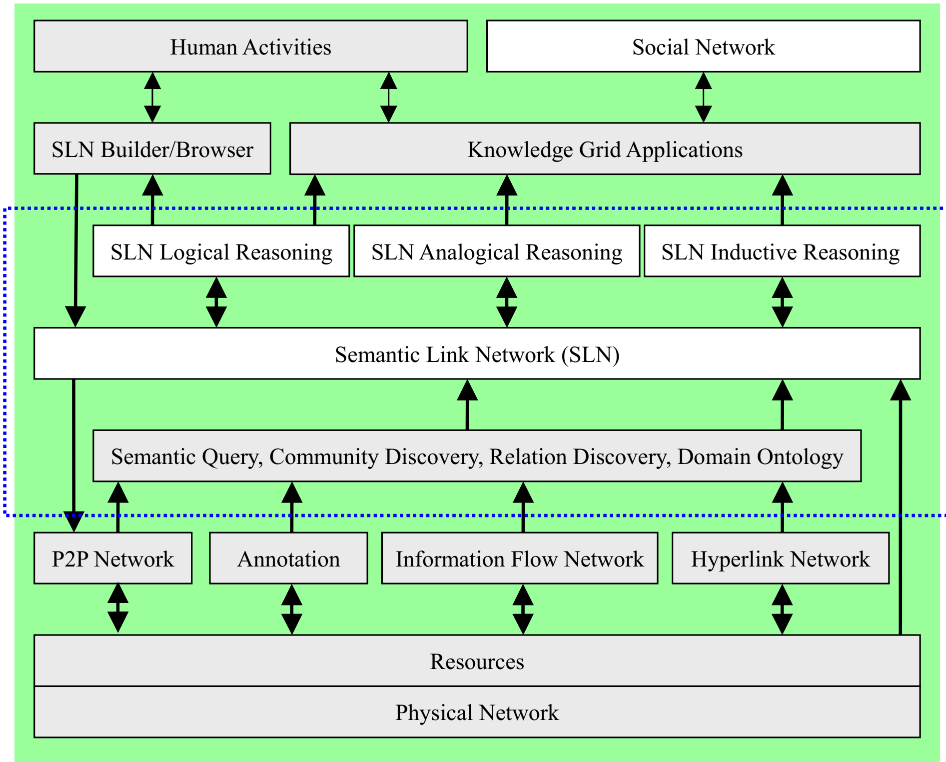

Figure 2. General architecture for an autonomous SLN.

(1) *Autonomous semantic networking*. Using building tools to build a SLN is a labor-intensive approach although it is necessary [7]. Autonomous semantic networking means that semantic relations could be created and adapted by reasoning or by automatically discovering in various networks such as a hyperlink network, social network and information flow network [8,9]. Peer-to-peer querying the semantic structures used inside a node and matching between structures can establish some semantic relations such as *similar-to* and *inclusion* [5].

(2) *SLN reasoning*. The SLN logical reasoning can generate the implied semantic relations in exiting SLNs. The SLN analogical reasoning approach can generate useful conjectures on semantic links or features [10]. 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.

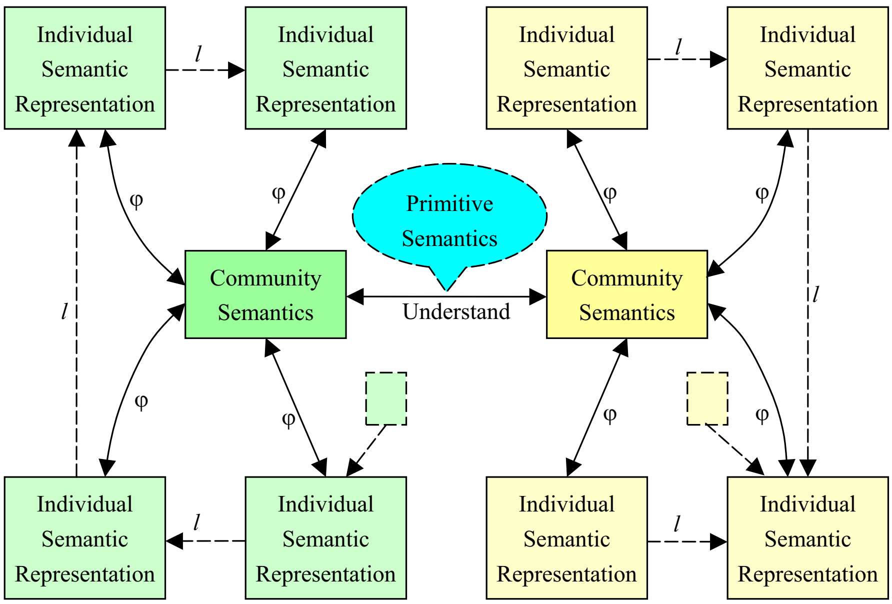

Figure 3. Self-organization of a SLN.

