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Basic operations, completeness and dynamicity of cyber physical socio semantic link network CPSocio-SLN

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SUMMARY

Cyber Physical Socio Semantic Link network (CPSocio-SLN) is a model and method for self-organizing cyber physical socio resources in Cyber Physical Society (CP-Society). This paper views CPSocio-SLN as an evolution process through a series of operations, and investigates its basic operations, completeness, and dynamicity. A strategy for efficiently storing and managing CPSocio-SLN based on the basic operation set is proposed to support efficient query and maintenance. An approach is suggested for simplifying CPSocio-SLN reasoning by estimating the importance of reasoning at multiple levels. The study of the dynamicity can help understand its basic characteristics. Copyright © 2010 John Wiley & Sons, Ltd.

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KEY WORDS: cyber physical society; cyber physical socio; cyber physical systems; semantic link network; evolution; dynamicity

1. INTRODUCTION

1.1. Motivation

Things in the world are related, but humans only know very limited relations in physical space and society. The Cyber Physical Socio Semantic Link Network (CPSocio-SLN) is to link things in a

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meaningful way and enable humans and agents to know more relations and its evolution through relational reasoning and operations in Cyber Physical Society (CP-Society) [1–5]. It is a general method to study various self-organized relational networks in and through cyber space, physical space, mental space and society.

A CPSocio-SLN uses semantic links to connect nodes and carry out reasoning according to rules. A node can be resources in physical space, society, cyber space (e.g. text and image) and mental space (e.g. thought) [5]. The static semantics of semantic link is determined by Attributes, Relations, Class and Rules (ARCR). The static semantics of semantic node is determined by Attribute, Relation, Class, Neighbors and Instances (ARCNI) [5]. Behaviors of nodes and interaction between nodes will influence the semantics of a semantic link network [3, 4].

Different from previous studies on various types of links, a distinguished characteristic of CPSocio-SLN is that it keeps evolving from the beginning due to its reasoning ability. When we add a new semantic link to the network, more semantic links will emerge because of influence and relational reasoning [6]. This dynamic nature brings many interesting research issues.

This paper studies the basic operations that can be used to compose any operation on CPSocio-SLN and their completeness. We regard CPSocio-SLN as an evolution process through a series of operations. The issues and characteristics about CPSocio-SLN structure and operations will be discussed.

1.2. Related work

The ideal of the CP-Society was early described from ecosystem point of view in [1]: 'An Eco-Grid is an open worldwide interconnection environment reflecting the characteristics of natural ecological environments. Its versatile resources and social roles coexist harmoniously yet evolve, provide appropriate on-demand services to one another, are transformed from one form to another, and communicate in terms of information, knowledge, and service flows through social and economic value chains. It maintains a reasonable rate of expansion of useful resources and assimilates waste resources in light of overall environment capacity.' The importance of harmonious development of the nature, society, environment and cyber world pointed out that networks pervade nature, society and virtual worlds, giving structure and function to a variety of resources and behaviors, and that the future interconnection environment will be a large-scale human–machine environment that unites three worlds: physical world, virtual world and mental world [7]. The term CP-Society was used for the first time to emphasize the importance of cyber space, physical space and society in the future interconnection environment in [5]. The Cyber Physical Socio Ecology was proposed in [8].

Hyperlink networks and various labeled networks were extensively studied in hypertext, web and semantic web areas [9–11]. The Semantic Web is to create machine understandable semantics on the web [12]. Semantic Web is mainly based on ontology mechanisms and markup languages such as XML (www.w3.org/XML) and RDF [13]. XML describes the structure of Web resources to make cross-platform information exchange. RDF (www.w3.org/RDF) describes the universal resources and their relationships based on the triple (object, attribute, value). Based on RDF and XML, OWL (www.w3.org/2004/OWL/) uses ontology to describe the semantics of resources and uses roles to describe their relationships [14]. Operators were proposed for RDF to manipulate data [15]. Radio-frequency identification (RFID) was incorporated into product, animal or person for the purpose of identification and tracking using radio waves. RFID was a basic element to realize the Web of Things and Internet of Things.

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Ontology explicitly specifies the concepts of a domain [16]. A set of ontology-change operations was introduced in [17]. The effects of changes and ontology evolution were discussed. The evolution of ontology is based on the basic atomic changes, and basic additions to or deletions from an RDF graph, which can be aggregated to compound changes [16]. A simple model of network growth had more than 5 million people and 10 million friendship links, annotated with metadata capturing the time of every event in life was discussed in [18]. Some basic relationships characterizing community evolution were addressed in [19].

The initial motivation of the semantic link network SLN was to extend the hyperlink networks by enriching links and inclusion of rules and rule reasoning [2, 3, 6, 20–23]. Semantic Link Network Builder and Intelligent Semantic Browser are tools for SLN designers and users to build and browse SLN [24]. The approach to query routing in a peer-to-peer semantic link network and semantic link-based top-k join queries in P2P were proposed in [6, 24]. SLN can reflect social network and emerge semantic community [3]. SLN is regarded as an important component of the Knowledge Grid [22].

Previous semantic net, semantic web, hyperlink, and semantic link are too static to represent dynamic relations in nature, minds, and society. Hence, SLN was extended to Socio-Natural Thought SLN for semantic networking in CP-Society [5]. The distinguished characteristics and philosophy were introduced.

Some important questions should be answered: What are the characteristics of the CP-Society? What are its basic operations? How it evolves?

1.3. Notations and definitions

We first introduce some basic notions:

Reversion semantic link. If there is a semantic link α from r_1 to r_2, then there is a reverse semantic link of α from r_2 to r_1, denoted as *Reverse* (α) or α^R.

Figure 1 demonstrates a simple relational reasoning. Semantic link β could be derived from semantic link α and semantic link θ according to some rules, e.g. paternity relation can be derived from brother relation and paternity relation. The new semantic link μ could be further derived from β and λ.

