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# Semantic linking through spaces for cyber-physical-socio intelligence: A methodology ☆

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ABSTRACT

Humans consciously and subconsciously establish various links, emerge semantic images and reason in mind, learn linking effect and rules, select linked individuals to interact, and form closed loops through links while co-experiencing in multiple spaces in lifetime. Machines are limited in these abilities although various graph-based models have been used to link resources in the cyber space. The following are fundamental limitations of machine intelligence: (1) machines know few links and rules in the physical space, physiological space, psychological space, socio space and mental space, so it is not realistic to expect machines to discover laws and solve problems in these spaces; and, (2) machines can only process pre-designed algorithms and data structures in the cyber space. They are limited in ability to go beyond the cyber space, to learn linking rules, to know the effect of linking, and to explain computing results according to physical, physiological, psychological and socio laws. Linking various spaces will create a complex space — the Cyber-Physical-Physiological-Psychological-Socio-Mental Environment CP$^3$SME. Diverse spaces will emerge, evolve, compete and cooperate with each other to extend machine intelligence and human intelligence. From multi-disciplinary perspective, this paper reviews previous ideas on various links, introduces the concept of cyber-physical society, proposes the ideal of the CP$^3$SME including its definition, characteristics, and multi-disciplinary revolution, and explores the methodology of linking through spaces for cyber-physical-socio intelligence. The methodology includes new models, principles, mechanisms, scientific issues, and philosophical explanation. The CP$^3$SME aims at an ideal environment for humans to live and work. Exploration will go beyond previous ideals on intelligence and computing.



## 1. Introduction

The invention of telegraphy and telephone realizes real-time interaction cross regions for the first time in human history.

In 1935, Turing conceived the modern computer (the universal Turing machine) for the first time. He described computer intelligence as a machine that can learn from experience and can alter its own instructions in 1947 and then proposed Turing test [68,69]. Since then, scientists have been pursuing artificial intelligence.

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In 1945, Vannevar 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 [8]. Since then, scientists have been pursuing an ideal cyber space.

### *1.1. The hyperlink*

Hypertext pioneer Engelbart proposed a conceptual framework for augmenting man's intellect in 1963 [21]. He pointed out that a number of reference links could be established between statements within files and between files. He regarded information system as automated external symbol manipulation, and designed the system H-LAM/T (Human using Language, Artifacts, and Methodology, in which he Trained). In 1968, he created NLS (oN Line System) as the early hypertext system with three features: a database of nonlinear text, view filters for selecting information from the database, and views that structure the display of information for the terminal.

Nelson suggested to place the entire world's literary corpus online [54], and proposed the characteristics of hypertext: linked and windowing texts can be stored and retrieved, documents can have windows to other documents, the evolving corpus is continually expandable without fundamental change, and, new links and windows can continually add new access pathways to old materials. Trigg described the Textnet system as supporting nonlinear text-text where documents are organized as primitive pieces of text connected with typed links to form a network similar to the semantic net. The work focuses on specific link types that support literary criticism [67].

The hypertext can be regarded as the prototype of the World Wide Web. The Web implements the hyperlink network on the Internet so that people all over the world can browse and search web pages in different machines distributed around the world.

The typed link in the hypertext system is a link between documents or parts of document that includes information about the character of the link. The CREF (Cross-Referenced Editing Facility) system supported four kinds of link: the reference link for cross-referring, the summarization link for summarizing, the supersede link for versioning, and the precede link for ordering. The Guide system used three kinds of links: the replacement link for replacing the texts in the current window, the note link for displaying text in a pop-up window, and the reference link for bringing up a new window with the destination text [7]. A 5-tuple typed link (link type, source node, destination node, a set of structured link attributes, and a free text annotation to the link) is introduced [25]. The motivation is to integrate the hypertext browsing with information retrieval. They suggest restrict authors and users to a few link types to facilitate mutual understanding.

The display of hypertext has explicit text and implicit link structure. Reading hypertext has no big difference from reading text in paper although different front sizes and colors of words can be easily set to attract readers' attention. Hyperlink has the following characteristics:

(1) Its construction relies on programmers. Any page can link to any other page.
(2) The labels given by the programmers are not enough to express the relations between texts.
(3) It denotes a kind of reference relation and enables reference texts to be immediately available for readers.
(4) There is no restriction to inserting a hyperlink into hypertext.
(5) It does not support reasoning. No hyperlinks can be derived from existing hyperlinks.
(6) It does not concern linking rules.
(7) It does not concern the effect of adding or removing hyperlink.

Machine-enabled links within and between documents were regarded as a new opportunity to improve the ability of information systems at the early stage of hypertext research. Although the typed hyperlink was called semantic link sometimes [25], *the semantics of semantic link and the laws of linking are ignored*.

### *1.2. The semantic net*

Semantic Net SN is a directed graph, where nodes are concepts, and edges are the relations between concepts. It was firstly used in natural language processing, and then developed by Collins and Quillian [13]. The concept dependency was used for natural language understanding [63]. Some expert systems adopted SN as a kind of knowledge representation method.

While SN was developing in AI related areas, hyperlink was developing in the hypertext area and Web area. Concepts in SN are connected by the labeled links, while hyperlinks are more arbitrary. Some researchers try to extend SN to construct hypertext by typed nodes, semi-structured nodes (frames), and inheritance hierarchies of nodes and link types. SN aims at symbol representation, reasoning and interpretation, while hypertext is for human to browse with ease. The common point is that the construction of both relies on human (programmer and knowledge engineer respectively). More comparisons were given in [14].

### 1.3. The linked structures

Various data structures like the linked list and tree can be regarded as a kind of link on data or data types for machine processing rather than for human to read [85]. In database area, Bachman's network database model is a linked structure [1]. Two important links were used in the relational database model: the functional dependence relation between attributes and reference relations between tables [12].

Relations like inheritance were defined in the object-oriented method for modeling the world [6,61]. The linked data is to connect Web data based on URIs, HTTP, RDF (Resource Description Framework) and metadata. Some linked data can be extracted from the collaborative online repository like Wikipedia on the Web.

Much effort has been made on the Semantic Web since Berners-Lee initiated the vision [2]. The key idea is to make machine understandable semantics. Logics, proof and trust are at the high level in the Semantic Web stack. Efforts include the development of various Web languages like RDF and OWL, RIF, ontology, and query languages like SPARQL. Semantic Web research has formed a research community, although there are some different opinions [45], for example, the logic-based semantic web technologies cover only a fraction of relevant phenomena related to semantics, and RDF is similar to SN and the classic conceptual modeling approaches such as entity-relation model and class diagrams in the object-oriented modeling.

Hyperlink, SN, and RDF are graph-based model in general. Hyperlink is mainly for human to browse, while SN and RDF are for supporting application systems.

### 1.4. Link mining, analysis and prediction

Generally, data mining is to find the implicit link in large closed data set by using statistical method [31]. The similar relation can be detected by analyzing the contents of nodes based on such approaches as the Latent Semantic Analysis (LSA) and the Vector Space Model (VSM) [46,62]. Similarity between documents has been used to raise the efficiency of query routing in the peer-to-peer (P2P) document network [76]. An approach to automatically discovering relations between Web pages was suggested in [75,86].

Mining the structure in information network is a way to understand and make use of the network [10]. Link structure was analyzed and used to improve web information retrieval [42,57]. The local structural information was used to improve navigation in large-scale peer-to-peer document networks [76]. The approach to detecting the future link according to network topology was proposed [44]. The probabilistic method was used to predict the missing links in networks [11].

Various socio relations support intelligent behaviors although they are sometimes indirect and implicit [58]. Communities and reasoning on some relations have some stability in competition society [17]. Recognition of various physical and socio relations carries out in individuals' lifetime and accompanies socio development.

Hyperlinks and previous typed links are created for structuring the cyber space.

### 1.5. The semantic link network

Previous links are too simple to represent rich socio relations, and various link structures cannot reflect the semantics of real socio networks. Assigning semantic indicators and rules to links enables some implicit links to be derived and some semantics to emerge with network motion [87,90]. A set of semantic links such as implication, subtype, cause-effect and reference as well as a set of reasoning rules were suggested [77]. The assumption is that users have consensus on the semantic indicators and rules. A simple semantic space suggested for regulating the semantics of a Semantic Link Network (SLN) consists of a classification hierarchy of concepts and a set of linking rules [81,87].

The initial motivation of SLN includes the following aspects:

(1) To support intelligent applications by assigning semantic indicators and rules to links and enabling relational reasoning, analogical reasoning, inductive reasoning, and complex reasoning.
(2) To explore the laws of semantic linking. It pursues diversity and user experience of linking and exploring rather than the correctness, because users mainly concern satisfactory rather than correctness during experience. A system based on SLN is expected to have some preliminary intelligence such as answering queries on relations, guided browsing, and explanation based on reasoning.
(3) To provide with a light-weight semantic networking approach to peer-to-peer knowledge sharing [76,81].

SLN has been developed toward *a self-organized semantic networking model* to manage decentralized resources. The key is to establish and maintain the semantic links between peers according to their schemas, and to develop routing strategies that can make use of the links. A self-organized SLN can realize resource sharing regardless of heterogeneity among peers [76]. An object-oriented SLN language was suggested to implement the SLN [66]. A virtual ring method for building small-world structured P2P overlays was proposed [84].

