

The Complex Semantic Space Model

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Abstract — The cyber-physical society is a complex space where human abilities are extended to various spaces by coordinating the cyber space, physical space, socio space and mental space. A challenge issue is to seek the uniformity in managing resources in these spaces. This keynote introduces a complex semantic space model that is suitable for managing various resources in different spaces in the cyber-physical society. The model is based on *classification* and *link*, which are basic mechanisms in forming and evolving spaces. Its distinguished characteristics and functions support the implementation of cyber-physical-socio intelligence. Applications in supporting co-navigation in multiple spaces in the cyber-physical society and in modeling the management of semantic images are introduced.

Keywords – *Cyber-physical society; semantic space; Resource Space Model; Semantic Link Network; faceted navigation.*

I. INTRODUCTION

A. Effort toward an intelligent cyber space

To create an intelligent cyber space is the common ideal of computer scientists.

Turing described computer intelligence as a machine that can learn from experience and can alter its own instructions [6].

Bush introduced the ideal of memex, which could browse and make notes in an extensive on-line text and graphical system, and contain a very large library, personal notes, photographs and sketches, and several screens and a facility for establishing a labeled link between any two points in the entire library [1].

Engelbart proposed a conceptual framework for the augmentation of man's intellect [3]. He designed the system H-LAM/T (Human using Language, Artifacts, and Methodology, in which he Trained).

Gray proposed to enhance the cyber space by extending the memex to the following two types: The personal memex can record everything a person sees and hears, and can quickly retrieve any item on request. The world memex can answer questions about the given text and summarize the text as precisely and quickly as a human expert in that field [4].

B. The cyber-physical society

The *physical space* contains physical resources, which move and transform from one form into another according to physical laws. Resources can be classified from physical structures or features. The physical space provides the

material basis for the generation and evolution of human beings and civilization.

The *socio space* includes individuals (human, agent, behaviour, event, etc), structures, and rules. Individuals are self-organized into classes according to economic, politic or cultural statuses.

The development of human society created the cyber space, which is linking the physical space and the other spaces to form a future interconnection environment [8]. The *cyber space* contains information resources and service resources including computing and communication.

The *mental space* is for knowing, reasoning and guiding behaviours. It consists of knowledge in form of concept, commonsense, rule, method and theory.

Different spaces can explain specifically on what, where, why, when, and how in intelligent applications. The physical space, socio space, mental space, and cyber space will cooperate with each other in the cyber-physical society.

The cyber-physical society is a multi-dimensional complex space that generates and evolves diverse subspaces to contain different types of individuals interacting with, reflecting or influencing each other directly or through the cyber, physical, socio and mental subspaces. Versatile individuals and socio roles coexist harmoniously yet evolve, provide appropriate on-demand information, knowledge and services for each other, transform from one form into another, interact with each other through various links, and self-organize according to socio value chains. It ensures healthy and meaningful life of individuals, and maintains a reasonable rate of expansion of individuals in light of overall capacity and the material, knowledge, and service flow cycles [14].

C. Challenge

A challenge is to create a unified model for managing various resources in different spaces. The model should reflect the basic form and motion of various spaces.

Classifying, linking and reasoning are the most basic form and motion for knowing, organizing and managing resources in the cyber space, physical space, socio space and mental space.

II. SEMANTIC LINK NETWORK MODEL

Human consciously and subconsciously wave various semantic link networks in lifetime, and act intelligently based on the semantic link networks in various spaces and through spaces. The Semantic Link Network model includes form and semantics.