The dotted block in Figure 2 shows the core of an autonomous SLN. 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 [11].

Figure 3 depicts a self-organized SLN. Individual resources are allowed to use diverse semantic representations. For interchange, they need a transformation function (φ) 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.

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 $S \xrightarrow{<l,cd>} S'$, 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*),

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part (*part-of*), *att* (*attribute-of*), *sim* (*similar-to*), *ins* (*instance*), *seq* (*sequential*), *ref* (*reference*), *e* (*equal-to*), *N* (*unknown*), *feature* and *opp* (*opposite*) [3,6,7,10,12]. The *unknown* link means that the semantic relationship is unknown so far. To avoid a repeat statement, here we do not explain the meaning of each primitive semantic factor individually, 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 (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 the following.

(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 [3,6].

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

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

(1) $m_{ii} = \{<e, 1>\}$;
(2) if $i \neq j$ and there exist $S_i \xrightarrow{<l_1, cd_1>} S_j$, $S_i \xrightarrow{<l_2, cd_2>} S_j, \ldots, S_i \xrightarrow{<l_m, cd_m>} S_j$ and $S_j \xrightarrow{<l'_1, cd'_1>} S_i$, $S_j \xrightarrow{<l'_2, cd'_2>} S_i, \ldots, S_j \xrightarrow{<l'_n, cd'_n>} S_i$, then $m_{ij} = \{<l_1, cd_1>, <l_2, cd_2>, \ldots, <l_m, cd_m>, <l_1'^{\mathrm{R}}, cd'_1>, <l_2'^{\mathrm{R}}, cd'_2>, \ldots, <l_n'^{\mathrm{R}}, cd'_n>\}$;
(3) otherwise, $m_{ij} = \{<null, 1>\}$.

A set of semantic linking rules such as $S{<}l'_n, \xrightarrow{ce} S', S' \xrightarrow{ce} S'' \Rightarrow S \xrightarrow{ce} S''$ was introduced to support semantic reasoning in [6].

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

(1) $\zeta : N \rightarrow \{<id, description> \mid id \in \textit{Identity-Set}\}$, a mapping from the integer set $N = \{1, 2, \ldots, n\}$ 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 a SLN.

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(2) $SLN = <\{M, Rules\}, OP>$ 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 ($\cup$) and minus ($-$) [12]. *Add-Node*(n, M) adds node n to M.

(3) The element m_{ij} at the ith row and jth 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 the SLN are defined for simplicity, correctness and connectivity [3].

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

A SLN 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 [13,14]. Similar to the *PageRank*, ranking SLN is to rank the semantic nodes according to semantic link structure analysis [3]. A search on a ranked SLN can return results according to the rank order.

4. SLN LOGICAL REASONING

SLN logical reasoning is used 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. $S_1 \xrightarrow{st} S_2$) and S_1 has feature A (i.e. $S_1 \xrightarrow{feature} A$) $\Rightarrow S_2 \xrightarrow{feature} A$. 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. $S_1 \xrightarrow{ins} S_2$) $\Rightarrow S_1$ and S_2 share the same feature set.

(3) **Rule**: S_2 is equal to S_1 (i.e. $S_1 \xrightarrow{e} S_2$) $\Rightarrow S_1$ and S_2 share common features.

(4) **Rule**: S_2 is similar to S_1 (i.e. $S_1 \xrightarrow{sim} S_2$) $\Rightarrow S_1$ 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 Rules 4 and 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 $SLR_{\mathrm{ins}} = \{l \bullet ins = ins \mid l \in \{e, st, imp\}\}$.

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- $S \xrightarrow{e} S'$, $S' \xrightarrow{ins} S'' \Rightarrow S \xrightarrow{ins} S''$ (i.e. S is semantic-equivalent to S' and S'' is the instance of S', then S'' is the instance of S).
- $S \xrightarrow{st} S'$, $S' \xrightarrow{ins} S'' \Rightarrow S \xrightarrow{ins} S''$ (i.e. S' is a subtype of S and S'' is the instance of S', then S'' is the instance of S).
- $S \xrightarrow{imp} S'$, $S' \xrightarrow{ins} S'' \Rightarrow S \xrightarrow{ins} S''$ (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 [6] can be generalized as follows.