SLN can have schemas to regulate its semantics by specifying node types, link types, and reasoning rules [88]. Resources and semantic link instances are regulated by their types. Reasoning on instances is based on reasoning rules defined in the schema. A global SLN schema reflects consensus on indicating the basic semantics of the domain. Users can define

SLN instances by instantiating the global schema, or defining a sub-schema first and then instantiating the sub-schema. Usually, a schema is determined by designers. An important issue is *how to automatically generate a schema from a set of SLN instances*. This concerns clustering semantic nodes according to their attributes, and determining the semantic links between clusters. An approach to automatically determining semantic links is to integrate statistical approaches and various reasoning mechanisms. Different from the schemas of databases, *the self-organized SLN needs an adaptable schema that meets the need of changes* because the clusters and links may need adapting when new instances are continuously generated.

### *1.6. Linking brain to words and behaviors*

Much research has shown the feasibility of establishing links between language units (e.g., a limited set of words) and brain signals [5,22,40]. Some links between brain function and language have been found, e.g., Wernicke's area is more related to high-level understanding of language, and the facial motor cortex is related to the control of facial muscles that help produce sounds. Some rules have been found, e.g., signals recorded from the facial motor cortex can more precisely distinguish one word from the other. Relevant research has potential applications like locked-in syndrome. Effort has been made to detect whether people are telling the truth by analyzing magnetic-resonance images (MRI) [32]. But the current devices for obtaining brain signals limit the applications. If some soft, light and mobile detection devices can be invented in the future, many new applications can be imagined, for example, people can get some services while thinking. Experiments have demonstrated that humans can regulate the activity of their neurons in the medial temporal lobe (MTL) to alter the outcome of the contest between external images and their internal representation to a certain extent [9].

Recent study on the links between brain signals and behaviors has shown that human behaviors are relevant to two coordinates: the gaze-centered coordinates and the body-centered coordinates [4]. Human brain uses different maps to plan for different behaviors.

The problems are whether brain signals are enough to reflect the rich semantics of various socio interactions and events, whether the mappings between brain signals and larger language units like the description of a story can be established, and *whether the mappings between the traces of brain signals and the thinking processes can be established*. The applications also concern security and privacy issues.

Mind is different from brain just as software is different from hardware. Research on minds concerns multiple disciplines such as philosophy, psychology, and sociology.

### *1.7. Linking mental agents*

Mind was studied from such aspects as philosophy, social psychology and artificial intelligence [47,51]. Minsky used the mechanism called k-line to activate and link agents to model some mental effects. K-lines are generated as experience by grouping the net effects of a problem-solving episode.

The mechanisms called nemes were used to invoke representations of things. The associate mechanism *polynemes* invoke partial states of agents for representing some different aspects of a thing's meaning, e.g., recognizing an apple arouses its properties and relevant experience. The associate mechanisms *micronemes* provide a global context to the agents, or describe the subtle situations or concepts.

The mechanisms called nomes control the operations on representations. The associate mechanism called *isonomes* inform agents of performing the same type of operations, for example, they can ask some agents to save their current state to short-term memory and load in a different state, or ask them to begin training a new long-term k-line to reproduce the current state, or ask them to imagine the consequences of taking a certain action. *Pronomes* are isonomes for controlling the use of short-term memory representations, especially in a larger situation. Some pronomes connect to restricted types of short-term memories that can store only specific types of knowledge, while others are more general-purpose and influential and can reach most of the agents. *Paranomes* are sets of pronomes linked to each other so that assignments or changes made by one pronome to some representation produce corresponding operations to related representations. A paranome was used to describe how knowledge represented in different ways could be related and treated together in a uniform manner. Using paranomes, one can coordinate the use of these multiple representations.

Newell proposed the unified theory of cognition to explain how intelligent organisms flexibly react to stimuli from the environment, how they exhibit goal-directed behavior and reach goals rationally, how they represent knowledge, and how they learn [56].

To unveil the principle of mind and the interaction among minds is a grand challenge. Human beings are still far from understanding their minds.

### *1.8. Linking cyber space to physical space and social space*

Extending Bush's memex vision, Gray proposed the notion of personal memex and world memex. 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 [29]. He raised a new aim of enhancing the cyber space.

Efforts have been made to link the cyber space to the physical space and the social space.

The ideal of a harmoniously evolved interconnection environment Eco-Grid was proposed from the ecosystem point of view: “an Eco-Grid balances the competing interests of its numerous species as its social, economic and technological environments evolve. It 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 various 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” [78].

Patterns of social individuals’ movement can be collected and analyzed to reflect the status of an individual or a society [20,27]. The patterns are useful in providing appropriate services for individuals and in making decision to change the status.

Improving socio interaction will help establish a knowledge society by supporting socio activities at multiple levels (e.g., the physical level and the mental level) and in different spaces. “Knowledge Grid is a virtual socio grid, where people enjoy and provide services through versatile flow cycles” [77]. Newell explored the issue of knowledge level [55]. The network structures that favor the rapid spread of new ideas, behaviors or techniques have been studied [53].

The future interconnection environment was regarded as a large-scale human-machine environment that unites the nature, society and cyber space. Harmonious development of the physical space, society, and cyber space becomes more and more important. *Exploring the uniformity and diversity in the complex environment will be a challenge*. Various links pervade the physical space, society, and cyber space, giving the structure and function to a variety of resources and behaviors. The environment will be an autonomous, living, sustainable, and intelligent system in which the society and physical space evolve cooperatively. It will gather and organize resources into semantic forms that both machines and people can use with ease. Users in different regions will cooperatively accomplish tasks and solve problems by using various links to actively promote the flows of material, energy, technique, information, knowledge, and service in this environment. A set of parameters of the environment was proposed in [79].

The *situated* or *grounded* issues have been studied, for example, how to linking language to the physical space [34]. A mechanism for linking perceptions to language description was introduced [37]. A framework called semiotic schemas for grounding language was introduced [60]. It provides a computational path from sensing and motor action to words and speech acts by combing concepts from semiotics and schema theory to develop a holistic approach to linguistic meaning. Schemas serve as structured beliefs that are grounded in an agent’s physical environment through a causal-predictive cycle of action and perception. Words and basic speech acts are interpreted according to grounded schemas.

Relevant works include the Web/Internet of Things [30] and the cyber-physical systems. The Web/Internet of things is to link things to the Web/Internet through devices. Once things are linked to the Web through the current Web/Internet standards, things will become a part of Web/Internet. So, Web/Internet of Things can be regarded as an application of Web/Internet. Some characteristics will be lost when things are transformed into the cyber space through various sensors. Humans have created various artifacts and cyber-physical systems such as airplanes and robots. Modern airplanes can sense and record flying data such as location, height, temperature, and fuel, have communication ability, and can even autopilot according to pre-designed program. The real-time status can be linked to the ground control center. Space stations and shuttles are advanced cyber-physical systems.

### *1.9. Semantics in different spaces*

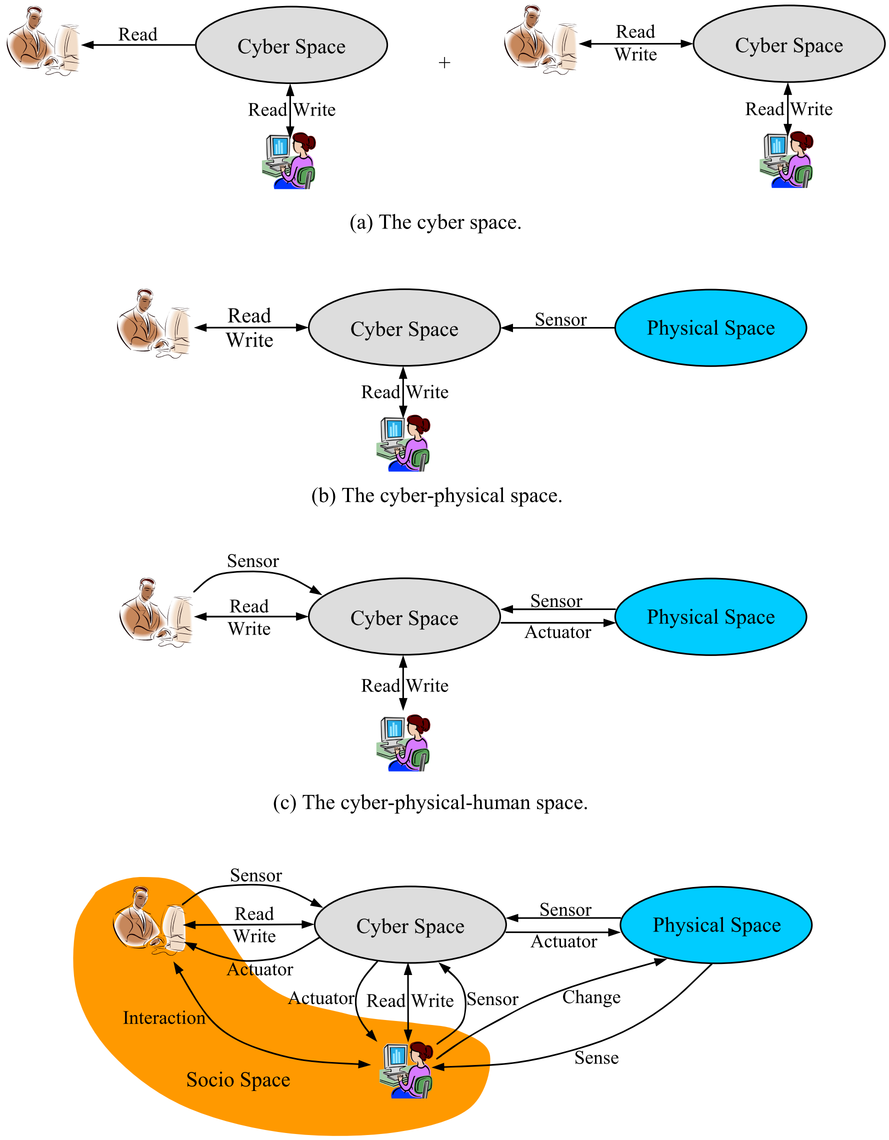
Semantics is fundamental in artificial intelligence, computer science, and future interconnection environment. Previous study on semantics mainly concerns the representation and processing of various symbol languages. A different vision on semantics research was proposed: semantics needs to be studied in four worlds: real world, mental world, machine world, and document world rather than just in single machine world [82]. Commonsense is the basis of representing and understanding semantics. McCarthy and Minsky studied the commonsense for AI [49,52]. Efforts have been made to create large commonsense base in the cyber space, for example, the Cyc project (started in 1984) and the Open Mind Common Sense project (started in 1999). Socio interaction usually uses light-weight language unit to indicate commonsense rather than the heavy logic mechanisms [89,90].