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A. Form

The form of the Semantic Link Network is as follows: $SLN = \langle N, L, Rules, OP \rangle$, where

- N is a set of semantic nodes. A semantic node can be a concept, structure, or specific object such as text, image, video, and audio. A semantic node has a class c , indicated by n or $n[c]$. The class of semantic node is rendered by a set of attributes. When status of node is important in some applications, the *status of node* can be rendered by the attributes' values at certain time t , denoted as $n(t) = \langle a_1(t) = v_1, \dots, a_n(t) = v_n \rangle$.
- L is a set of semantic links. A semantic link indicates a relation between two semantic nodes. A semantic link takes the following form: $n \rightarrow a \rightarrow n'$ or $n \rightarrow a[c] \rightarrow n'$, where a is the relational indicator. Some semantic links reflect the relationships between attributes (i.e., attribute-based semantic link). Some semantic links reflect behaviors of semantic nodes (i.e., behavior-based semantic link). The behavior-based semantic links cannot be derived from the attributes of semantic nodes.
- $Rules$ is a set of rules of linking such that new semantic links can be appropriately added between semantic nodes as the effect of reasoning, influence or evolution. For $\alpha, \beta \in L$, if there is a rule $\alpha \cdot \beta \Rightarrow \gamma$, then γ can be added to L .
- OP is a set of basic operations on SLN. Users can add semantic nodes, semantic links and rules to or delete them from SLN, and can also add themselves to the SLN as semantic nodes. Two basic operations are *Add* and *Delete*, which can be specialized into eight operations: *AddLink*, *DelLink*, *AddNode*, *DelNode*, *AddRule*, *DelRule*, *AddOp* and *DelOp*. Individuals have certain privilege to add semantic nodes, semantic links and rules to SLN or delete them from SLN. For a self-organized SLN, nodes can add or delete themselves by peer-to-peer negotiation [9].

Semantic nodes are usually explicit, while semantic links are usually implicit and rely on semantic nodes' attributes and behaviors. Some semantic links are one-way while others are two-way. Some semantic links reflect the relations between attributes called attribute-based semantic link, while others reflect the behaviors between semantic nodes called behavior-based semantic link, e.g., friend relation reflects the satisfactory of interaction between semantic nodes. The behavior-based semantic links cannot be directly derived from the attribute-based semantic links, vice versa. Rules are laws of linking semantic nodes. For example, co-location is a socio rule for linking related functions in physically nearby locations. Knowing this rule, navigation systems can work efficiently and effectively.

Different from previous graph models, the semantic link network is dynamic in nature due to its reasoning ability. Semantic communities emerge and evolve with operations. Since the basic operation set is fix, SLN can be simplified as $SLN = \langle N, L, Rules \rangle$.

B. Semantics

The semantic space consists of the classification hierarchy of concepts and rules [9][12]. The super-class concepts and the subclass concepts determine the semantic range of concept. The classification hierarchy of concepts reflects the consensus of people who build the network. The concept hierarchy contained in online resources created by many users like Wikipedia can help create such a hierarchy. The advantages are that explanations on concepts are available and the classification hierarchy can keep updating with the expansion of online resources.

The semantics of a semantic link is indicated by *attributes, relations, class, and rules*. The semantics of a semantic node is indicated by *attributes, relations, class, neighbors, and instances*. Any semantic link γ indicated by the concept hierarchy C can be added to L if it can be derived from L according to *Rules*.

The semantics of SLN is indicated by *network structure, semantic space, and semantic images in mind* [14]. SLN is the abstraction of various autonomous relational networks in various spaces. It can be specialized for dynamic or functional modeling by incorporating the class mechanisms of the object-oriented method [5].