(1) $SLR_{\mathrm{st}} = \{st \cdot st = st\}$.
(2) $SLR_{\mathrm{imp}} = \{imp \cdot l = imp \mid l \in \{imp, st\}\} \cup \{l \cdot imp = imp \mid l \in \{st, ins\}\}$.
(3) $SLR_{\mathrm{ref}} = \{l \cdot ref = ref \mid l \in \{ref, ins, st, imp\}\}$.
(4) $SLR_{\mathrm{ce}} = \{ce \cdot l = ce \mid l \in \{ce, imp, st, sim, ins\}\} \cup \{l \cdot ce = ce \mid l \in \{ce, imp, st, ins\}\}$.
(5) $SLR_{\mathrm{seq}} = \{seq \cdot seq = seq\}$.

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

The addition of two inexact semantic factors is denoted as $<l, cd> + <l', cd'>$. 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. $<l, cd> + <l, cd'> = <l, max(cd, cd')>$.

4.3. Reasoning on semantic link

For a *semantic matrix* with n semantic nodes M, its full semantic matrix *FSRM* can be obtained by $n-1$ self-multiplications denoted as M^{n-1} (see [3,12]). 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, user 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 $\{l_1, l_2, \ldots, l_k\}$ can be defined as $[w_{ij}]_{n\times n}$, such that:

(1) $w_{ii} = m_{ii} = <e, 1>$;
(2) if $i \ne j$ and $m_{ij} = <null, 1>$, then $w_{ij} = m_{ij}$;

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(3) otherwise, $w_{ij} = \sum_l$ <l, cd>, where <l, cd> is involved in m_{ij} and $l \in \{l_1, l_2, \ldots, l_k\}$; if no <$l$, cd> is involved in m_{ij} satisfying $l \in \{l_1, l_2, \ldots, l_k\}$, then $w_{ij} =$ <$null$, 1>.

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

(1) $\partial_{\{l_1^R,l_2^R,\ldots,l_k^R\}}M = (\partial_{\{l_1,l_2,\ldots,l_k\}}M)^{\mathrm{T}}$, the transpose of $\partial_{\{l_1,l_2,\ldots,l_k\}}M$;
(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 [3,12].

(1) Reasoning on *subtype* link:
$$\partial_{\{st\}}(M^{n-1}) = (\partial_{\{st\}}M)^{n-1}$$
(2) Reasoning on *instance* link:
$$\partial_{\{ins\}}(M^{n-1}) = \partial_{\{ins\}}((\partial_{\{st,imp,ins\}}M)^{n-1})$$
(3) Reasoning on *implication* link:
$$\partial_{\{imp\}}(M^{n-1}) = \partial_{\{imp\}}((\partial_{\{st,imp,ins\}}M)^{n-1})$$
(4) Reasoning on *reference* link:
$$\partial_{\{ref\}}(M^{n-1}) = \partial_{\{ref\}}((\partial_{\{ref,st,imp,ins\}}M)^{n-1}) = \partial_{\{ref\}}((\partial_{\{st,imp,ins\}}M)^{n-1}(\partial_{\{ref\}}M)^{n-1})$$
(5) Reasoning on *cause–effect* link:
$$\begin{aligned}\partial_{\{ce\}}(M^{n-1}) &= \partial_{\{ce\}}((\partial_{\{ce,sim,st,imp,ins\}}M)^{n-1}) \\ &= \partial_{\{ce\}}((\partial_{\{st,imp,ins\}}M)^{n-1}(\partial_{\{ce\}}M)^{n-1}(\partial_{\{sim\}}M)^{n-1}(\partial_{\{st,imp,ins\}}M)^{n-1})\end{aligned}$$
(6) Reasoning on *sequential* link:
$$\partial_{\{seq\}}(M^{N-1}) = (\partial_{\{seq\}}M)^{N-1}$$

5. SLN STRUCTURAL ISOMORPHISM

A semantic node is a two-tuple $S =$ <C, L>, 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 $\{c_i \xrightarrow{<l,cd>} c_j \mid c_i, c_j \in C\}$. If L is a *null* set, then S is a set of isolated semantic nodes. Assume that U is the set of all semantic nodes in a SLN. The semantic inclusion, structure-isomorphic and partial structure-isomorphic relations can be defined on U. In [3], we define the notion of *orthogonal semantic links*, the *implication* relationship between SLNs, *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 this in detail here.