*The interactive semantics emphasizes the importance of interaction in forming, understanding and evolving semantics.* Semantics is classified into natural semantics and social semantics. Natural semantics is the structure and laws of the nature. Social semantics is the explanation, indication, or metaphor of natural and socio existence. It cannot be accurately and completely represented. The notions of *semantic worldview, interactive semantic base, semantic image*, and *semantic lens* were proposed in [89]. It is important to explore the semantics of different categories by using different approaches [59].

### *1.10. Cyber-physical-socio space*

The cyber-physical-socio space is the fusion of the physical space, the cyber space, and the socio space. It is also called cyber-physical society [92]. Evolution from the cyber space to the cyber-physical-socio space is depicted in Fig. 1.

Fig. 1 (a) depicts two types of the cyber space: one only allows users to read information in the cyber space like the Web, and the other allow users to read and write information in the cyber space like the Web 2.0. Both rely on humans to add information to the cyber space for sharing with others. Fig. 1 (b) depicts the extension from the cyber space to




(a) The cyber space.

(b) The cyber-physical space.

(c) The cyber-physical-human space.

(d) The cyber-physical-socio space.

**Fig. 1.** The emerging cyber-physical-socio space.

the physical space through various sensors. Some significant information in the physical space can be automatically sensed, stored and transmitted through the cyber space. Web of things can be regarded as a kind of cyber-physical space.

Fig. 1 (c) depicts an important extension of (b): user behaviors can be sensed and fed back to the cyber space for analyzing the patterns of behaviors, and humans can remotely control the actuators to behave in the physical space through the cyber space. This enables the cyber space to adapt services according to the feedback since behavior change may indicate some psychological change. For example, this enables e-learning systems to capture student behaviors during studying so that leaning materials and processes can be organized and adapted in real time to raise the effectiveness of study. This concerns the classification on students' behaviors (including micro-expressions) and carrying out real-time analysis and adaptation.

Fig. 1 (d) depicts a simple cyber-physical-socio space. Not only individual's behaviors but also socio interactions can be fed back into the cyber space for further processing. Users have socio characteristics and relations rather than isolated individuals. Sensors are limited in ability to collect all information in the physical space, so users still need to directly collect the significant information in the physical space and then put them into the cyber space after analysis (including experiment). Users can also change physical objects in the physical space, which can also be fed back into the cyber space to reflect the real-time situation. Users' status, interests and knowledge evolve with socio interaction and operations in the cyber space.

Based on above discussion, the following question naturally emerges: Can links semantically pass through spaces (e.g., physiological space, psychological space, and mental space) to extend machine intelligence and human intelligence? From perspective of multiple disciplines, this paper explores the methodology of semantic linking through spaces for cyber-physical-socio intelligence under the background of developing a complex space — the Cyber-Physical-Physiological-Psychological-Socio-Mental Environment CP$^3$SME.

## 2. Cyber-physical-physiological-psychological-socio-mental environment CP$^3$SME

### 2.1. Definition

The Cyber-Physical-Physiological-Psychological-Socio-Mental Environment CP$^3$SME is a multi-dimensional complex space that generates and evolves diverse spaces to contain various types of individuals interacting with, reflecting, or influencing each other through various links within space or through spaces. The cyber space, physical space, physiological space, psychological space, socio (social and economic) space, and mental space cooperate with each other to extend human intelligence, machine intelligence and socio intelligence. Versatile individuals and socio roles coexist and harmoniously co-evolve, provide appropriate on-demand material, information, knowledge and services for each other, transform from one form into another, interact with each other directly or through links, and self-organize according to socio value chains. Change of individuals, communities or links in one space could influence those in the other spaces. The environment and individuals have cyber semantic images to reflect their past and present status and the effect of interactions. Cooperation and competition as well as composition and decomposition accompany the evolution of the CP$^3$SME. The environment will ensure healthy and meaningful life of individuals, and maintain a reasonable expansion of population of various individuals and the scopes of behaviors according to the overall capacity and the material, energy, information, knowledge and service flow cycles. Minds evolve with interaction between various individuals and reflect the patterns in different spaces. Research concerns origin and essence of material, energy, information, knowledge, service, life, mind and society in the environment, harmonious and sustainable development of the environment, and the methodology for studying, developing and maintaining the environment.

### 2.2. Distinguished characteristics

CP$^3$SME has the following distinguished characteristics:

(1) *Real-time multi-space situation aware*. Life Web pages will be the first stage of immigrating from the Web to the CP$^3$SME. Photos in personal Web pages will be real-time images in the multi-dimensional classification space including such dimensions as time, location, event, audio, and video about the person. People with different privileges can view information from different dimensions and different scales. Moreover, the individual to be viewed can sense the viewer, know the viewer, and presence virtually to events. Resources in different spaces can be self-organized in multi-dimensional classification space.

(2) *Complex link*. Complex link is the composition of semantic link and interactive channels [89]. It can not only indicate the relation but also transmit material, energy, content, and control information to realize real-time interaction between individuals.

(3) *Complex health evaluation.* As individuals will live in a complex space, unhealthy individual or community in one space will influence the health of individuals or communities in the other spaces. For human individuals, influence of unhealthy or sub-healthy will come from physical, physiological, psychological, socio, mental, and cyber spaces. Health should be detected and evaluated from multiple spaces.

(4) *Multi-space coordination through times*. The effect of psychological space, physiological space, mental space and socio space distinguishes the CP$^3$SME from the Internet/Web of Things and Cyber-Physical Systems. Individuals can know their own situations through interaction. Situation includes health status, current micro-environment, socio attributes, socio energy, and the lifetime semantic images of individuals.

(5) *Pervasive undetermined interaction*. Different from the processes of controlling and computing, CP$^3$SME executes with pervasive interactions between individuals within and cross spaces. Interactions follow different types of rules in different spaces.

(6) *Multiple semantic layer reflection and lifetime preserving*. The CP$^3$SME will reflect individuals, communities, interactions and events at multiple semantic layers. Different from digital archival, the CP$^3$SME's preserving will be real-time, lifetime, and at multiple semantic layers.

(7) *Coordinating spaces.* Brain nets navigate with a kind of triangle-based grid cells [18], while humans often use distance space (e.g., using orthogonal latitude and longitude to locate surface objects on map) to locate objects in the physical space. In the cyber space, zooming is an effective means to navigate from different facets, at different abstraction levels, and in different scopes. Coincidently, the Semantic Link Network reasons through triangle links [86]. CP$^3$SME will coordinate triangle reasoning/navigation, orthogonal locating and zooming.

(8) *Harmony*. $CP^3SME$ concerns harmonious development of the cyber space, physical space, physiological space, psychological space, socio space and mental space rather than just the speed and capacity of computing and communication. Through socio interaction, humans actively create and maintain complex links between spaces, evaluate and evolve socio values, and make final decisions to change personal statuses and influence the evolution of the spaces with certain probability. The well-being of humans and the harmony of the complex space take the priority.
(9) *Reflecting minds*. $CP^3SME$ reflects minds by establishing and evolving cyber semantic images for various behaviors in multiple spaces, for example, by tracing language using, interactions, and the change of various patterns during behaving. A multi-dimensional classification space is suitable for organizing classes in different spaces [77,82].
(10) *Time dimension*. Time dimension can be compressed and stretched in the $CP^3SME$. Time compression accelerates evolution and enables interaction to pass through times. Evolution simulation can be slowed down by stretching time, which enables the details of evolution to be clearly observed. This requires $CP^3SME$ to have an elastic time dimension and the models for the evolution of communities and individuals. Adding a time dimension to the multi-dimensional classification space can form the space for showing the change of resources when compressing and stretching the time dimension [82].