Rules are given by human users, and take the following form: $S=\{e_1\times e_2\rightarrow e_3, e_3\times e_4\rightarrow e_5, e_6\rightarrow e_7\ldots\}$, where e_i $(i=1,2,\ldots,7)$ represents semantic links. If there are two semantic links sharing a common node and satisfying a reasoning rule, then a relational reasoning can be conducted, e.g. $d_1\xrightarrow{e_1} d_2$, $d_2\xrightarrow{e_2} d_3\Rightarrow d_1\xrightarrow{e3} d_3$ according to the first rule in S, and one semantic link can imply the other link, i.e. $d_1\xrightarrow{e_6} d_2\Rightarrow d_1\xrightarrow{e_7} d_2$ according to the third rule in S.

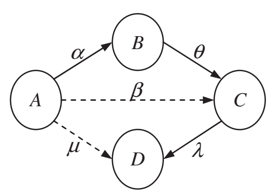

Figure 1. Example of relational reasoning.

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Semantic closure. A closure of a CPSocio-SLN S is a semantic link network S^+ such that all semantic links in S are also in S^+, and any semantic link that can be derived from reasoning on S^+ is also in S^+.

Minimum semantic cover. A CPSocio-SLN M is the minimum semantic cover of another CPSocio-SLN S, if it satisfies the following conditions: (1) $M^+ = S^+$ and (2) no semantic link sl exists in M such that $(M - sl)^+ = M^+$ holds.

2. CHARACTERISTICS OF MINIMUM SEMANTIC COVER AND CONFORMATION SEQUENCE

Theorem 1
The minimum semantic cover of CPSocio-SLN is not unique.

The theorem can be proved through instances. Figure 2 is a CPSocio-SLN with the following rules $e_7 \times e_1 \to e_8, e_8 \times e_2 \to e_9, e_9 \times e_3 \to e_{10}, e_{10} \times e_4 \to e_{11}, e_{11} \times e_5 \to e_{12}$, and $e_{12} \times e_6 \to e_7$. It has the following six minimum semantic covers: $\{\{e_1, e_2, e_3, e_4, e_5, e_6\} \cup \{e_7\}\}$, $\{\{e_1, e_2, e_3, e_4, e_5, e_6\} \cup \{e_8\}\}$, $\{\{e_1, e_2, e_3, e_4, e_5, e_6\} \cup \{e_9\}\}$, $\{\{e_1, e_2, e_3, e_4, e_5, e_6\} \cup \{e_{10}\}\}$, $\{\{e_1, e_2, e_3, e_4, e_5, e_6\} \cup \{e_{11}\}\}$, and $\{\{e_1, e_2, e_3, e_4, e_5, e_6\} \cup \{e_{12}\}\}$; hence the minimum semantic cover for a CPSocio-SLN is not unique. Note that the semantic links in the minimum semantic cover may also be derived out by other semantic links in CPSocio-SLN.

The minimum semantic cover of CPSocio-SLN is not unique, but the importance of different minimum semantic covers is different. Hence, we can select the most important one and regard it as the representative. Usually, the earlier formed one should take the priority as the representative.

Conformation sequence is a sequence of operations on nodes and semantic links when building a CPSocio-SLN. No matter how the structure of the CPSocio-SLN is, it is built by operations gradually.

Take the link set $\{e_7, e_8, e_9, e_{10}, e_{11}, e_{12}\}$ shown in Figure 2 for example. The first link added to the CPSocio-SLN (the conformation sequence can give this information) should be in the important minimum semantic cover. Adding e_7, the CPSocio-SLN obtains semantic links $\{e_8, e_9, e_{10}, e_{11}, e_{12}\}$. Hence, e_7 should be in the important minimum semantic cover.

An important minimum semantic cover for a CPSocio-SLN is unique. Hereafter, the *minimum semantic cover* refers to the *important minimum semantic cover*. Actually, Figure 2 implies a reasoning circulation.

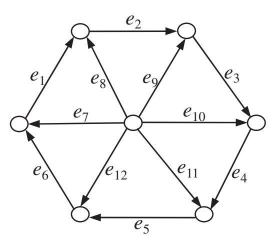

Figure 2. Example of the minimum semantic cover.

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Definition 1
Assume that a semantic link e does not exist in CPSocio-SLN M. Change M to M' by adding e to M, and calculate the semantic closure. If e can be also derived out through reasoning initiated by e, there must be a *reasoning circulation* in M' and e is in the reasoning circulation.

Assume a semantic link set in a CPSocio-SLN. If adding any semantic link to the set will lead to the same effect, the link set is called equivalent link set. Figure 2 shows that $\{e_7, e_8, e_9, e_{10}, e_{11}, e_{12}\}$ is an equivalent link set.

We can detect whether there is a reasoning circulation after addition operation. A reasoning circulation can also be found by checking the log of CPSocio-SLN system.

We can see that the cause of Theorem 1 is the existence of the equivalent semantic link set, because adding any link to this set leads to the same effect. 'A CPSocio-SLN has equivalent link set' and 'The minimum semantic cover for one CPSocio-SLN is not unique' are sufficient and necessary condition to each other.

CPSocio-SLN should handle the reasoning process if it has found a reasoning circulation.

3. BASIC OPERATIONS AND CHARACTERISTICS OF CPSocio-SLN

3.1. Basic operations of CPSocio-SLN

A basic operation set satisfies the following conditions:

(1) *Expression ability*. Operations in the set can transform one CPSocio-SLN to any CPSocio-SLN.
(2) *Orthogonality*. In this operation set, there is no such operation that can be represented by other operations.

The first condition means that the set is for all operations and the second condition means that the number of operations in the set is the smallest.

Definition 2
Let e and a be semantic links in CPSocio-SLN G, and $G_{\min}$ be the minimum semantic cover of G. Given a CPSocio-SLN $G_1 = G_{\min} - \{e, a\}$, if the closure of G_1 does not include a and the closure of $G_1 \cup \{e\}$ include a, we say that e determines a (or a is determined by e). All semantic links determined by e is called a determining set of e.