C. Characteristics

SLN has the following distinguished characteristics:

- *Open system*. New semantic nodes, semantic links, rules and even users will be added to SLN from time to time.
- *Dynamicity*. Operations on SLN may have little or much influence on the network due to different roles of nodes and links. The addition of new semantic links and rules may trigger new reasoning or influence.
- *Diversity*. Diversity of semantic nodes, semantic links, rules and users lead to diverse semantic communities and complex network evolution.
- *Self-organization*. There is no central control on the construction and evolution of SLN. Any semantic node can link to any semantic nodes with a semantic link when necessary.
- *Autonomous reasoning*. Reasoning on semantic links is different from traditional reasoning on production rules due to the diversity of semantic links and rules. Reasoning can carry out locally because it is not necessary to derive out all relations, which overload storage. A semantic node can trigger reasoning when necessary according to neighbor semantic links and relevant rules. SLN supports multiple reasoning (e.g., relational reasoning, analogical reasoning, and inductive reasoning) and complex reasoning integrating multiple reasoning mechanisms.
- *Integrating structure, classification hierarchy, and rules into semantic space*. The rules guide semantic networking, enable reasoning, and restrict the semantics of semantic links. The reasoning characteristic leads to the dependence between semantic links and between operations.

- *Sensitive operation order.* The result may be different if different order of operations is applied to an SLN [16]. An SLN may be changed when deleting a previously added semantic link. As adding a semantic link may derive new semantic links, which may derive other links. If we remove the previously added link, the SLN may not be able to return to the original SLN. The operation result relies on the definitions of addition and removal operations. If \cup and $-$ are graph operations, $SLN \neq SLN \cup L' - L'$, $SLN \neq SLN \cup Rule' - Rules'$. If $SLN \cup SLN' = \langle N \cup N', L \cup L', Rules \cup Rules' \rangle$, and $SLN - SLN' = \langle N - N', L - L', Rules - Rules' \rangle$, $SLN \neq SLN \cup SLN' - SLN'$. The minimum semantic cover of the network and the rules can indicate the semantics of an SLN with clear structure. With adding a certain number of semantic links, different semantic covers on different topics may emerge, therefore, the indicated semantics changes.
- *Complex.* A semantic node can be a semantic link network. For example, $f = m - a$ indicates the equivalence between the abstract concept f and a complex semantic node consisting of concepts m and a as well as the multiplication relation “ $-$ ”. The whole formula can also be a semantic node.
- *Humanized.* Semantic link and semantic node include rich content so that an SLN is not only for machine processing but also for human to read and think. A semantic link is indicated by the subclass and superclass of the relation as well as its *use case*.

III. THE RESOURCE SPACE MODEL

From human point of view, human need to explore large-scale resource set from multiple dimensions, e.g., faceted browsing on the Web enables users to know contents of web pages from multiple facets. On the other hand, to increase or reduce dimension is an effective way to specialize or generalize knowledge in mind and resources in the cyber space.

The Resource Space Model RSM is to manage versatile resources with a multi-dimensional classification space. It supports generalization and specialization on multi-dimensional classifications.

A set of resources can be classified by multiple classification methods. If a classification method is regarded as a dimension, a multi-dimensional classification space can be formed by coordinating the classification methods.

A *resource space* is an n -dimensional classification space represented as $RS(X_1, X_2, \dots, X_n)$, where X_i are *dimensions* (i.e., axes) defined by a set of *coordinates*. A coordinate can be a coordinate tree (i.e., a classification tree), where every node represents a basic concept or a pattern representing a category of resources. A child node is the subclass of its parent node. One point in the space represents the resources of one category under multiple classifications [7][10][11].

The hierarchical structure of dimension supports generalization and specialization, and it distinguishes the resource space from ordinary distance space. Herein, $R(C)$

and $R(p)$ denote the resource sets that coordinate C and point p represent respectively.

Axis $X = (C_1, C_2, \dots, C_m)$ forms a *fine classification* on coordinate C_i' at another axis X' (denoted as C_i'/X) if and only if $R(C_k) \cap R(C_p) \cap R(C_i') = \emptyset$ ($k \neq p$, and $k, p \in [1, m]$), and $(R(C_1) \cup R(C_2) \cup \dots \cup R(C_m)) \cap R(C_i') = R(C_i')$. As the result of fine classification, $R(C_i')$ is classified into m classes: $R(C_i'/X) = \{R(C_1) \cap R(C_i'), R(C_2) \cap R(C_i'), \dots, R(C_m) \cap R(C_i')\}$.