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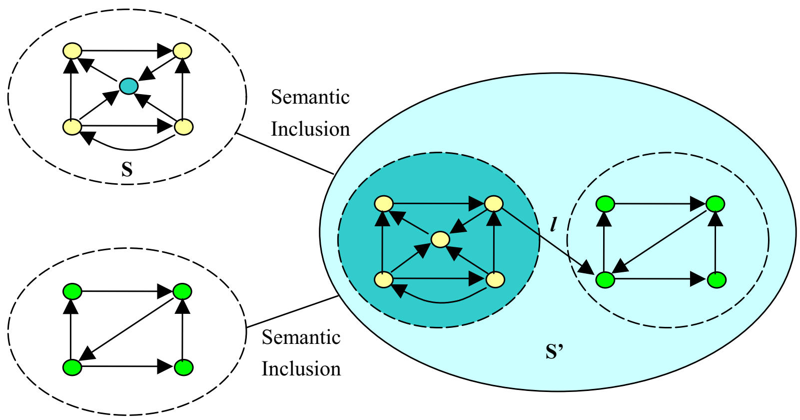

Figure 4. Example of semantic inclusion.

Definition 3 (Semantic inclusion degree). Let $S = <C, L>$ and $S' = <C', L'>$ 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':

$$IncD(S, S') = \left(\frac{|C|}{|C'|} + \frac{|L|}{|L'|}\right)\Big/2$$

obviously, $IncD(S, S') \in [0, 1]$ because of $|C| \leq |C'|$ 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 $S_1 \subseteq S_2 \subseteq \cdots \subseteq S_n$ 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 $S_1 \subseteq S_2 \subseteq \cdots \subseteq S_n$ and the answer cannot be found in S_n, then we do not need to search in $S_k (k = 1, \ldots, n - 1)$. Reversely, if an answer can be found in S_1, then it can also be found in S_n.

Definition 4 (Structure isomorphism). For any two semantic nodes $S = <C, L>$ and $S' = <C', L'>$, $|C| = |C'|$, $|L| = |L'|$, S is isomorphic to S' (denoted as $S \cong S'$) if:

(1) there exists a one-to-one and onto mapping $\theta : C \to C'$; and

(2) there exists a one-to-one and onto mapping $g : L \to L'$, and for any semantic link $c_i \xrightarrow{l} c_j$ in L, there exists a corresponding semantic link $c'_i \xrightarrow{l} c'_j$ in L', where $c'_i = \theta(c_i)$ and $c'_j = \theta(c_j)$.

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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 λ be a 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 similarity degree between S and S'. Two semantic nodes S and S' are called a partial structure isomorphism denoted as $S \approx S'$ if there exist two semantic components S_1 and S_1' 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 $S_1, \ldots, S_n$, and S' semantically includes $S_1', \ldots, S_n'$ such that $S_1 \cong S_1'$, $S_2 \cong S_2', \ldots, S_n \cong S_n'$ and $IncD(S_k, S) = max(IncD(S_1, S), IncD(S_2, S), \ldots, IncD(S_n, S))$, where $1 \le k \le n$, then we have $IncD(S_k', S') = max(IncD(S_1', S'), IncD(S_2', S'), \ldots, IncD(S_n', S'))$.*

The similarity degree between S and S' can be measured by $SD(S, S') = IncD(S_k, S') \times IncD(S_k', S')$. The larger $SD(S, S')$ is, the greater the 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 $R_{\cong} \subseteq R_{\approx}$.*

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 $S_1 \xrightarrow{<l,cd>} S_2 \Rightarrow S_2$, S_2 is a solution to the problem of finding 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 an appropriate abstraction level to participate reasoning.

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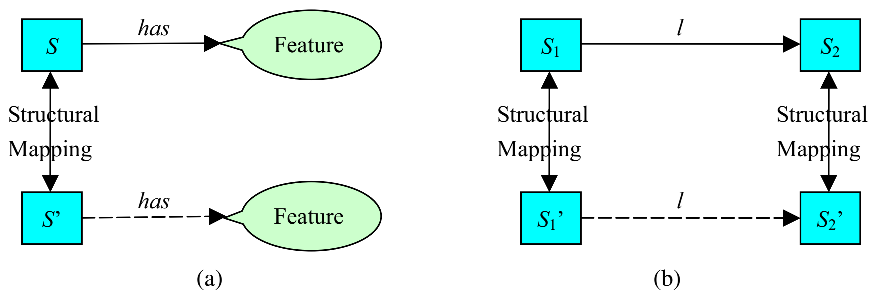

Figure 5. (a) Analogy on feature and (b) analogy on semantic link.

6. SLN ANALOGICAL REASONING

Analogy helps people understand one situation by comparing it with a known situation. It could guide reasoning, generate conjectures in an unfamiliar domain or generalize experienced instances as an abstract schema [15]. Conjectures of analogical reasoning do not follow logically from the premises [16]. However, it can help in understanding and discovering new semantic relationships.