A semantic link can be represented as (n_1, n_2, α, G), where n_1 and n_2 are nodes and α is a semantic link in CPSocio-SLN G. The following are the basic operation set:

(1) Adding a new resource node n, *AddNode* (n, G).
(2) Deleting a semantic link α between two nodes n_1 and n_2, *DelLink* (n_1, n_2, α, G). Semantic links determined by α should also be deleted. In this operation, if n_1 and n_2 are not given, the operation should delete all semantic links with semantic relation α.
(3) Deleting an isolated node n, *DelNode* (n, G). If the node to be deleted is conjoint to other nodes, we should first use *DelLink* to delete the semantic links between them. (Semantic links are classified into inter-attribute semantic link and inter-resource semantic link. The term *isolated* here means that there is no inter-resource semantic link among resources.)

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(4) Adding a semantic link a between two nodes n_1 and n_2, *AddLink* (n_1, n_2, a, G). If n_1 and n_2 do not exist, *AddNode* should be used to add n_1 and n_2 first.
(5) Adding a new rule, *AddRule*(*RuleID*, $P \to S$). *RuleID* is the identity of the rule, P and S are, respectively, the predecessor (in the form of $e_1 \times e_2 \times e_3 \times \cdots \times e_n$) and the successor of the rule.
(6) Deleting a rule, *DelRule* (*RuleID*). Delete a reasoning rule according to *RuleID*.

Theorem 2
The above operation set is complete.

First, the operation set's expression ability can transform any CPSocio-SLN into another. If there are some differences between two CPSocio-SLNs, the difference must be from three parts: resources, semantic links, and rules. There is a series of corresponding basic operations to transform one into the other. The basic operations (1) and (3) are for transforming resources. The basic operations (2) and (4) are for transforming semantic links. The basic operations (5) and (6) are for transforming rules.

Second, any pair of operations in the set is orthogonal, since no one can be represented by the other in this operation set.

The following algorithm is for calculating the semantic closure of a given CPSocio-SLN:

Algorithm *GetClosure*
Input: a CPSocio-SLN
Output: the semantic closure of the input CPSocio-SLN

(1) Initialize a semantic link queue Q. Check all semantic links in CPSocio-SLN, find semantic links that can be derived out from existing links, and then add these new links to the CPSocio-SLN and Q.
(2) Get the first element of Q. Find new links that can be derived out by this element, and then add them to the CPSocio-SLN and Q.
(3) If Q is not empty, go to step 2, else the algorithm ends.

3.2. *Characteristics of the basic operation set*

Based on the determination relation among semantic links, the following theorem can be reached.

Theorem 3
Semantic links are only determined by the semantic links in the minimum semantic cover.

Proof
Let α and e be two semantic links in CPSocio-SLN G, a is determined by e, and $G_1 = G - \{e, a\}$. If e is not in the minimum semantic cover, then G_1 is equal to $G_1 \cup \{e\}$. According to Definition 2, it is impossible that G_1 does not include a and $G_1 \cup \{e\}$ includes a. Hence, e does not determine a. Since the semantic link a is anyone, there is no semantic link determined by e. The conclusion is inconsistent with the assumption. Hence, the theorem holds. □

Characteristic 1
If the semantic link to be deleted is not in the minimum semantic cover, the CPSocio-SLN equals to the original CPSocio-SLN after operating DelLink on it.

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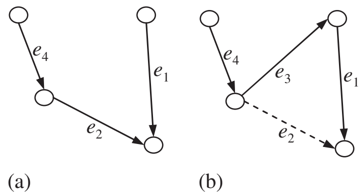

Figure 3. Change of the minimum semantic cover: (a) original minimum semantic cover and (b) minimum semantic cover after adding e_3.

Characteristic 2
If the semantic link to be added is in the closure of the CPSocio-SLN, the CPSocio-SLN equals to the original CPSocio-SLN after operating AddLink on it.

Characteristic 3
Deleting a semantic link between two semantic nodes and then adding it between the same pair of nodes, this CPSocio-SLN is unchanged.

However, if we change the order of operations, the result will be different.

Characteristic 4
Adding a semantic link between two nodes and then deleting it, the minimum semantic cover of the CPSocio-SLN may be changed.

Take Figure 3 for example, e_3 is added, if there is a rule $e_3 \times e_1 \rightarrow e_2$, e_2 should not be in the minimum semantic cover. Hence, e_2 should be removed from the minimum semantic cover. Based on the basic operation 3, if we delete e_3, e_2 should be deleted too. Compared with the original minimum semantic cover, the CPSocio-SLN has been changed because of missing e_2.

Characteristic 5 can be easily obtained from characteristic 4.

Characteristic 5
Adding a semantic link between two nodes and then deleting it between the same pair of nodes, the CPSocio-SLN may be changed.

Hence, after adding (deleting) a semantic link, we cannot simply use the deleting (adding) operation to recover the CPSocio-SLN.

Characteristic 6
If a semantic link h in the minimum semantic cover can be derived out by $j \times k \rightarrow h$, and the determining set of h does not include j or k, h should not be in the minimum semantic cover.

As shown in Figure 4, if there is a rule $m \times d \rightarrow a$, a is in the minimum semantic cover. But a should not be deleted from the minimum semantic cover, otherwise a cannot be reasoned out. Figure 4 shows the semantic link m that can reason out a can be reasoned out by a, because a's determining set includes m. If we delete a, then the semantic links that are determined by a will not be reasoned out.

Characteristic 7
Two semantic links' determining set may have intersection.

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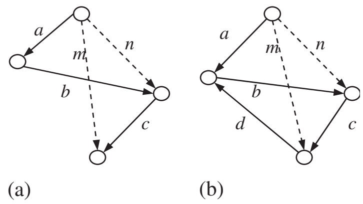

Figure 4. (a) CPSocio-SLN with rules $a \times b \rightarrow n$ and $n \times c \rightarrow m$ and (b) CPSocio-SLN after adding semantic link d. a can be reasoned out by m and d, but a should not be removed from the minimum semantic cover.