For two different axes X and X' , X forms a fine classification on X' (denoted as X'/X) if and only if X forms a fine classification on each coordinate of X' . X and X' are called *orthogonal with each other in classification* (denoted as $X \perp X'$) if X'/X and X/X' . Accordingly, we have:

$X \perp X'$ if and only if $R(X') \cap R(X) = R(X)$ and $R(X) \cap R(X') = R(X')$, where $R(X) = R(C_1) \cup R(C_2) \cup \dots \cup R(C_m)$.

This indicates the following lemma:

Lemma . $X \perp X'$ if and only if $R(X') = R(X)$.

That is, *two axes are orthogonal in classification if and only if their expression ability is the same.*

Any point p is determined by its projections on all axes, $p[X_i]$ or $p.X_i$ denotes the *projection* of p on X_i . A point can determine a resource set, where each element is called a *resource entry*. Point and resource entry are two basic operation units of RSM. The resources represented by point p is $R(p) = R(p[X_1]) \cap R(p[X_2]) \cap \dots \cap R(p[X_n])$.

To ensure the correctness of operating resources, RSM defines a set of normal forms. The following are main normal forms:

- *The first normal form resource space (1NF) is a resource space where there are no duplicated axes and there are no duplicated coordinates at any axis, i.e., there is no duplicated subclasses in each class hierarchy.*
- *The second normal form resource space (2NF) is a 1NF resource space where coordinates at any axis are independent of each other, i.e., a coordinate is neither a part of another nor can represent another coordinate at the same axis.*
- *The third normal form resource space (3NF) is a 2NF resource space where different axes are orthogonal with each other.*

The 1NF is to avoid explicit redundancy. The 2NF enables a resource space to accurately locate a class of resources. The 3NF enables any point to uniquely locate a class of resources. Resources in a 3NF resource space can be accessed from any axis. The 4NF can be further defined by ruling out the empty points in resource space.

When the ontology of a domain is available, the normal forms of a given resource space can be automatically verified according to the relations between concepts in the ontology.

IV. INTEGRATION OF RSM AND SLN

As semantic nodes in SLN can be anything: a class or an instance, RSM and SLN can be integrated by semantically

linking resources, coordinates, points, and even resource spaces.

Figure 1 depicts the way to construct the complex semantic space by integrating semantic link into resource space. Users can select either the link style or the classification style as the main operation interface based on the integrated model. The dotted arrows represent the inter-coordinate semantic links and the inter-point semantic links.

The integrated model can be represented as follows:

$\langle RSS, L, Rules, Operations, Ontology \rangle$, where

- *RSS* is a set of resource spaces. In every resource space, each coordinate has a *weight* — a function of the number of resources it specifies and the times of being accessed. Therefore a point has a *weight* determined by the weights of its projections on every axis.
- *L* is a set of semantic links between resource spaces, between points, between axes, between coordinates, or between resources.
- *Rules* consists of three parts: *reasoning rule set* for deriving semantic links; *influence rule set* for reflecting the influence of semantic link operations on the resource spaces and the influence of resource space operations on the semantic link network; and, *operation rule set* for regulating operations.
- *Operations* includes the operations on the resource space and the operations on the semantic links.
- *Ontology* is a class hierarchy that is consistent with the coordinate hierarchies in the resource spaces.

The 1.5 NF enables the linked coordinates to be accessed at the same time. In addition to the faceted browsing, the complex semantic space model can provide SQL-like query language for functioning services [15]. The following are three examples of this type of query:

```
SELECT POINT  $p$  FROM  $RS(X, Y, Z)$ 
WHERE  $p[X]=a$  &  $p[Y]=b$  &  $p[Z]=C$ 
```

```
SELECT POINT  $p'$  FROM  $RS$ 
WHERE  $p'$  links  $p$  [WITH RELATION  $r$ ].
```

```
SELECT POINT * FROM  $RS$ 
WHERE * links  $p$  [WITH RELATION  $r$ ].
[AFTER/BEFORE REASONING].
```

Users can query a set of points according to the emerging active points in the mental space by giving one coordinate or several coordinates at every axis.