Figure 5 shows two forms of analogical reasoning. Figure 5(a) reasons on feature, that is, if there exists a structural mapping (an isomorphism or a semantic link) between S and S', then we can conjecture that they share some features. Figure 5(b) reasons on semantic link, that is, given two structural mappings (isomorphism or semantic link) between S_i and S'_i $(i = 1, 2)$ and the semantic link l between S_1 and S_2, then we can conjecture that there exists a semantic link l between S'_1 and S'_2.

An analogical reasoning mode consists of a premise and a conjecture. The premise includes a known semantic link (or feature) and some existing relationships such as semantic inclusion, structural isomorphism and partial structure-isomorphic relations between relevant semantic nodes. The conjecture is the semantic link (or feature) generated from the premise. The certainty degree of the conjecture depends on the following factors: the certainty degrees of the semantic links in the premise, the inclusion degrees of the inclusion relations and the degrees of the similarity relations in the premise. To differentiate the certainty degree in the premise, we use $\sim cd$ to represent the certainty degree in the conjecture.

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, $cd = SD(S_1, S_2)$

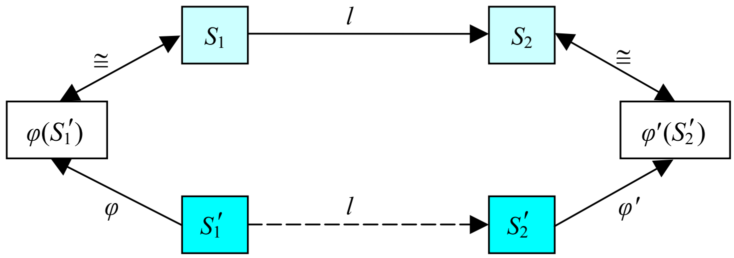

Figure 6. Analogical reasoning via transformation.

Analogical reasoning mode 2

The following analogical reasoning is about semantic links:

Premise: $S_1 \xrightarrow{<l,cd>} S_2$ and $S_1' \subseteq S_1$

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

Premise: $S_1 <l, \xrightarrow{<l,cd>} S_2$ and $S_2' \subseteq S_2$

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

Analogical reasoning mode 3

Premise: $S_1 \xrightarrow{<l,cd>} S_2,\ S_1' \cong S_1,\ S_2' \cong S_2$

Conjecture: $S_1' \xrightarrow{<l,\sim cd>} S_2'$

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

Premise: $S_1 \xrightarrow{<l,cd>} S_2,\ \phi(S_1') \cong S_1,\ \phi'(S_2') = S_2$

Conjecture: $S_1' \xrightarrow{<l,\sim cd>} S_2'$

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Analogical reasoning mode 4

Premise: $S_1 \xrightarrow{<l,cd>} S_2,\ S_1' \approx S_1,\ S_2' \approx S_2$

Conjecture: $S_1' \xrightarrow{<l,\sim cd'>} S_2'$, where $\sim cd' = cd \times f(SD(S_1, S_1'), SD(S_2, S_2'))$.

Sometimes we need two transformation functions ϕ and ϕ':

Premise: $S_1 \xrightarrow{<l,cd>} S_2,\ \phi(S_1') \approx S_1,\ \phi'(S_2') \approx S_2$

Conjecture: $S_1' \xrightarrow{<l,\sim cd'>} S_2'$, where $\sim cd' = cd \times f(SD(S_1, \phi(S_1')), SD(S_2, \phi'(S_2')))$

Analogical reasoning mode 5

For two semantic nodes $S = <C, L>$ and $S' = <C', L'>$, the union of S and S' is $S \cup S' = <C \cup C', L \Delta L'>$, 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 $i = 1, 2, \ldots, k$, if the following analogical reasoning is true for all i:

Premise: $S_{1i} \xrightarrow{<l,cd>} S_{2i},\ S_{1i}' \cong S_{1i},\ S_{2i}' \cong S_{2i}$

Conjecture: $S_{1i}' \xrightarrow{<l,\sim cd>} S_{2i}'$

then, we have

Premise: $S_1 \xrightarrow{<l,cd>} S_2$

Conjecture: $S_1' \xrightarrow{<l,\sim cd'>} S_2'$, where

$$\sim cd' = f\left(cd, \left(\left|\bigcup_{i=1}^{k} C_{1i}\right| \Big/ |C_1| + |\Delta_{i=1}^{k} L_{1i}| \Big/ |L_1|\right) \Big/ 2\right.$$

$$\left(\left|\bigcup_{i=1}^{k} C_{2i}\right| \Big/ |C_2| + |\Delta_{i=1}^{k} L_{2i}| \Big/ |L_2|\right) \Big/ 2$$

$$\left(\left|\bigcup_{i=1}^{k} C_{1i}'\right| \Big/ |C_1'| + |\Delta_{i=1}^{k} L_{1i}'| \Big/ |L_1'|\right) \Big/ 2$$

$$\left.\left(\left|\bigcup_{i=1}^{k} C_{2i}'\right| \Big/ |C_2| + |\Delta_{i=1}^{k} L_{2i}'| \Big/ |L_2'|\right) \Big/ 2\right)$$