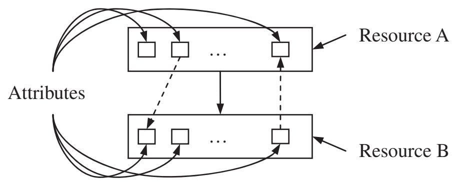

Figure 5. Inter-attribute semantic link (dotted arrows) and inter-resource semantic link (solid arrows).

This characteristic implies that its determining set should not be deleted after deleting a semantic link, because there may be another determining set that has intersection with it.

Except these basic operations, we should provide some complex operations for convenience. These complex operations, such as union, disjoin, etc., can all be implemented by the basic operations.

3.3. Inter-attribute semantic link and inter-resource semantic link

For a given set of resources, there are two essential types of semantic links: the semantic links between attributes of resources and the semantic links between resources. The former is called *inter-attribute semantic link* (e.g. *older* or *younger* links between attributes *age* of two nodes). The latter is called *inter-resource semantic link* (e.g. *friend* relation). Figure 5 shows the inter-attribute semantic links and inter-resource semantic links. Inter-resource semantic links may change from time to time, but inter-attribute semantic links are relatively stable as long as the nodes are stable. The change of inter-resource semantic link helps humans deepen the recognition of resources.

Is there any relationship between the two types of semantic links?

Inter-resource semantic links cannot be derived from attributes. For example, we can clearly find out a semantic link *older* or *younger* between attributes of two persons, but semantic links, such as *friend* and *enemy*, cannot be derived out from attributes.

Characteristic 8
Attributes can only determine inter-attribute semantic links.

Users can set rules for attributes on how to automatically find inter-attribute semantic links.

Characteristic 9
Deleting or adding inter-attribute semantic links does not change inter-resource semantic links.

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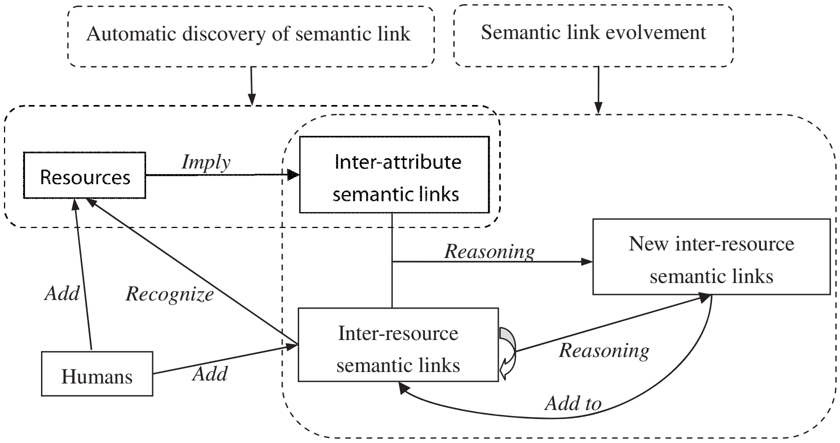

Figure 6. Influence between resources and inter-resource semantic links.

Inter-attribute semantic links can reason with inter-resource semantic links to obtain new inter-resource semantic links. Inter-resource semantic links may influence humans' understanding on attributes of resources. *The influences form an iterative and self-adaptive process to approach the semantics of CPSocio-SLN*. For example, semantic link *consanguinity* implies that the predecessor and successor of this link must have attribute *life-form*. Hence, the inter-resource semantic link can help resources find the attributes they do not know before.

The *minimum semantic cover* and *closure* are on inter-resource semantic links. The evolution of semantic link network is based on inter-resource semantic links. Figure 6 shows the relationship among resources, inter-attribute semantic links, and inter-resource semantic links. It explains the intrinsic relationships between discovery of semantic link and semantic link evolution.

4. MAINTENANCE AND QUERY

4.1. Strategy for storing in cyber space

The execution of operations is related to the storage of CPSocio-SLN. Hence, the structure of storage influences the way of operations. The following are the two basic storage strategies:

(1) Save the closure of CPSocio-SLN. This strategy leads to high efficiency in query, but the cost of maintenance is also high. Since the minimum semantic cover is not saved, many operations must calculate this cover first , which usually costs much time.
(2) Save the minimum semantic cover of CPSocio-SLN. This strategy leads to high efficiency in maintenance, but the cost of query is high. If we want to know a relation between two nodes, the reasoning cost is high. Sometimes, the closure of CPSocio-SLN must be reasoned out.

The third efficient storage strategy is to save both the semantic closure and the minimum semantic cover of CPSocio-SLN so that we can operate on the minimum semantic cover and can query on the closure. But, the minimum semantic cover and the closure must keep consistent after operations.

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The following are the advantages of the third storage strategy:

(1) The semantic links to be queried must have been reasoned out. As the closure of CPSocio-SLN is stored, we can find these links efficiently.
(2) Easy to maintain. Operations can directly be applied to the minimum semantic cover of CPSocio-SLN.
(3) Update operations can be put to background; hence, CPSocio-SLN can quickly answer query and execute operations.

4.2. Minimum spanning graph set

Definition 3
The spanning graph of a semantic link α is a subgraph of the minimum semantic cover such that this subgraph's closure includes α.

Definition 4
The minimum spanning graph of a semantic link m is a subgraph of the minimum semantic cover such that this subgraph's closure includes m, and there is no proper subgraph of this subgraph, its closure also has m.

A semantic link may have several minimum spanning graphs, and these minimum spanning graphs may have intersection.

Definition 5
A semantic link may have several minimum spanning graphs. A semantic link's minimum spanning graph set is a graph set of these minimum spanning graphs.