The integration of the two models can reflect not only the classification on various resources and generalization and specialization on classifications but also the linkage, reasoning and influence between resources and between spaces.

The semantic links between coordinates may break the 2NF of a resource space, so the following normal form is suitable for the integrated model:

A 1.5 NF resource space is a 1NF resource space, and the semantic links between all interdependent coordinates at the same

axis have been established.

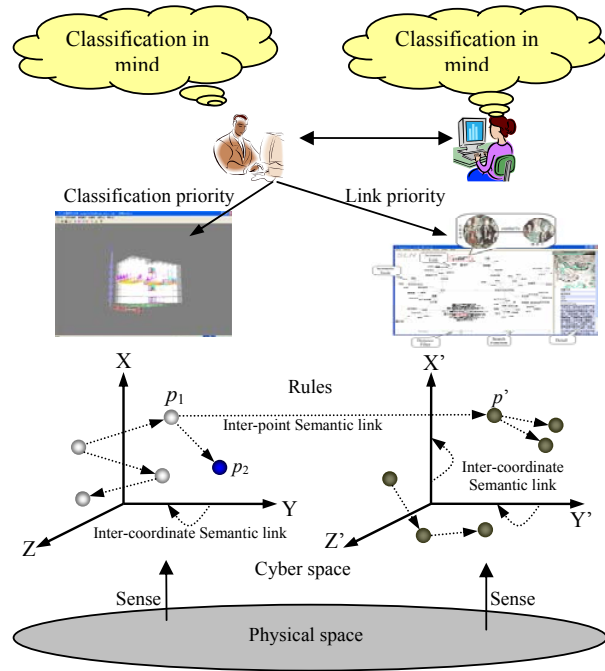


Figure 1. An example of the integrated semantic space.

V. THE COMPLEX SEMANTIC SPACE

The complex semantic space model can also be the mental model for recognition, understanding and interaction [13]. Various semantic link networks' complex reasoning mechanisms evolve the network and the indicated semantics. The effect of semantic networking and the abstraction ability of resource space cooperate with and enhance each other to evolve the structure of the cyber-physical society.

The complex space can be represented as follows:

$\langle CyberSpace, PhysicalSpace, SocioSpace, MentalSpace, Link, Flow, \varphi \rangle$, where:

- (1) Every space uses the complex semantic space to manage resources.
- (2) *Link* is a set of semantic links that connects resources or points in spaces.
- (3) *Flow* includes material flow, energy flow, and information flow. A flow may be transformed from one form into another when it passes through spaces.
- (4) φ is the reflection from one space or subspace into another space or subspace such that a link (a resource or a point) in one space can be reflected as a link (a resource or a point) in another space. A link, a resource, or a point can be reflected in more than one space.
- (5) The change of the status of resources in one space can influence the change of the status of corresponding resources in the other space through the reflection.

Resources (individuals) with different energy may have different extents of influence [13].

The complex semantic space has the following advantages:

- (1) *Based on classification, semantic link and reasoning.* It organizes resources of the same class in the same point or relevant points so that relevant resources can be retrieved at the same time. The generalization and specialization on classifications enable users or applications to effectively organize and manage heterogeneous resources according to contents. *It can reflect not only the classification on resources and generalization and specialization on classifications but also the linkage, reasoning and influence between resources and between spaces.* The traditional relational data model is based on identity, attribute and values as well as the dependence between attributes [2]. It does not support generalization and specialization on attributes. In addition, the reasoning ability of semantic link networks enables the integrated model to support relational query and explanation based on reasoning.
- (2) *Normalization of multi-dimensional classifications.* The normalization is based on the relations between classification methods. It naturally supports multi-dimensional view and search (navigation or browsing) on resources [15]. The relational data model can manage multiple flat tables and support views on them, but it is difficult in maintaining the consistency between many tables, e.g., thousands of tables in some applications. It is also hard for the relational data model to support generalization and specialization as well as reasoning.
- (3) *Content-based.* For open domain applications, resources become more and more important. The contents of resources cannot be reflected only by attributes, for example, the contents of texts and images cannot be reflected by their attributes. If patterns in the resources to be managed are available, some advanced functions of the resource space such as automatic construction, adaptation, and uploading resources are feasible [15].

VI. CO-NAVIGATION IN CYBER-PHYSICAL SOCIETY

Previous intelligent systems separate users from system, and only enable users to operate in one space — the cyber space. In the cyber-physical society, different spaces can cooperate with each other through semantic links during operation. Multiple spaces will respond to user's operation in one space through various channels, i.e., co-navigation.

The complex semantic space model supports faceted co-navigation in the cyber space, physical space, socio space, and mental space. An example is described in Figure 2.

User's mental space reflects the hotel services as the following 3-dimensional resource space according to experience: $RS(quality, location, facility)$. The dimension *quality* = (1-star, 2-star, 3-star, 4-star, 5-star). The dimension *location* consists of multiple levels: the first-level coordinates are *country*, the second-level coordinates are *province* or *city*, and the third-level coordinates could be *district*. The number of levels depends on experience. The dimension *facility*

= (entertainment, room, food, meeting). The coordinate *entertainment* = (swimming, fitness, spa, sauna). The coordinate *room* = (standard, moderate, superior, deluxe, suite). The coordinate *food* = (Chinese, Indian, Western). If user concerns price, a 4-dimensional resource space: $RS^4(quality, location, facility, price)$ will emerge in mind.

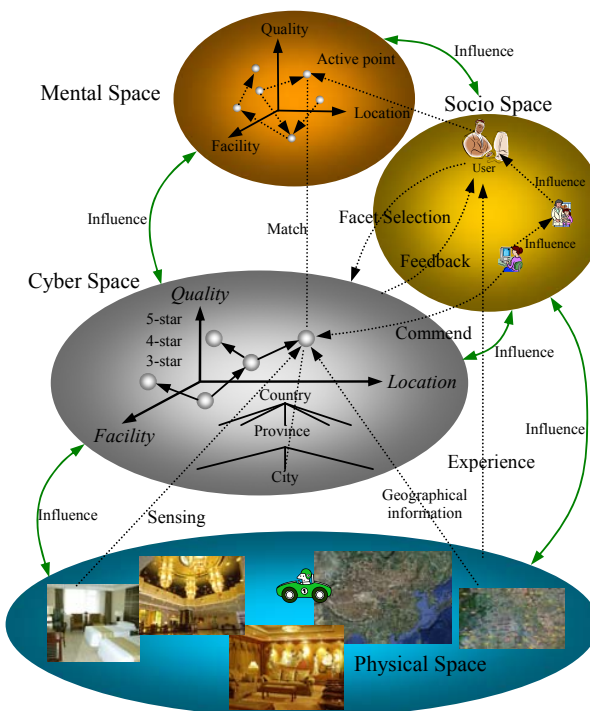


Figure 2. Co-navigation in the cyber-physical society.

The user creates the resource space in the cyber space according to the resource space in the mental space. Information about the physical space such as the features of hotels and the regions is collected and organized in the cyber space through various sensors. Services of many hotels can be viewed and felt in the space. The cyber space enables users to query from the following dimensions: *quality, location and facility* according to the active points emerged in the mental space. User's query incites the emerged semantic images about hotels with relevant quality, facility, and location through semantic links.

In the socio space, users can influence each other through socio interaction networks. Various resource spaces will emerge in minds and evolve with socio interactions.