### *2.3. Multi-disciplinary revolution*

Sciences and technologies specific to a single space will converge to a general theory and methodology for studying and developing the $CP^3SME$. The following are some revolution aspects of the environment:

(1) *Science. Scientists will be able to access research objects and thoughts as well as their formation processes on demand through times*. This means that they can not only communicate with peers but also access important thoughts through time. *They can not only use languages to express ideas but also link the language representations to reasons in multiple spaces, to relevant research, and to applications*. This requires a new form of publication that uses complex links. Scientific thoughts will efficiently influence society through complex links. Scientists can easily involve in scientific knowledge flows through the whole processes of research [80].
(2) *Education*. *Students can learn natural and socio laws not only from linguistic and mathematical description in textbooks but also from the linked physical, physiological, psychological and socio phenomena through times*. *Learning materials and processes can be self-organized and adapted according to students' real-time interest and psychological statuses*. Knowledge is created, enhanced, and rebuilt through interaction between coherent motions in different spaces. Questions can be raised, answered and explained through the cooperation of multiple spaces.
(3) *Engineering*. Artifacts can be linked to the ideas, to the design processes, to the manufacturers, and to the manufacturing processes. The statuses of artifacts (e.g., bridges) can be monitored in lifetime so that necessary maintenance can be carried out on time to ensure healthy status. *Function, structure, designer, owner, developer, and even ecological, physiological, psychological and socio effects will be accessible*. *All spaces will cooperatively reflect the formation processes of artifacts when they are required, designed, built, sold, used, and recycled*.
(4) *History and culture*. *Individuals, family trees, thoughts, and socio events will be sensed and preserved as cyber semantic images that can be accessed through times*. Evidences of historical and cultural research will be easily available. Both material culture and non-material culture will be preserved and efficiently shared. Recommendation or evaluation will be explained from historical and cultural point of view. Science fiction will not only imagine in the symbol space but also link imagination in the mental space to materials, culture and events in the physical space, physiological space, psychological space, and social space.
(5) *Society and life*. Society will be safer and life quality will be higher as the status of key individuals (e.g., people, socio facilities, and production sites), communities, and events will have cyber semantic images that can help make precaution. *Health of individuals can be detected and evaluated on time, and evaluation results can be linked to measures*. Evaluation result will be linked to socio influence through time. In the long run, the $CP^3SME$ will also help individuals fulfill the meaning of life.
(6) *Intercultural collaboration*. Previous machine translation approaches are in essence operations on forms: transforming one form of symbols into another form of symbols with the help of grammar analysis, statistics and corpus. They are limited in ability to support effective intercultural collaboration as little semantics and culture are concerned. The $CP^3SME$ will help *people with different cultural backgrounds collaborate effectively by transforming symbol forms, linking symbols to different spaces, and establishing peers' semantic images in their mental spaces*. As the consequence of collaboration, the collaborators' mental spaces evolve toward more commonalities. This may lead to breakthrough in natural language processing.
(7) *Green society*. The $CP^3SME$ will be efficient and low carbon as it will ensure optimal coordination between knowledge flow, information flow, material flow, energy flow, and value flow through spaces. *The closed loop from production to consumption can be established to minimize the waste of material and energy with awareness of situations in multiple spaces*. *The energy of computing will be taken into account in multiple spaces rather than just in one space*.
(8) *Human-centered environment*. The dynamic human-centered micro-environment will be known by linking sensors to mobile phones and vehicles, collecting real-time information, and classifying information according to the location,

distribution of population and pollution sources. *The CP$^3$SME will help people know pollution sources and take appropriate control measures according to dynamic real-time micro-environment and recommendations.*

(9) *Interactive virtual presence*. Children at home will be able to feel the presence of their parents who are not at home through complex links, and parents can know the situations around children, especially when special events occur. Senior peoples can feel the presence of their children and relatives who live in different places at the right time. *Patients in rural areas can not only see doctors in major cities but also get necessary treatment in time.*

(10) *Energy and traffic. Energy supplies will link to requirements, road maps, patterns of traffic situation, parking spaces, and environment status.* Traffic jam will be avoided based on certain socio priority and real-time situation. *Vehicles can be guided to appropriate destination according to intentions and minimization of energy consumption.*

(11) *Ecology*. In the long-run, *the global climate and the diversity of species in the physical space will be reflected* in CP$^3$SME through complex links. Warnings will be issued and influence will be simulated and explained when abnormal phenomena are detected. The Cyber-Physical-Socio Ecology concerns how to keep a reasonable expansion of the cyber space and the socio space so that they can harmoniously evolve with the physical space otherwise it may form negative influence on the whole environment [64].

The revolution of CP$^3$SME will also bring new security issues. As human behaviors will influence the physical space, physiological space, psychological space, and socio space through the cyber space, previous security issues isolated in one space will pass through multiple spaces. This also brings research challenge.

## 3. The evolving complex space

The physical space, since created, has been evolving with composition and decomposition as well as cooperation and competition through various physical, chemical, biological and socio interactions of multiple scales. Interactions not only generate materials and life, but also generate various networks such as the food web and the World Wide Web. Versatile spaces such as the mental space and the socio space are generated as the effect of evolution. New spaces will have special functions and operate with special rules. The following are some great events of decomposition:

(1) The generation of the *mental space* to reflect various forms in the physical space and socio space as semantic images, to evolve the semantic images, to make abstraction and analogy by classification, linking and reasoning, to generate some flows through semantic images, and to emerge and re-emerge semantic images of different scales through the semantic lens [89]. Based on individual interactive semantic base, individual mental spaces can also self-organize into communities through multiple interaction channels. A model of the mental space will be discussed in Section 6.

(2) The generation of the *physiological space* to hold the functions of living individuals. Each physiological organ has a definite function. Some organs provide services to the other, some reflect the other, and some sense the environment and link the sense to a semantic image in the mental space. Diverse physiological organs link one another to perform complex functions. If the organs are abstracted as service nodes and the relations between organs are abstracted as complex semantic links, an individual physiological space can be abstracted as a complex semantic link network evolving with physiological rules and the flows of material, energy and information through the links.

(3) The generation of the *psychological space* to hold the perception, cognition, attention, emotion, motivation, behavior, and some underlying physiological and neurological processes. Individuals construct their psychological spaces through individual mental and socio processes [41]. Communities construct their psychological spaces through social construction process based on individual psychological spaces [71]. Abstracting behaviors as active semantic nodes and abstracting the relations between behaviors and the relations between the external situation and internal condition as semantic links, the psychological space can be regarded as a complex semantic link network evolving with psychological rules.

(4) The generation of the *artifact space* as the effect of the mental space development and interactions between the mental space, psychological space, physiological space, and physical space. Human beings live in the space with more and more artifacts. Cities are including more and more artifacts such as buildings, bridges, cars, and roads. Some artifacts like paintings are passive, but some like robots can act according to the pre-designed programs. If artifacts are abstracted as semantic nodes with function descriptions, and the relations between artifacts are abstracted as semantic links, the artifact space can be regarded as a semantic link network evolving with scientific, technological and socio rules.

(5) The generation of the *socio space* to contain socio individuals (e.g., human, behavior, goods, and event), communities, relations, values, and rules. With the development of the socio space, subspaces such as art space and economic space were separated from the socio space to hold respective rules. Various languages are interaction tools for constructing the socio space. Socio space is objective reality although some socio events temporally exist. If socio individuals are abstracted as active semantic nodes and socio relations between individuals are abstracted as semantic links, the socio space can be regarded as a complex semantic link network evolving with socio rules and interactions.

(6) The generation of the *symbol space* to help indicate semantics according to rules of languages. Some symbol spaces are based on mathematical languages, while some are based on natural languages. Humans have created a huge symbol space that keeps expanding through times. Individuals can only know a small part of the space and will know relatively less due to the limitation of lifetime and unlimited expansion of documents. Humans have been creating various subspaces of the symbol space such as the Euclidean space and the resource space [82,83]. If symbols or symbol units (e.g.,

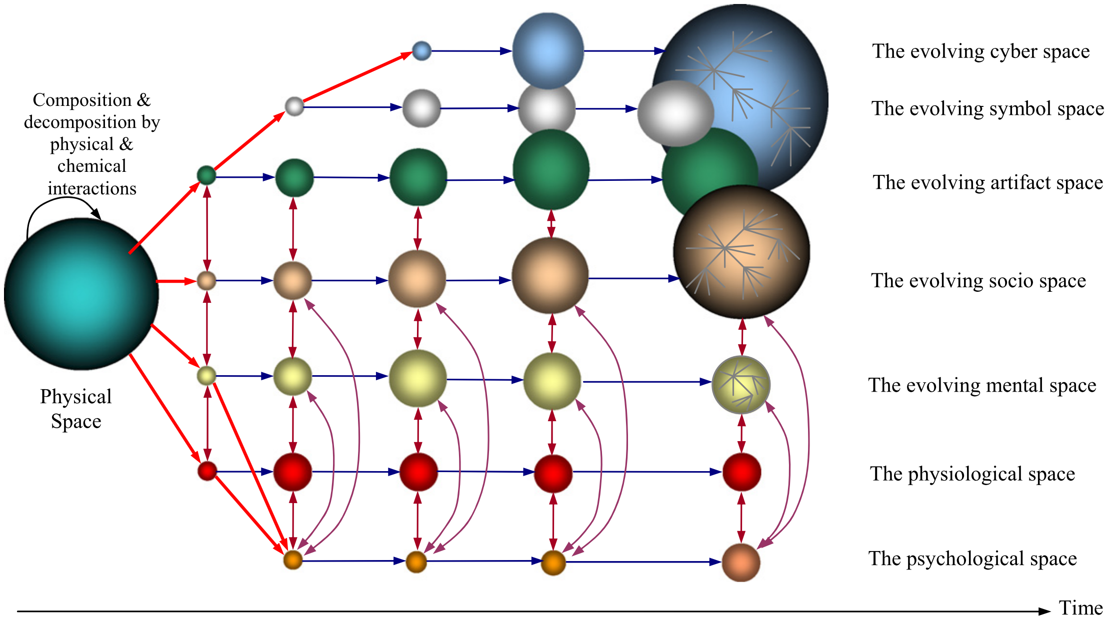



**Fig. 2.** The evolving spaces and interactions between spaces. The thick red one-way arrows represent generation. The bi-direction arrows represent interaction. The blue one-way arrows represent evolution. The interaction between the psychological space and the mental space bridges the gap between the physiological space and the mental space. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

words, phrases, and sentences) are abstracted as semantic nodes, and the relations (e.g., sequential relation and cause-effect relation) between symbols are abstracted as semantic links, the symbol space can be regarded as an evolving semantic link network with rules of languages.