As shown in Figure 7, e_1, e_2, e_3, e_4, e_5, e_{10}, and e_{11} are the semantic links in the minimum semantic cover, other semantic links are derived. The reasoning process is as follows: $e_2 \times e_5 \rightarrow e_6$, $e_1 \times e_6 \rightarrow e_7$, $e_3 \times e_4 \rightarrow e_8$, $e_7 \times e_8 \rightarrow e_9$, and $e_{10} \times e_{11} \rightarrow e_9$. Hence, the minimum spanning graph set of e_1, e_2, e_3, e_4, e_5, e_{10} and e_{11} is $\{\{e_1\}\}$, $\{\{e_2\}\}$, $\{\{e_3\}\}$, $\{\{e_4\}\}$, $\{\{e_5\}\}$, $\{\{e_{10}\}\}$, $\{\{e_{11}\}\}$ and the minimum spanning graph set of e_6, e_7, e_8 and e_9 is $\{\{e_2, e_5\}\}$, $\{\{e_1, e_2, e_5\}\}$, $\{\{e_3, e_4\}\}$, $\{\{e_1, e_2, e_5, e_3, e_4\}, \{e_{10}, e_{11}\}\}$. Link e_9 has two minimum spanning graphs.

Characteristic 10
Let G be the minimum spanning graph of semantic link e. If any semantic link in G has been deleted, G cannot reason out e any more.

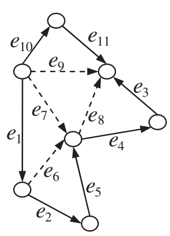

Figure 7. Example of the minimum spanning graph.

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Proof
If G still can reason out e after deleting semantic link a in the minimum spanning graph, the graph G-{*the deleted link*} is also a spanning graph of e and a proper subgraph of G. Hence, G is not the minimum spanning graph of e. It is inconsistent with the definition of the minimum spanning graph. □

Every link has a minimum spanning graph set. If a link is in the minimum spanning graph set, we add its rank by one. After checking all links' minimum spanning graph set, we can get a link set, links in this set have the same rank and links that are not in the set have a smaller rank. Hence, the links in the set are the most important. They form the core and represent the meaning of the CPSocio-SLN.

Obviously, only the inter-resource semantic links have the minimum spanning graph set. The inter-attribute semantic links are generated by resources' attributes; hence, they do not have the minimum spanning graph set.

4.3. Maintenance operations for the basic operations

Characteristic 4 shows that adding semantic links may change the minimum semantic cover. We need to maintain the closure, and modify the minimum semantic cover. After operations on the minimum semantic cover, the process of maintenance operations is as follows:

(1) Carrying out reasoning and analysis on CPSocio-SLN according to the operations on the minimum semantic cover, maintaining the closure of CPSocio-SLN, and recording the place that needs to be modified in the minimum semantic cover.
(2) Modifying the places in the minimum semantic cover and re-maintaining the semantic closure.

Based on the basic operations, there are six kinds of maintenance operations. Since Characteristic 4 must be considered, these update operations must adjust the minimum semantic cover if needed.

(*1*) *Maintenance for adding a semantic link AddLink*

The update operation needs to find all semantic links that can be derived out from this new link, instead of visiting the entire CPSocio-SLN graph. We use the *possibility reasoning set* of semantic link a to represent the semantic links that can reason with a. The semantic links that are not in this set never reason with a. For every semantic link, for example a, the semantic links set *Ereasoning* $(a)=\{e|e$ and a are adjacent$\}$. The following algorithm solves this problem: Add a semantic link $e=(n_1, n_2, \alpha)$ and calculate the semantic closure of the new CPSocio-SLN.

Algorithm *OriginalAddLink*:

Input: Closure of original CPSocio-SLN and e (the new semantic link that has already been added to the minimum semantic cover).

Output: Closure of new CPSocio-SLN, which includes original CPSocio-SLN and e.

(1) Add e to CPSocio-SLN's closure.
(2) Find new links which should be added to CPSocio-SLN because of adding link e, and then add these new links to CPSocio-SLN.
(3) Go to (2) until there is no change on CPSocio-SLN.
(4) Modify CPSocio-SLN's minimum semantic cover to satisfy the definition of the minimum semantic cover (Characteristic 4).
(5) Algorithm ends.

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(2) *Maintenance for deleting a semantic link DelLink*

To delete a semantic link means the deletion of the link and its determining set. The minimum spanning graph brings advantages to deleting a semantic link. Assuming semantic link e has n minimum spanning graphs, the minimum spanning graph set is $C_e = \{G_1, G_2 \ldots G_n\}$. The semantic link set of this CPSocio-SLN's minimum semantic cover is $E = \{e_1, e_2 \ldots e_m\}$. Hence, all the semantic links in G_i $(i = 1, 2, \ldots, n)$ are in E. If users delete a semantic link e_k in E, should e be deleted?

We first calculate the graph set $Ce_k = \{G_i | G_i$ includes $e_k, G_i \in C_e\}$, then update the minimum spanning set of $e: C_e = Ce - Ce_k$. If C_e is empty, e should be deleted after deleting e_k since e cannot be reasoned out by any part of the CPSocio-SLN.

Hence, we should find a way to obtain the minimum spanning graph of every semantic link.

Every CPSocio-SLN has a conformation sequence. That means every CPSocio-SLN can be obtained by adding nodes and semantic links orderly. Hence, what we need to do is updating the minimum spanning graph set of every link when we add a new link to CPSocio-SLN graph. Based on Characteristic 4, adding a new link may change the other links' minimum spanning graph sets. We should also calculate the new link's minimum spanning graph set.

If a CPSocio-SLN only has one semantic link, this link's minimum spanning graph set only has one minimum spanning graph which is this semantic link itself. For a complex CPSocio-SLN, when the minimum spanning graph set of every semantic link has been obtained, if we add a new semantic link $e = (n_1, n_2, \alpha)$, we use the following algorithm to update all of the minimum spanning graph sets.

Algorithm *NewAddLink*

Input: The closure of original CPSocio-SLN, the minimum spanning graph set of every semantic link in original CPSocio-SLN, and new link e which has already been added to the minimum semantic cover.

Output: The closure of the new CPSocio-SLN that includes original CPSocio-SLN and e, the updated minimum spanning graph set of every semantic link.