Analogical reasoning mode 6

Premise: $S_1 \xrightarrow{<l,cd>} S_2,\ S_1' \subseteq S_1,\ S_2' \subseteq S_2,\ IncD(S_1', S_1) > \sigma,\ IncD(S_2', S_2) > \sigma$
σ is the low bound of inclusion degree

Conjecture: $S_1' \xrightarrow{<l,\sim cd'>} S_2'$, where $\sim cd' = cd \times f(IncD(S_1', S_1), IncD(S_2', S_2))$

Sometimes we need a transformation ϕ:

Premise: $S_1 \xrightarrow{<l,cd>} S_2,\ \phi(S_1') \subseteq S_1,\ S_2' = \phi'(S_2''),\ S_2'' \subseteq S_2,$
$IncD(\phi(S_1'), S_1) > \sigma,\ IncD(\phi(S_2'), S_2) > \sigma$

Conjecture: $S_1' \xrightarrow{<l,\sim cd'>} S_2'$, where $\sim cd' = cd \times f(IncD(\phi(S_1'), S_1), IncD(S_2'', S_2))$

7. SLN INDUCTIVE REASONING

SLN inductive reasoning carries out from special to general. Here we give two SLN inductive reasoning modes.

(1) *From entity to concept*

$E_i \xrightarrow{l} E_i'$, $i = 1, \ldots, n$ are semantic links between entities
$S \xrightarrow{instance} E_i$ (E_i is an instance of S)
$S' \xrightarrow{instance} E_i'$ (E_i' is an instance of S')

$S \xrightarrow{<l,cd>} S$, *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.

$S_i \xrightarrow{feature} F_i$ (S_i has feature set F_i, $i = 1, \ldots, n$)
$S \xrightarrow{subtype} S_i$ (S_i is a subtype of S)

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

The following reasoning is about semantic link.

$S_i \xrightarrow{l} S_i'$ ($i = 1, \ldots, n$)
$S \xrightarrow{subtype} S_i$ (S_i is a subtype of S)
$S' \xrightarrow{subtype} S_i'$ (S_i' is a subtype of S')

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

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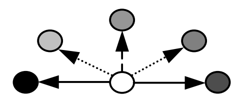
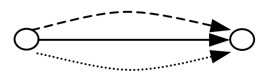
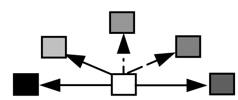
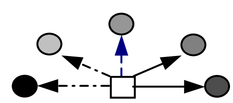
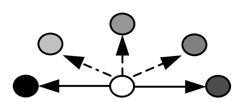
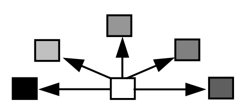
Table I. Some basic functions of semantic search.

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 ●	
$S \xrightarrow{\alpha} ?$ ○⟶	$S \xrightarrow{\alpha} X_1, \ldots, S \xrightarrow{\alpha} X_n$	
$E \xrightarrow{\alpha} ?$	$E \xrightarrow{\alpha} X_1, \ldots, E \xrightarrow{\alpha} X_n$	
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. APPLICATION PERSPECTIVE

8.1. Semantic-based search

The proposed autonomous SLN supports semantic search. Table I 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