(7) The generation of the *cyber space* to reflect more of the other spaces and facilitate socio interaction, computation, and information services. Scientists and engineers have been making great efforts to extend and enhance the cyber space [2,29,36,50]. If information clusters like web pages or function clusters like services are abstracted as semantic nodes and the relation between clusters are abstracted as semantic links, the cyber space can be abstracted as a complex semantic link network evolving various interactions.

Different abstraction ways can be used to model these spaces. The semantic link network is a kind of abstraction. The semantic link networks in different spaces have different forms and follow different rules. For example, they are explicit in the cyber space, implicit in the socio space, and even intangible in the mental space.

Individuals have diversity and can belong to more than one space, e.g., artifacts belong to the physical space and the socio space. Human bodies belong to the physical space, while human behaviors belong to the socio space, physiological space and psychological space, and thoughts belong to the mental space. Different from other individuals, *humans can actively link symbols to the physical space, and to the socio space through the physiological space, psychological space, and mental space*. *Humans have the ability of mapping a continuous space into discrete space and linking discrete spaces into a continuous space*.

Fig. 2 depicts some stages of generating and evolving spaces as well as interactions between spaces. These spaces will co-evolve, reflect one another, and interact with each other as a complex space. Individuals link one another according to the rules in different spaces. Some uniform laws may exist in the complex space.

More spaces will be generated with continuous evolution of the CP$^3$SME. *Competition and cooperation as well as unification and separation will accompany the evolution of the environment*. A space can contain many subspaces that link one another.

These spaces influence one another. A significant event in the physical space may generate or influence an event in the socio space. For example, the event of volcanic eruptions in the physical space will lead to cancellation of relevant flights, and lead to cancellation of the socio events like conferences held within the region.

Different spaces have different types of distances. A complex distance can be defined to support individuals to behave intelligently in the environment. For example, the complex distance between individuals involved in a socio event can be defined according to the physical distances such as road length and straight-line distance, socio distances based on friendship or harmonious interaction, and symbol distances based on profiles.

The evolving spaces and time constitute the dimensions of the CP$^3$SME at the high level with the constraints of the influence and links between spaces. *Continuous classification is the basic movement that generates and evolves these spaces*. The process of classification indicates the semantics of the form.

The psychological space links the physical space, physiological space and the mental space. To explore the interaction between the mental space, psychological space, physiological space, and socio space is fundamental to understand human

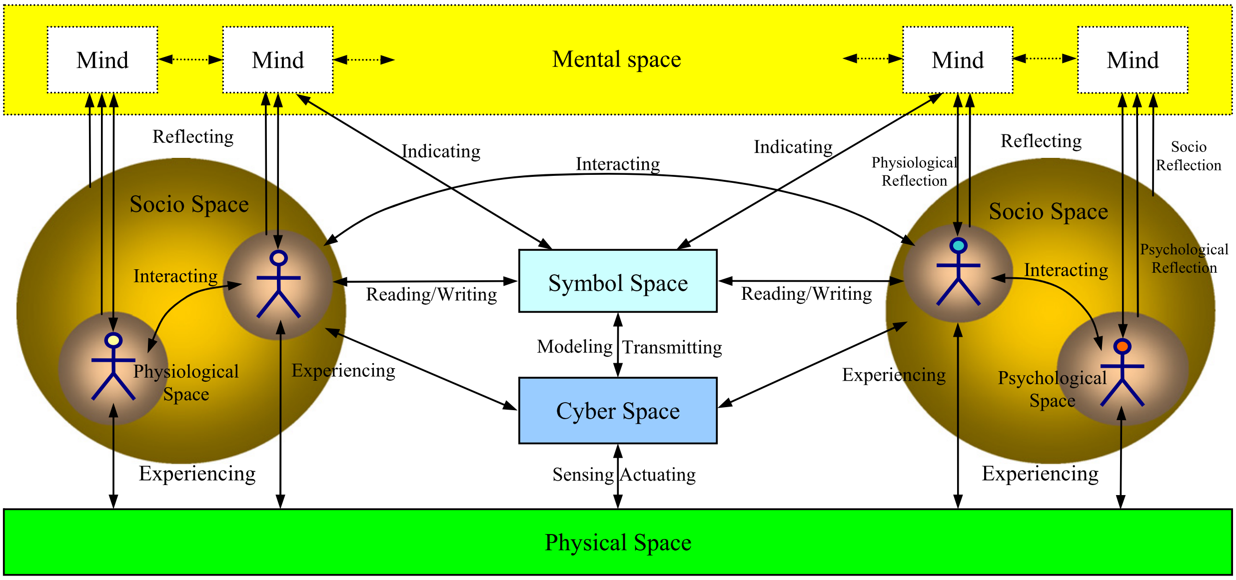



**Fig. 3.** Interaction pattern in complex space.

intelligence. Previous intelligent systems try to use symbols to instruct machines to behave intelligently. In $CP^3$SME, symbols will be linked to the cyber space, physical space, psychological space, physiological space, socio space, and mental space. Socio value and individual requirement motivate socio interaction.

## 4. Interaction pattern and behavior principle in complex space

Interactions involve in motion in the physical space, computing and communicating in the cyber space, behaviors in the psychological space, socio space, and physiological space, and various flows that change the statuses of individuals. A pattern of interactions in the complex space is depicted in Fig. 3.

The socio space interacts with the physical space, cyber space, symbol space and mental space during work and daily life. Human behaviors and reasons are based on various processes of co-experiencing in multiple spaces. Various communities will be formed in the processes. Communities will emerge and evolve with continuous behaviors and interactions. Some communities have long life while others have only short life due to the differences between individuals. Humans are the bridges between the mental space and the other spaces. Interaction among socio individuals constructs various SLNs in the socio space, reflecting various relations between individuals and events.

The cyber space interacts with the physical space, socio space and symbol space. With various sensors and actuators, it senses and actuates in the physical space and socio space (even in the physiological space), transmits information, and executes the models created by humans.

The symbols space interacts with the cyber space, socio space and mental space. Symbols and the composition of symbols according to symbol rules instruct execution of machines and indicate semantic images in the mental space accompanying reading and writing behaviors.

The mental space reflects the interactions in the socio space, psychological space, physiological space, and symbol space. The minds reflect and influence each other indirectly through human interactions. Semantic images emerge in the processes of co-experiencing, indicating, interacting and behaving denoted by the two-way arrows. The mental space has the mechanism for processing languages.

Languages are rules of composing symbols for indicating and linking semantic images in the mental space during interaction [24]. As the effect of learning and using languages for interaction, languages develop with the evolution of the mental space and the symbol space. Different communities may use the same language unit to indicate different semantics. *Humans obtain language ability and establish individual interactive semantic bases for effective interaction through the process of learning, interaction and co-experiencing*. The difference of experiences may lead to the differences in using languages.

Fig. 4 refines the scenario of interaction among the spaces, and shows that the development of $CP^3$SME concerns multiple disciplines. In addition to the reflection through the cyber space and artifact space, *direct reflection from the physical space and the socio space are important to establish the right semantic images in the mental space*.

The physiological space interacts with the physical space, the psychological space, and the mental space. It organizes material flow and transforms materials to energy to support physiological functions from low level to high level. The psychological space interacts with the mental space, the physiological space, and the socio space to regulate behaviors when humans co-experience in the physical space and socio space.