(1) Add e to CPSocio-SLN's closure.
(2) Find new links which should be added to CPSocio-SLN because of adding link, and then add these new links to CPSocio-SLN.
(3) Calculate the new links' minimum spanning graph set, update every link's minimum spanning graph set and record these links that should not be in the minimum semantic cover (Characteristic 4).
(4) Go to step 2 until there is no change on CPSocio-SLN.
(5) Remove these links which should not be in the minimum semantic cover, and change the corresponding links' minimum spanning graph set.
(6) End.

Through analyzing the minimum spanning graph, we can obtain the algorithm of updating based on deleting a semantic link.

Algorithm *DeleteLinkUpdate*

Input: Original CPSocio-SLN's closure, original minimum spanning graph set of every link, and the link we want to delete e_k.

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Output: New CPSocio-SLN's closure (It does not include e_k and the links derived from e_k), and the new minimum spanning graph set of every link.

(1) Delete e_k from the CPSocio-SLN's closure.
(2) Update the minimum spanning graph sets of all links. If a link's minimum spanning graph set has a minimum spanning graph that includes e_k, then delete this minimum spanning graph.
(3) Check all links; if a semantic link's minimum spanning graph set is empty, delete this link from CPSocio-SLN.
(4) After checking all links, the algorithm terminates.

(*3*) *Maintenance for adding or deleting a node*
The following are maintenance operations for adding a node *AddNode*:

(1) Add the same node to both of the semantic closure and the minimum semantic cover.
(2) The approach to discover attribute-based link will be used to find out all inter-attribute semantic links between the new node and other nodes.
(3) Call **Algorithm** *NewAddLink* to redo the reasoning process to update the new closure.

If nodes in the minimum semantic cover are isolated, they are also isolated in closure, and vice versa. Hence, the maintenance operation of operation deleting a node *DeleteNode* is as follows:

(1) Delete the same node in both the semantic closure of CPSocio-SLN and the minimum semantic cover.
(2) Delete the inter-attribute semantic links connected to the node.
(3) Do the same operation as step 3 in the maintenance operation of AddNode.

(*4*) *Maintenance for adding or deleting a rule AddRules*
The maintenance operation of adding or deleting a rule is to update the CPSocio-SLN according to new rule set by using step 3 in maintenance of the AddNode operation.

4.4. Complexity of algorithms

The time complexity of *DelLink* is $O(E^2)$. After deleting a semantic link e, the algorithm must check all of the other links if they have a minimum spanning graph that includes e; hence the time complexity of deleting a semantic link is $O(E^2)$. After adding a semantic link e, the algorithm will add all implied links. Hence, the time complexity of adding a semantic link *AddLink* is $O(E_2 \times \sum_{i=1}^{k-1} n_i)$, n_i denotes the number of new links generated at step i. The time complexity of *AddNode*, *DelNode*, *AddRule*, *and DelRule* is the same as *AddLink* because they all use the Algorithm *NewAddLink*.

The space complexity of *DelNode* and *AddNode* is $O(1)$. To store a minimum spanning graph set for every link needs $O(E^2)$ space, other space cost is small; hence, the space complexity of *DelLink* and *AddLink* is $O(E^2)$. The space complexity of *AddNode*, *DelNode*, *AddRule and DelRule* is the same as *AddLink* because they all use Algorithm *NewAddLink*.

5. AN EXAMPLE ON BASIC OPERATIONS

Take Figure 7 as an example. We use basic operations to add or delete semantic links and nodes. e_1, e_2, e_3, e_4, e_5, e_{10}, and e_{11} are semantic links in the minimum semantic cover, other links are reasoned out by other links in the minimum semantic cover.

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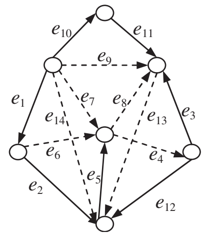

Figure 8. CPSocio-SLN after adding semantic link e_{12}.

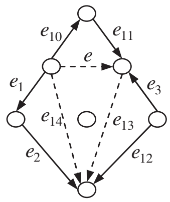

Figure 9. The CPSocio-SLN after deleting e_5.

The following is the reasoning process: $e_2 \times e_5 \to e_6$, $e_1 \times e_6 \to e_7$, $e_3 \times e_4 \to e_8$, $e_7 \times e_8 \to e_9$, and $e_{10} \times e_{11} \to e_9$.

As introduced, the minimum generating graph set of e_1, e_2, e_3, e_4, e_5, e_{10}, e_{11} is $\{\{e_1\}\}$, $\{\{e_2\}\}$, $\{\{e_3\}\}$, $\{\{e_4\}\}$, $\{\{e_5\}\}$, $\{\{e_{10}\}\}$, $\{\{e_{11}\}\}$ and e_6, e_7, e_8, e_9 is $\{\{e_2, e_5\}\}$, $\{\{e_1, e_2, e_5\}\}$, $\{\{e_3, e_4\}\}$, $\{\{e_1, e_2, e_5, e_3, e_4\}, \{e_{10}, e_{11}\}\}$. Now, we add a semantic link e_{12} as shown in Figure 8.

Semantic link e_{12} can bring the following reasoning: $e_{12} \times e_5 \to e_4^R$, $e_{12} \times e_3^R \to e_{13}$, and $e_{13} \times e_9 \to e_{14}$. Hence, e_4 should not be in the minimum semantic cover.

The minimum generating graph set of e_1, e_2, e_3, e_5, e_{10}, e_{11}, and e_{12} is $\{\{e_1\}\}$, $\{\{e_2\}\}$, $\{\{e_3\}\}$, $\{\{e_5\}\}$, $\{\{e_{10}\}\}$, $\{\{e_{11}\}\}$, $\{\{e_{12}\}\}$ and e_4, e_6, e_7, e_8, e_9, e_{13}, e_{14} is $\{\{e_5, e_{12}\}\}$, $\{\{e_2, e_5\}\}$, $\{\{e_1, e_2, e_5\}\}$, $\{\{e_3, e_5, e_{12}\}\}$, $\{\{e_1, e_2, e_5, e_3, e_{12}\}, \{e_{10}, e_{11}\}\}$, $\{\{e_{12}, e_3\}\}$, $\{\{e_1, e_2, e_5, e_3, e_{12}\}, \{e_{12}, e_3, e_{10}, e_{11}\}\}$.