This is different from previous intelligent systems that need rigid design, and that designers and users are separated to play different roles [14].

Items in a point contain real-time situations sensed through various sensors deployed in the cyber-physical society, e.g., available room, real-time traffic, and comments from previous guests.

Movement in the spaces forms and evolves various patterns corresponding to each other, e.g., the pattern of car movement in the physical space corresponds to the pattern of

the events of traffic jam, air pollution, and health status in the socio space and to the pattern of mobile communication networks in the cyber space. These patterns can be mapped into the resource space of corresponding spaces as semantic images.

The multi-dimensional classification mechanism is suitable for organizing cyber-physical-socio services and enabling users to retrieve services from different dimensions and different abstraction levels. The semantic link networks enable resources such as hotel services to be linked to relevant services such as shopping and sightseeing to provide comprehensive services, and will enable users to virtually try and feel the services.

VII. MANAGING SEMANTIC IMAGES

Senses from different channels are independent of each other. For example, if vision, tasting and hearing about apple are separated, people cannot recognize an apple.

A fundamental intelligence is the ability of linking senses from different channels and forming closed loops through behaving, sensing, and emerging semantic images in mind. Behaving through one channel like writing accompanies sensing through another channel like views. Practice like dictation helps establish the links between the behaviors and senses through different channels. This is why blind people cannot write in normal natural language.

The semantics of sense will be enhanced when linking the new semantic image to the existing semantic images. Different people may generate different semantic images when sensing the same situation.

The cyber-physical society will be able to reflect the semantic images in mind as a cyber image while people interact with each other and with other individuals in the society. Managing the cyber semantic images can support various individuals to behave intelligently.

In addition to computing and communication, human ability of controlling behaviors and sensing situations can be extended in the cyber-physical society. Semantic images can be enriched by forming various closed flows through multiple channels.

One sense may emerge multiple semantic images. Multiple senses may correspond to one semantic image. *A semantic image can be modeled by a semantic link network of points in the resource space.*

Figure 3 depicts the emerging semantic images while co-experiencing in multiple spaces. Semantic images evolve with the closed flows through sensing, emerging semantic images, linking new semantic images to existing semantic images, and behaving in multiple spaces. For example, when human looks at an apple falling from the tree, the semantic images emerge in the mental space including the feeling of movement, the scene of tree and apple, the sound of hitting land, the symbol of apple, the structure of the scene, geometric line of falling, and the process of falling.

The closed loops are also in various flows through various social networks in the cyber-physical society. How to control the formation and evolution of the closed loop is an important issue.

Macroscopic closed loops concern the material flows in the physical space, information flow in the cyber space, goods

flows and money flows in the socio space, and knowledge flows in the mental space. Human co-experience in the cyber space, physical space and socio space, transform information into knowledge, and create techniques for transforming materials into goods. Goods provide services for human and incur money flow in the socio space. Closed loop is formed by decomposing goods into materials after end of use.