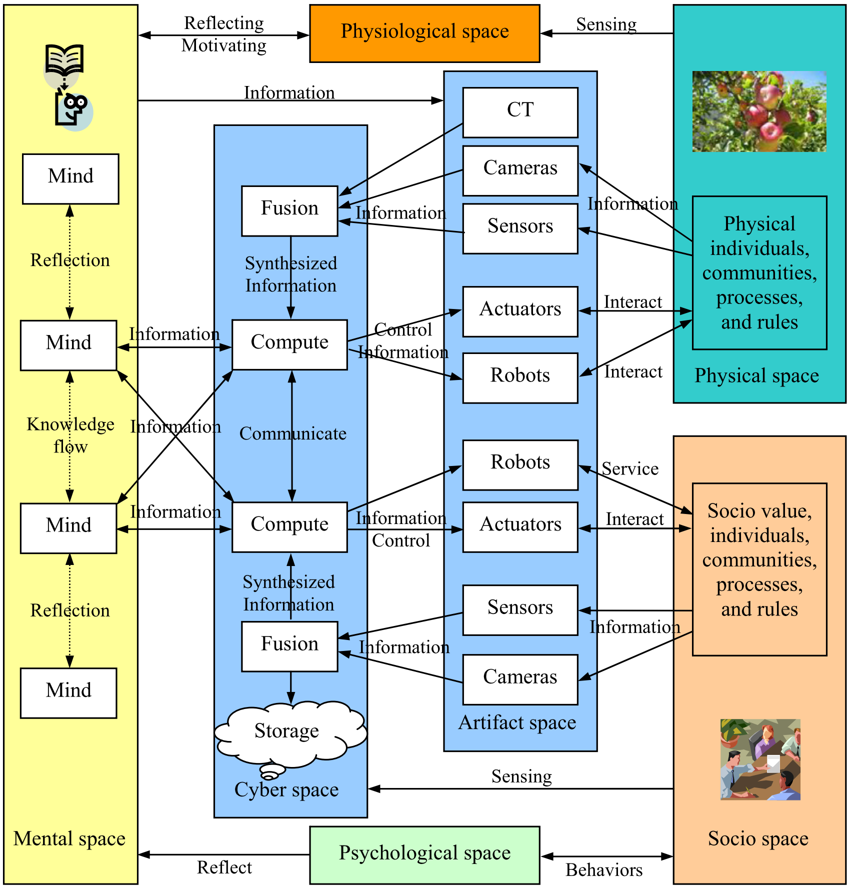



**Fig. 4.** Inter-space and intra-space interactions.

*Minds reflect various spaces, and guide behaviors for interaction, reflection and creation. Minds can be indicated, shared and inherited to a certain extent through various links and multi-channel interaction. There is a gap between the external existence in the physical space and socio space and the internal existence in the mental space* (*the semantic images*).

Exploring the mystery of minds is a grand challenge.

Behaviors in CP$^3$SME follow some principles:

(1) *The maximized performance with the minimized cost in multiple spaces.* It is the principle of optimized behaviors in multiple spaces rather than in just one space.
(2) *Short-term locality*. Firstly, individuals can only know a small part of the large-scale networks due to energy limitation and privacy. Secondly, to minimize energy, behaviors need to be localized. The other nodes do not know the behaviors unless reasoning or information flow can pass through the nodes according to rules. Thirdly, individuals of the same class should be organized in nearby locations so that they can be assessed at the same time.
(3) *Long-term globality*. Any behavior may influence the whole community or the whole network due to the long-term movement of the network (e.g., continuous evolution, complex reasoning, and information flow cycle). Influence will propagate within community first, and then it will propagate in the other communities through inter-community links in the long run. Individuals with different socio energy have different effects and scopes of influence.

## 5. Symmetry, self-similarity and multi-level semantic images

Symmetry widely exists in various spaces. It is an important concept in science, for example, symmetry refers to the invariance under any transformation in physics. Self-similarity means that the whole is similar to its part. Knowing symmetry and self-similarity can help raise the effectiveness of operations such as control and navigation. Exploring symmetry and self-similarity is an important research method and research topic in many scientific areas [16,26,33,43].

Symmetry and self-similarity could exist in different spaces and at different abstraction levels and scales in CP$^3$SME.

Human minds reflect one another and reflect the patterns in the physical space and socio space and evolve themselves patterns, make artifacts such as mirrors and lens to reflect more of themselves and the other spaces, and create the cyber

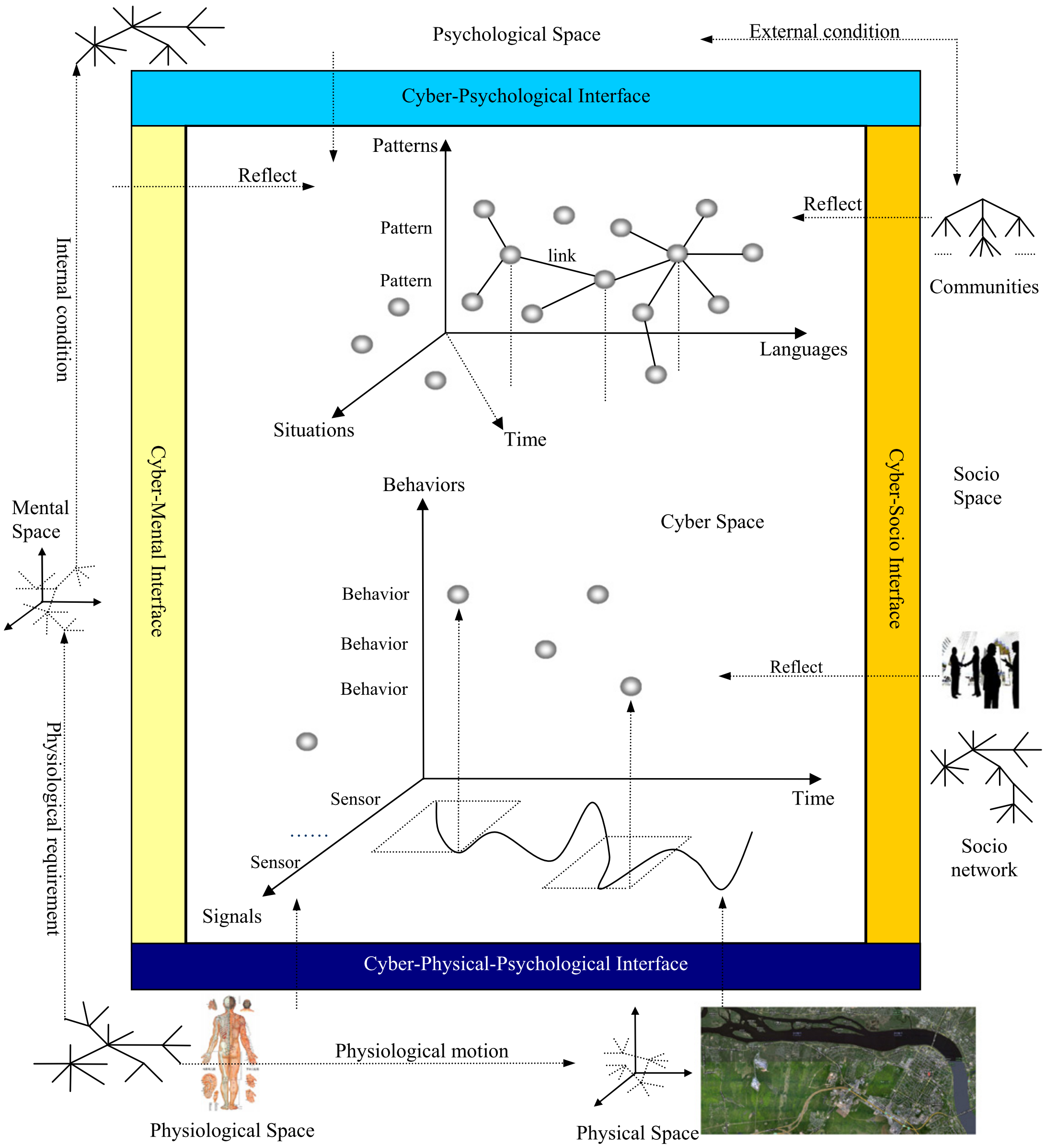



**Fig. 5.** Symmetry and self-similarity in $CP^3$SME.

space to reflect the society. As a kind of mirror, the cyber space reflects the other spaces by recording and linking various interactions in other spaces [89]. *Exploring the symmetry and self-similarity in various spaces is an approach to understand the intrinsic principles in these spaces.*

To create an adaptive model enables the cyber space to reflect the other spaces as depicted in Fig. 5. The socio space and the mental space cooperatively create, evolve and reflect the cyber space in real time. This enables the mental space to reflect more of the other spaces and enables the cyber space to support the complex space. The cyber-mental interface, cyber-socio interface, cyber-physiological interface, and cyber-physical interface are responsible for various reflections.