If we delete e_5 based on the mentioned rules, e_4, e_5, e_6, e_7, and e_8 should also be deleted, but e_9 and e_{14} will not be deleted. Their number of minimum generating graphs will be less by one. The result is as shown in Figure 9.

The minimum generating graph set of e_1, e_2, e_3, e_{10}, e_{11}, and e_{12} is $\{\{e_1\}\}$, $\{\{e_2\}\}$, $\{\{e_3\}\}$, $\{\{e_{10}\}\}$, $\{\{e_{11}\}\}$, $\{\{e_{12}\}\}$, and that of e_9, e_{13}, e_{14} is $\{\{e_{10}, e_{11}\}\}$, $\{\{e_{12}, e_3\}\}$, $\{\{e_{12}, e_3, e_{10}, e_{11}\}\}$.

6. SUMMARY

Understanding various relational networks and their evolution is important for developing future CP-Society. CPSocio-SLN emphasizes relations, relation evolution, relational reasoning, and operation influence. We view CPSocio-SLN as an evolution process through operations, and investigate its basic operations, completeness, and dynamicity. The conformation sequence reflects its evolution process. To merge two CPSocio-SLNs, their conformation sequences should be merged first, and then calculate the minimum semantic cover and the minimum spanning graph of every semantic link based on the merged conformation sequence.

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CPSocio-SLN should know its minimum semantic cover. If there is a reasoning circulation, then a semantic link in the equivalent link set can be randomly selected and added to the minimum semantic cover. The CPSocio-SLN system can simulate the process of conformation—adding links to the minimum semantic cover orderly and calculating the minimum spanning graph. The conformation information helps to know the evolution characteristics and rules.

The minimum semantic cover and the minimum spanning graph indicate the semantics of CPSocio-SLN as the minimum spanning graph can indicate the most important semantic links in the minimum semantic cover. Since a CPSocio-SLN could be very large, the strategy for efficiently storing and managing CPSocio-SLN based on the basic operation set is proposed to support efficient query and maintenance.

This research is a part of CPSocio-SLN theory, which will play an important role in establishing and analyzing the CP-Society.

APPENDIX A

Algorithm *GetClosure*

We give every node a number as $1, 2, 3, \ldots, \ldots, n$, then set up a matrix; P_{mn} represents the location of *mth* row and *nth* column.

If there is a semantic link from the *mth* node to the *nth* node, and the semantic relation is a, we mark a on the location of P_{mn} and a^R on the location of P_{nm} (one location may have multiple semantic relations). Now we can analyze that the semantic links that can reason with P_{mn} are at the mth column or at the nth row. Take Figure 3(a) for example. We number these nodes from left to right as 1, 2, 3, and 4. The following is the algorithm *GetClosure*.

Algorithm *GetClosure*.

Input: A CPSocio-SLN graph.

Output: A new CPSocio-SLN graph (the new CPSocio-SLN is the closure of the original CPSocio-SLN).

1. Initialize queue Q, its element is (i, j, S), m and n represent P_{ij}, S is the semantic relation set in location P_{ij}.
2. Check matrix by rows; for every semantic link with location P_{mn} on every row, check every semantic link on the mth column or nth row to find if they can reason out new semantic links.
   (1) If new semantic links can be reasoned out, we add these new semantic links to the matrix and Q.
   (2) If not, continue checking, until all semantic links are checked.
3. Get the first semantic link P_{rt} from Q, and then delete the semantic link from Q. For this semantic link P_{rt}, check every semantic link on rth column or tth row to find if they can reason out new semantic links.
   (1) If semantic links can be reasoned out and these links do not exist in the CPSocio-SLN, add these semantic links to matrix and Q.
   (2) If not, go to step4.
4. If Q is not empty, go to step3. If Q is empty, the algorithm ends.

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Proof
The correctness can be shown by the following two points:

1. Finding a new semantic link means that the semantic links that can reason out a new semantic link are adjacent and there is a rule to reason out this new semantic link. Hence, no wrong semantic links are derived.
2. The algorithm implies that every pair of semantic links has been checked. If the algorithm ends and Q is empty, then satisfy: no rule can reason out new semantic links for all adjacent semantic links. Hence, if the algorithm ends, there is no semantic link that should be reasoned out, but have not been found.

Algorithm *OriginalAddLink*:
Input: Closure of original CPSocio-SLN, the semantic link e we want to add.
Output: Closure of new CPSocio-SLN that includes original CPSocio-SLN and e.

1. If e is already in the original closure, the algorithm is terminated. If not, build queue Q that only includes e.
2. Get the first element of Q, and delete the element in Q, this element is assumed to be k, calculate the possibility reasoning set *Ereasoning*(k), then check if there is a semantic link in *Ereasoning*(k) can reason with k. If such a link already exists (assume it is h, the semantic link reasoned out is p), we have:
   (1) If p is not in the original closure, add p to CPSocio-SLN graph, and then add p to Q.
   (2) If p is already in the original closure, do nothing.
3. If Q is empty, jump to step4, if not, jump to step2.
4. Check the minimum semantic cover G; if there is a semantic link x, the closure of $G-x$ is equal to the closure of G; then remove x from the minimum semantic cover.
5. The algorithm ends.

Algorithm *NewAddLink*
Input: The closure of original CPSocio-SLN, the minimum spanning graph set of every semantic link in the original CPSocio-SLN, and the new link e.
Output: The closure of New CPSocio-SLN that includes the original CPSocio-SLN and e updated the minimum spanning graph set of every semantic link.