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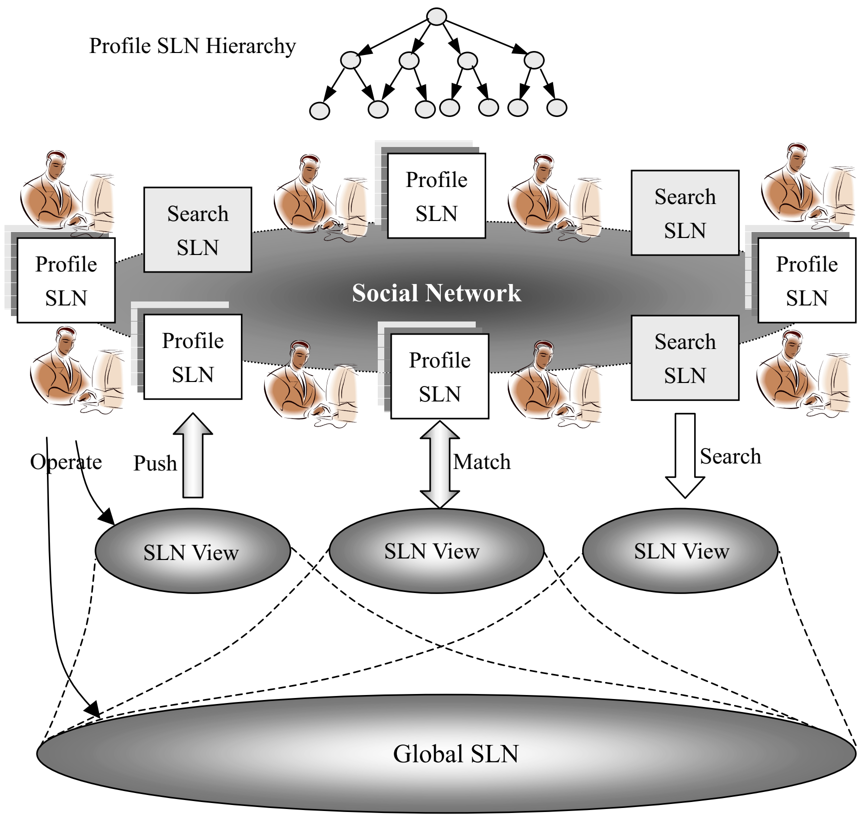

Figure 7. Autonomous semantic overlay incorporating the global SLN, SLN views, user profile SLNs and search SLNs.

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 a SLN, the search mechanism can find a view or a larger SLN about some semantic factors for localizing or extending the search scope.

8.2. Self-organization of the diverse scale of SLNs for an on-demand information service

The autonomous SLN can further extend into 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 a SLN view. With the profile SLNs, information can be accurately pushed to appropriate people. Semantic relations between user profiles self-organize a SLN overlay. With such overlays, an information service system does not need to establish and maintain a 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 the reasoning mechanism.

9. RELATED WORK AND DISCUSSION

Analogy is a kind of human innovative thinking and problem-solving mode. In Gentner's structure-mapping theory [15], analogy is a mapping from one domain (called a base) into another (called a target), which indicates some common relational structures between the base and the target [17]. Analogy can be used to guide reasoning, to generate conjectures in an unfamiliar domain and to generalize experiences into abstract schemas [15]. Various computational frameworks have been established for detecting analogies and structural equivalencies [16,18,19]. The object analogical reasoning model makes use of the object model and the abstraction relationship between objects to enhance analogical reasoning ability [11]. An implementation process of analogical reasoning modes was suggested in [3]. The development of the Semantic Web and the SLN provide an opportunity for research and applications on analogical reasoning.

The SLN, Web, databases, traditional semantic networks and cognitive maps 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 are not enough to support reasoning in distributed intelligent applications.

The World Wide Web uses hyperlinks to connect Web pages for humans 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 was designed to overcome this shortcoming by developing markup languages and ontology [1]. Current research and development on the Semantic Web still lacks the formalism for automatically generating semantics and semantic reasoning, especially for the analogical reasoning mechanism.

A traditional semantic network is a graph in which the nodes are concepts and the arcs are relations between concepts [20]. A semantic network uses multiple relations to connect concepts to represent knowledge [21]. Six types of semantic network are: (1) a definitional network, which emphasizes the

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subtype and *is-a* relationships to organize concepts into a hierarchy; (2) an assertional network, which can assert propositions and represent conceptual structures in natural languages; (3) an implicational network, which emphasizes the *causal* relationship between concepts; (4) an executable network, which includes executive mechanisms for inference, searching, etc.; (5) a learning network, which can acquire knowledge from examples by modifying the network; and (6) hybrid networks, which combine two (or more) of the above [22].

A 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 [23,24]. However, cognitive maps only reflect causal relation, they are unable to support various semantic-rich reasonings.

The 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 a SLN are connected by various semantic relationships. A semantic link builder was developed to support users to build small-scale SLNs, which can be connected to one another by semantic links to form a large and even global SLN [7]. The partitioned semantic matrix was used to improve the efficiency of large SLN computing [12]. The SLN was also used to describe the semantic relationship between images to realize semantic-based image retrieval [25].

The self-organization characteristic of the hyperlink-based World Wide Web leads to a 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 at attracting new nodes. However, for a SLN, a new node tends to link to 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 of expertise and workload rather than their ranks. So the evolution of a SLN is the process of forming semantic communities.

A semantic community can be discovered in a large SLN by removing those semantic links that could not reason with neighbor links. The semantic community discovery approach is different from the approach for discovering a community in semantic-poor networks [26], due to the fact that implicit semantic links could be derived.