Fig. 6 depicts how machine intelligence and human intelligence are extended in the complex space through reflecting, experiencing, linking, classifying, searching, navigating, locating, reasoning, interacting, influencing, and zooming in multiple spaces at multiple semantic levels. Every level takes the form of semantic link network. The lower levels support the higher levels, and the higher levels guide the lower levels. Individuals (humans or agents) wave socio networks and influence each other through the network while interacting and co-experiencing in multiple spaces. Individuals can zoom in the cyber space, physical space, physiological space, psychological space, and socio space while co-experiencing. Time, place, event, and individual will be linked when seeking the answer to the question about who, what, where, why, when, and how. The

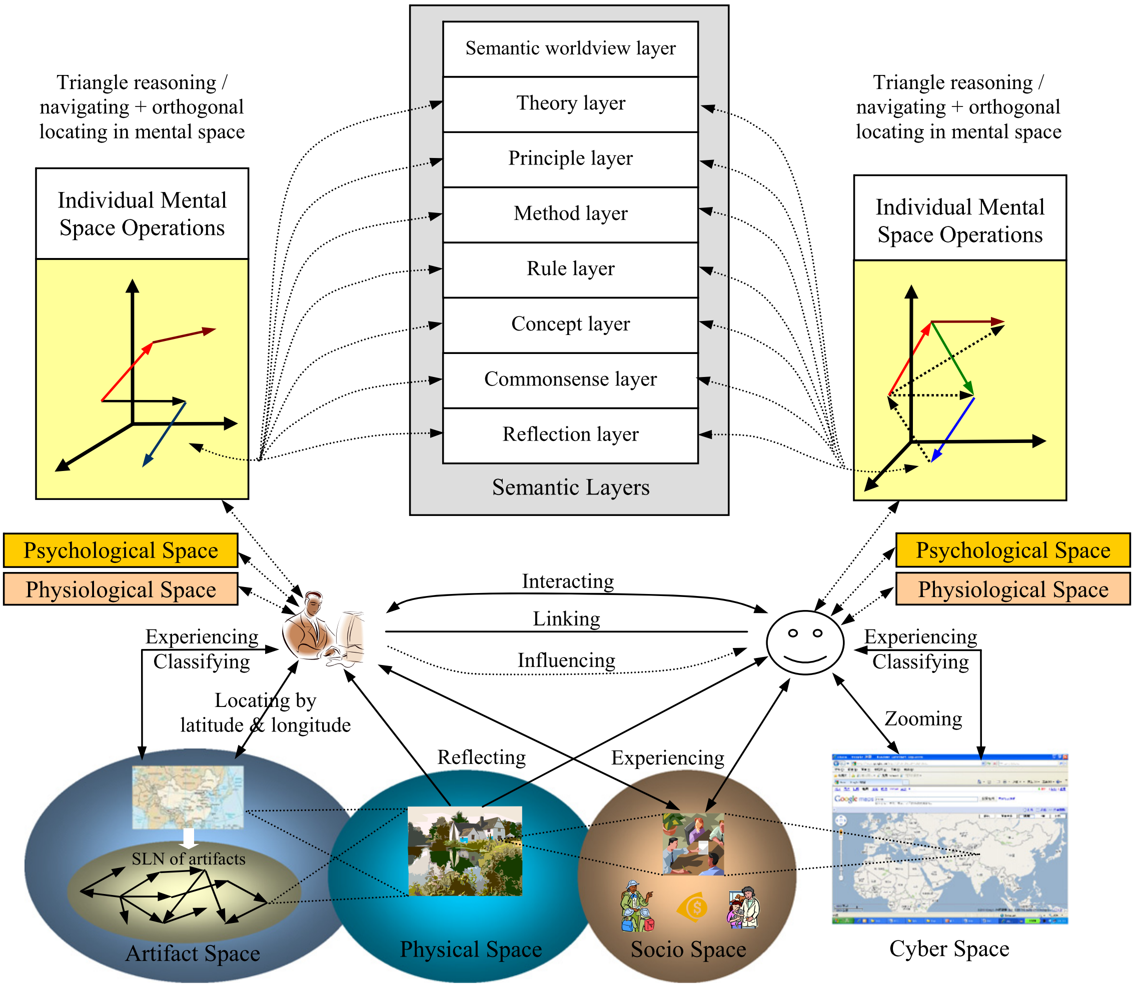



**Fig. 6.** Intelligence in CP$^3$SME: *classification/reflection/navigation/experience in physical space* + *flow/reflection/function in physiological space* + *classification/behaviors/rules in psychological space* + *classification/interaction/link/influence/experience in socio space* + *classification/link/navigation/experience in artifact space* + *classification/searching/zooming/reasoning in cyber space* + *classification/locating/navigation/reasoning in mental space*, where "+" denotes coordination and co-experience.

triangle reasoning and navigation on the semantic link networks will be coordinated with the orthogonal locating in the multi-dimensional classification space in the mental space.

Individuals and events belonging to the socio space are located in a place or a building in the physical space, which can be linked to a point on the map in another space — artifact space. Semantic links can reflect the distance and direction between places or buildings. *Different spaces have different types of distance*, for example, friendship between individuals, the difference between interests, and the distance between offices. Reflecting different aspects of the objects needs to use the distances in different spaces. Various sensors and mobile devices link the cyber space to the physical space and the socio space so that the real-time status in the places and buildings as well as individuals, communities and events can be assessed.

Linking spaces enables spaces to reflect one another while individuals co-experience in these spaces. The behaviors in one space can be extended to multiple spaces and be reflected in the other spaces. For example, the cyber space search can be extended to the socio space search, to the physical space search, to the artifact space search, and even to the physiological space search (for medical applications). At the same time, the cyber space can reflect the experiences and collect relevant real-time interaction from multiple spaces through various sensors.

A semantic image can have multiple layers: *reflection layer*, *commonsense layer*, *concept layer*, *rule layer*, *method layer*, *principle layer*, *theory layer, and semantic worldview layer*. Interactions among semantic layers support complex reasoning. The phenomenon of a falling apple leaves semantic images at the reflection layer through sensors, at the commonsense layer (e.g., the concept "apple is fruit, fruit is food"), at the concept layer (e.g., physical concepts force $f$, the mass of an object $m$, acceleration $a$, and gravity), at the rule layer (e.g., rule of multiplication), at the method layer (e.g., the multiplication operation), at the principle layer (e.g., $f = m \cdot a$), at the theory layer (e.g., physics), and at the semantic worldview layer (e.g.,

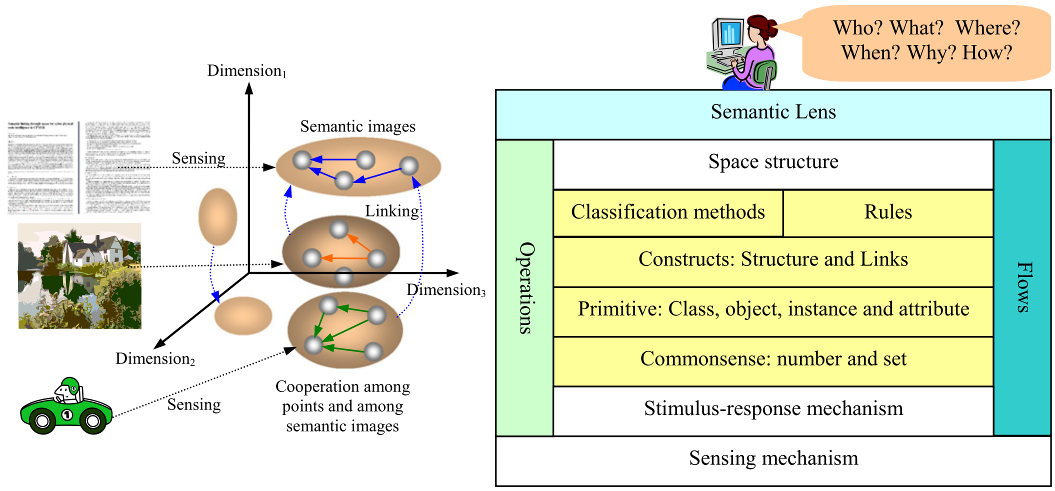



**Fig. 7.** The mental space model. The semantic lens can zoom-in and zoom-out from different dimensions and scales [89].

the recognition of the number of apples, and any external existence). A falling apple in the physical space will be sensed and linked to different semantic layers, which inspires relevant reasoning in the cyber space, socio space, and mental space.

*Future sciences will not only concern the principles in one space but also concern the influences between spaces and the principles in multiple spaces*. It is important to discover the implicit links between various symmetry and self-similarity in different spaces.

## 6. The mental space

### 6.1. The model

Different from previous notions about the mental space [23,47,51], the mental space model depicted in Fig. 7 is based on the multi-dimensional classification space, link, rule, reasoning, and the Interactive Semantic Base ISB [89], since classification, link, rules, reasoning, and interaction are the basis of the development of the mental space. The stimulus-response mechanism links the physical space and the socio space to the mental space through the physiological space and the psychological space.

*Classification, link, rule and reasoning are the basis of recognizing, organizing and managing resources in various spaces. The basic classification and linking mechanism in the mental space could be inherited and fused through learning, experiencing and influencing between individuals*. A multi-dimensional classification space can organize semantic images according to classifications and support zooming on classification hierarchies.

The mental space can be modeled by integrating an adaptive multi-dimensional classification space (e.g., the Resource Space Model) and a self-organized Semantic Link Network [81,87], which can evolve with co-experience in multiple spaces. Resources like texts and relevant senses will be mapped into a point in the space according to classifications. *One point can link to the other points with certain semantics and probabilities to render semantic images*. Points can be self-organized into communities and can cooperate to emerge motivations. The mental space can adapt its structure with continuously emerging semantic images and complex reasoning. Semantic worldviews influence the structure of the mental space and its evolution. An individual mental space can have multiple subspaces that are often operated.

Individual mental space keeps emerging and evolving semantic images with lifetime learning and continuous socio interactions. This is in line with the opinion that human brain develops its neural connections and nerve cells through continuous learning. *Imagination is the ability and process of linking one semantic image to the other, or significantly extending semantic images by complex reasoning*. Frequent interactions within community emerge the community mental space that reflects commonality of individuals in the community.