1. If e is already in the closure of original CPSocio-SLN, the algorithm ends; if not, build queue Q that only includes e; the minimum spanning graph set of e is initialized as $\{\{e\}\}$; build semantic link set M, which records the semantic links we want to delete in step4 of algorithm *OriginalAddLink*, and these links will be found in step2 of algorithm *NewAddLink*.
2. Get the first element of Q, and delete this element in Q. We assume this element is k; calculate *Ereasoning*(k), then check if k can reason with any element in *Ereasoning*(k), if not, get next element; else, assume that the semantic link that can reason with k is h, and the semantic link reasoned out by k and h is $p(k \times h \to p)$; the minimum spanning graph set of k is $C_k = \{K_1, K_2, \ldots, K_n\}$, and h is $C_h = \{H_1, H_2, \ldots, H_m\}$.
   (1) If p does not exist in the closure of the original CPSocio-SLN, then the minimum spanning graph set of p is $C_p = \{G_i | G_i = K_r \cup H_t, K_r \in C_k, H_t \in C_h, 1 <= r <= n, 1 <= t <= m\}$. Then add p to CPSocio-SLN and Q.

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(2) If p already exist in the closure of original CPSocio-SLN, and the minimum spanning graph set of p is $C_p old$, calculate C_p in the same way as (1), and then update C_p as follows:

$$C_p = (C_p old \cup C_p) - \{\{p\}\}.$$

and, do the following steps:

(a) If there is a minimum spanning graph which includes p in C_p (this graph can be denoted as $\{\ldots, p, \ldots\}$), update this minimum spanning graph to $\{p\}$.

(b) if p is in the minimum semantic cover and p is not e and the minimum spanning graph set of p does not include $\{p\}$,

add p to M.

3. If Q is not empty, jump to step2; if Q is empty, delete these semantic links in M from the minimum cover.
4. For every semantic link x in M, if there is a semantic link y in $\{closure\text{-}M\}$, the minimum spanning graph set of y includes a minimum spanning graph which includes x, then change x to its minimum spanning graph's elements.
5. End.

If a semantic link reasoned out is in the minimum semantic cover, there are two possibilities (assume that this reasoning is based on rule $k \times h \rightarrow p$):

1. k or h does not have a minimum spanning graph including p. This means that although p is in the minimum semantic cover, but it can be reasoned out from other links; hence, this link should be deleted from the minimum semantic cover.
2. k or h has a minimum spanning graph including p. This means that p is in the minimum semantic cover and p can be reasoned out, but the links that reason out p are reasoned out by p, these links form a reasoning circulation. In this case, we should not delete p, because it may break this reasoning circulation and even the entire meanings of the CPSocio-SLN.

In step 2(2)(b), the condition '… the minimum spanning graph set of p does not include $\{p\}$' guarantees that p is not in a reasoning circulation, which means that p should be removed from the minimum semantic cover.

It is obvious that the condition '…the minimum spanning graph set of p does not include $\{p\}$' equals the first aspect 'k or h does not have a minimum spanning graph including p.' If k or h has a minimum spanning graph including p, according to expression: $C_p = (C_p old \cup C_p) - \{\{p\}\}$, then the minimum spanning graph set must have an element like $\{\ldots\ldots$.p}; after step2-(2)(a), this minimum spanning graph should be changed to $\{p\}$. It is inconsistent with the condition '……the minimum spanning graph set of p does not include $\{p\}$'. On the other hand, because p is in the minimum semantic cover, p has a minimum spanning graph $\{p\}$ at the very beginning, but this minimum spanning graph should be deleted at step 2(2); hence if at last p has a minimum spanning graph $\{p\}$, it must come from the minimum spanning graph of k or h.

Based on the definition of the minimum spanning graph, step 2(2)(a) changes $\{\ldots\ldots p\}$ to $\{p\}$.

Another important reason is that every link is equivalent in a reasoning circle. Now we take one of them as the beginning (such as e_7 in Figure 2); if the beginning link is deleted, all links in the reasoning circle should be deleted.

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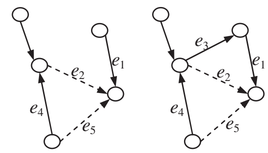

Figure A1. (a) The CPSocio-SLN before adding e_3 to the graph $e_4 \times e_2 \rightarrow e_5$ and (b) the CPSocio-SLN after adding e_3 to the graph $e_3 \times e_1 \rightarrow e_2$. The solid semantic links are in the minimum semantic cover, and the dotted semantic links are derived.

The reason we use step 4 in algorithm *NewAddLink* is as follows: The minimum spanning graph could only be constructed by semantic links in the minimum semantic cover. If a new semantic link changes the semantic link p in the minimum semantic covers, we must change these minimum spanning graphs that include p.

As shown in Figure A1, the original minimum spanning graph set of e_5 is $\{\{e_2, e_4\}\}$. e_1 and e_2 are in the minimum semantic cover, the new semantic link e_3 can reason out e_2 with e_1; hence, e_2 should be removed from the minimum semantic cover. These original minimum spanning graphs that include e_2 should change e_2 to the links that reason out e_2; hence, the new minimum spanning graph of e_5 is $\{\{e_4, e_3, e_1\}\}$.

Algorithm *DeleteLinkUpdate*

Input: Original CPSocio-SLN, the original minimum spanning graph set of every link, and the link e_k we want to delete

Output: New CPSocio-SLN that does not include e_k and links that are reasoned out by e_k, the new minimum spanning graph set of every link.

1. If e_k is not in the minimum semantic cover, algorithm ends, else delete e_k.
2. For every semantic link in CPSocio-SLN e:
   (1) Assuming that the minimum spanning graph of e is $C_e = \{G_1, G_2, \ldots, G_n\}$, calculate the minimum spanning graph set of e. First calculate $Ce_k = \{G_i | G_i \text{ includes } e_k, G_i \in C_e\}$, and then update the minimum spanning graph set of e, $C_e = C_e - Ce_k$.
   (2) If C_e is empty, delete e.
3. End.

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