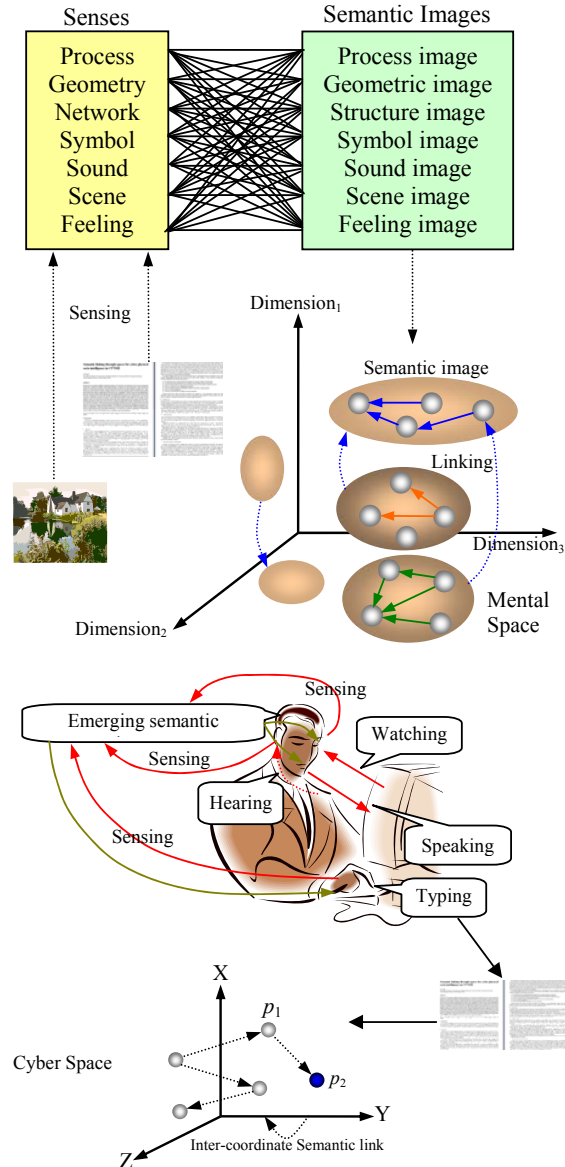


Figure 3. Emerging semantic images with the closed loops of flows through multiple channels of sensing, emerging, linking and behaving.

Macroscopic closed loops concern the inter-space influence. Significant change of the patterns in one space will influence the patterns in the other space. Changes in the physical space will influence the cyber space and the socio

space. Changes in the socio space like population increase will influence the physical space and the cyber space. Changes in the socio space and the cyber space will influence interaction between human, which will influence the mental space. The change of the mental space will influence the cyber space and the socio space.

VIII. SPACE AND DIMENSION

The generation of any space accompanies the creation of its dimensions. The physical space is the first space generated with time. The evolution of spaces accompanies the expansion or shrink of dimensions. A dimension can be viewed as a space from its coordinates. A space can be viewed as a dimension from its super-space.

Fig.1 depicts the generation of new spaces through time. The socio space, mental space, psychological space, psychological space, and artefact space are generated largely at the same time. The dimensions of the artefact space expand to include fire, iron, steam engine, electricity, PC, and Internet with the advance of time. The cyber space is separated from the artefact space with the development of the Internet.

The cyber-physical space is a complex space that fuses the cyber space, physical space, psychological space, physiological space, socio space, and mental space. It will evolve with the evolution of these spaces.

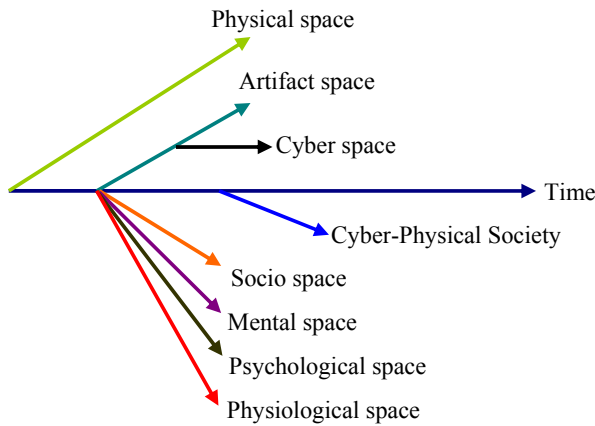


Fig.4 Generation and evolution of various spaces through time.

IX. SUMMARY

Classification and link are the most basic mechanisms for human to know, organize and manage resources in the cyber space, physical space, socio space and mental space. It is a fundamental way to create a semantic space based on classification and link for organizing resources in various spaces. The complex semantic space integrating the Semantic Link Network and the Resource Space Model based on multi-dimensional classifications is a promising model for managing various resources in the cyber-physical society.

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