10. CONCLUSION

The SLN 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 content at the entity level but also knowledge at the abstraction level. The SLN logical reasoning can derive 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 enough to establish an autonomous semantic overlay for supporting intelligent applications of the Knowledge Grid.

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REFERENCES

1. Berners-Lee T, Hendler J, Lassila O. The semantic Web. *Scientific American* 2001; **284**(5):24–43.
2. Zhuge H. Semantic Grid: Scientific issues, infrastructure, and methodology. *Communications of the ACM* 2005; **48**(4):117–119.
3. Zhuge H. *The Knowledge Grid*. World Scientific: Singapore, 2004.
4. Dublin Core Metadata Element Set Standard. http://dublincore.org [2005].
5. Zhuge H, Liu J, Feng L, Sun X, He C. Query routing in a peer-to-peer semantic link network. *Computational Intelligence* 2005; **21**(2):197–216.
6. Zhuge H. Active e-Document Framework ADF: Model and platform. *Information and Management* 2003; **20**(43):1–11.
7. Zhuge H, Jia R, Liu J. Semantic link network builder and intelligent browser. *Concurrency and Computation: Practice and Experience* 2004; **16**(14):1453–1476.
8. Green SJ. Building hypertext links by computing semantic similarity. *IEEE Transactions on Knowledge and Data Engineering* 1999; **11**(5):713–730.
9. Tudhope D, Taylor C. Navigation via similarity: Automatic linking based on semantic closeness. *Information Processing and Management* 1997; **33**(2):233–242.
10. Zhuge H *et al.* An automatic semantic relationship discovery approach. *Proceedings of WWW2004*. Available at: http://www.www2004.org/proceedings/docs/2p278.pdf [2004].
11. Zhuge H. Research on object analogical reasoning. *Chinese Journal of Advanced Software Research* 1994; **1**(2):166–177.
12. Zhuge H, Sun Y, Jia R, Liu J. Algebra model and experiment for semantic link network. *International Journal of High Performance Computing and Networking* 2005; **3**(4):227–238.
13. Henzinger MR. Hyperlink analysis for the Web. *IEEE Internet Computing* 2001; **5**(1):45–50.
14. Page L, Brin S, Motwani R, Winograd T. The pagerank citation ranking: Bringing order to the Web. *Technical Report*, Stanford University, Santa Barbara, CA 93106, January 1998.
15. Falkenhainer B, Forbus KD, Gentner D. The structure-mapping engine: Algorithm and examples. *Artificial Intelligence* 1989; **41**(5):1–63.
16. Dutta S. Learning of background knowledge for making reliable analogical inferences. *Artificial Intelligence in Engineering: Diagnosis and Learning*, Gero JS (ed.). Computational Mechanics Publications: Southampton, 1988; 305–331.
17. Gentner D. Structure-mapping: A theoretical framework for analogy. *Cognitive Science* 1983; **7**(2):155–170.
18. Holyoak DKJ, Kokinov B (eds). *Analogy: Perspectives from Cognitive Science*. MIT Press: Cambridge, MA, 2000.
19. Marx Z, Dagan I, Buhmann JM, Shamir E. Coupled clustering: A method for detecting structural correspondence. *Journal of Machine Learning Research* 2002; **3**(2):747–780.
20. Quillian MR. Semantic memory. *Semantic Information Processing*, Minsky M (ed.). MIT Press, Cambridge, MA, 1968.
21. Peters S, Shrobe H. Using semantic networks for knowledge representation in an intelligent environment. *Proceedings of the 1st Annual IEEE International Conference on Pervasive Computing and Communications*, Fort Worth, TX, March 2003. IEEE Computer Society Press: Los Alamitos, CA, 2003.
22. Sowa JF. Semantic networks, August 2002. http://www.jfsowa.com/pubs/semnet.htm.
23. Chaib-draa B. Causal maps: Theory, implementation and practical applications in multiagent environments. *IEEE Transactions on Knowledge and Data Engineering* 2002; **14**(6):1–17.
24. Miao Y, Liu Z, Siew C, Miao C. Dynamic cognitive net—an extension of fuzzy cognitive map. *IEEE Transactions on Fuzzy Systems* 2001; **9**(5):760–770.
25. Zhuge H. Retrieve images by understanding semantic links and clustering image fragments. *Journal of Systems and Software* 2004; **73**(3):455–466.
26. Wilkinson DM, Huberman BA. A method for finding communities of related genes. *Proceedings of the National Academy of Sciences of the United States of America* 2004; **101**:5241–5248.