Material, energy, information, and knowledge flow through links. Different from previous understanding of knowledge, knowledge flow can generate and evolve knowledge during flowing [80].

### 6.2. Major operations

The following are major operations of the mental space:

(1) *Selecting* the situation for reflection according to the active points in the mental space reflecting the physical, physiological, psychological, and socio requirements.

(2) *Mapping* a situation or a sequence of situations in the physical space or socio space into the mental space as a semantic image — a point, a link, or a semantic link network of points. A point is a class, which can have attributes, methods, constraints, and instances. Points can cooperate with each other for rendering and remembering semantic images as well as for generating and operating flows through semantic links.
(3) *Moving* the instances in one point to another point according to the change of the structure of the space.
(4) *Navigating* flow from one point to another point through a semantic link network.
(5) *Reasoning* on semantic link networks to find implicit semantic links.
(6) *Generalizing* a set of points and linking them to an abstract point.
(7) *Specializing* a point and linking it to one or several more specific points.
(8) *Analogizing* a point or a semantic link to the similar points or semantic links.
(9) *Emerging* a semantic image according to a given network in the physical space or socio space.
(10) *Linking one point to another point, linking one semantic image to another semantic image, and emerging effect from reasoning within limited time scale.*
(11) *Linking a semantic image to a language unit defined in the symbol space.*
(12) *Merging* two semantic images by linking semantic nodes.
(13) *Zooming semantic lens.* Zooming along the scale dimension: *zoom-in* to emerge the small-scale semantic image, and *zoom-out* to emerge the large-scale semantic image. Zooming-in and zoom-out can emerge semantic communities of different levels. Zooming along the abstraction dimension: *zoom-in* to emerge the specific semantic image, and *zoom-out* to emerge a more general semantic image. Zooming-in to the nearest, an instance together with its attributes and values will emerge, and *zoom-out* to the farthest, a universal class will emerge.
(14) *Composing* operations into a macro process with some constraints to achieve a complex mental effect.
(15) *Learning.* Linking a new semantic image to an existing semantic image, feeding back physical, psychological, physiological, and socio effect, and remembering the links between the macro processes and the effects.

Writing can be regarded as a process of selecting and organizing the appropriate language units corresponding to the semantic image emerged in mind. Reading can be regarded as a process of emerging semantic images with sensing the flow of language units in texts.

The mental space can compose semantic images and externalize it through various languages. Different languages (e.g., natural language, art language, and mathematic language) indicate semantic images at different abstraction levels and scales. There is no definite one-to-one correspondence between an artifact and its semantic image. Different people may have different semantic images when sensing the same artifact as people may have different experiences. Even for the author, different semantic images may emerge when sensing his/her artifact at different times, because semantic images in the author's mind keep evolving with experience.

The mental space will develop in the complex space to reflect more of the other spaces. Cyber semantic images reflecting the mental space and the complex space can be effectively preserved and accessed when individuals emerge questions, find answers, and select appropriate individuals to collaborate. The cyber semantic image has the following characteristics:

(1) It can be easily shared among individuals in different spaces.
(2) Its evolution and reasoning processes can be visualized.
(3) It can emerge more causes (in multiple spaces) from an effect, and emerge more effects (in multiple spaces) from a cause with the development of the complex space.
(4) It can route questions to answers efficiently within or through semantic images.
(5) Large-scale decentralized semantic images can be preserved, linked, clustered and refined.

*Given the same input, the output of mind can be differentiated from the output of any artifact* (*machine*). For example, given the same scene, painting is the output of mind while photo is the output of camera. Photos are direct mappings from one physical object into another (film or digital memory) while *paintings are externalization of semantic images in the mental space*. The process of painting concerns the processes of experiencing, emerging, reasoning, evolving and externalizing semantic images. Asking a group of students to draw paintings independently according to the same story, the paintings drawn by different students are different. This is because the semantic images in their minds are different. In contrast, machines will output the same thing if they input the same thing.

## 7. The semantic link network

Humans co-wave various semantic link networks (SLNs) when co-experience in multiple spaces in lifetimes. Unveiling the relations and rules in various spaces is the major goal of science. The basic semantic links in the physical space include the *spatial relation*, *movement relation*, *symbiosis relation*, *energy transformation relation* and *material flow* (*e.g., water flow and nutrition flow through food web*). The Euclidean distance between physical objects is a basic semantic link in the physical space.

SLN consists of two facets: *form* and *semantics*.

### 7.1. The form

The basic form of Semantic Link Network is $SLN = \langle N, L, Rules\rangle$, where

(1) $N$ is a set of semantic nodes. Anything can be a semantic node. The form of a semantic node can be denoted as $n[c]$, where $n$ is its name indicated in the symbol space, and $c$ is its class.
(2) $L$ is a set of semantic links. A semantic link indicates a relation between two semantic nodes. A semantic link takes the following form: $n{-}\alpha{\to}n'$, where $\alpha$ is the indicator of the relation determined by the attributes or the behaviors of $n$ and $n'$ in a certain space.
(3) *Rules* is a set of rules such that new semantic links can be appropriately added or the implicit semantic links can be found between semantic nodes as the effect of interaction, reasoning, influence, or evolution. If there are two connected links $n{-}\alpha{\to}n'$, $n'{-}\beta{\to}n'' \in L$, and a rule $n{-}\alpha{\to}n', n'{-}\beta{\to}n'' \Rightarrow n{-}\gamma{\to}n''$, then $n{-}\gamma{\to}n''$ can be added to $L$.

*Semantic nodes are usually explicit. The class of semantic node is described by a set of attributes.* When status of node is important in some applications, the *status of node* can be indicated by the attributes' values at certain time $t$, denoted as $n(t) = \langle a_1(t) = v_1, \ldots, a_n(t) = v_n\rangle$. For example, Zhuge(2010) $= [position(2010) = professor,\ age(2010) = 47,\ health(2010) = good]$.

*Semantic links are usually implicit and rely on semantic nodes' attributes and behaviors.* Some semantic links are one-way like *isPartOf* while others are two-way like *friendOf*. Some semantic links reflect the relations between attributes called attribute-based semantic link, e.g., *olderThan* reflects the order between *age* attributes. 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. For example, the *friend* link cannot be derived from *sameAge* link. Spatial relations and temporal relations can be regarded as attribute-based semantic links.

*Rules are laws of linking semantic nodes, reasoning, and restricting the evolution of SLN.* For example, co-location is a socio rule for linking related services in physically nearby locations. Knowing this rule enables navigation systems to raise efficiency.

Two basic types of operations are *Add* and *Delete*, which can be specialized into the following six basic operations: *AddLink*, *DelLink*, *AddNode*, *DelNode*, *AddRule*, and *DelRule* [74]. 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 themselves to or delete themselves from the network by peer-to-peer negotiation.

*SLN is an abstraction of various autonomous relational networks in different spaces. It can be specialized for dynamic or functional modeling by incorporating the class mechanisms of the object-oriented method* [6,39,61].

The Object-Oriented Modeling and Design (OOMD) tries to model application domain and software in a uniform way. Its basic opinion is that domain is a collection of collaborating objects, and that software should be organized dynamically according to the structure of the domain. The idea is in line with SLN, but SLN concerns complex reasoning in more spaces.

Fig. 8 depicts the way to enrich SLN for detailed function modeling by making use of OOMD, OOP (Object-Oriented Programming), and SOA (Service-Oriented Architecture), in the background of interactions between multiple spaces. The dotted arrows denote various interactions. Socio requirements trigger self-organization of services based on SOA to meet the requirements. The basic services can be implemented by composing the classes defined in OOMD. Regarding semantic nodes of SLN as agents, multi-agent (MA) techniques can be adopted to enhance SLN [72]. Regarding class or object as node, the object, class, inheritance, polymorphism, method, roles, and functional modeling in OOMD support the specialization of SLN. The characteristics of SLN such as rules, complex reasoning, community, centrality, linking effect, decentralized semantic networking, self-organization, and semantic image will also enhance OOMD and MA by regarding classes, objects or agents as semantic nodes.

### 7.2. The semantic image

A semantic image emerges in the mental space when humans sense a form. All possible semantic images constitute a semantic space, which can be modeled by integrating multi-dimensional classifications, the semantic links between points and between coordinates, the rules of linking and constraints, and relevant operations [89]. Mapping SLN into the semantic space concerns the following mappings:

(1) *Semantic link mapping*, which is determined by: the classes of two ends, the semantic link triangle that contains the semantic link, the classes (subclass and superclass) in the classification hierarchy corresponding to the semantic link indicator, the rules that use or derive the semantic link, and the use cases of the semantic link.
(2) *Semantic node mapping*, which is determined by: its class and subclasses, the semantic link triangle that includes the semantic node as vertex, the classes of the linked nodes, and its instances.
(3) *Community mapping*, which is determined by: the classes of the emerging semantic nodes and semantic links according to the emerging principles and the class of the high-level community that includes them [87].
(4) *SLN mapping*, which is determined by structural mappings between SLNs from different views through the semantic lens.
(5) *Mapping an SLN into a semantic range*, which is determined by the *minimum semantic cover* — the simplest SLN that reserves the capacity of indicating semantics; and, the *semantic closure* — the largest SLN that includes all possible

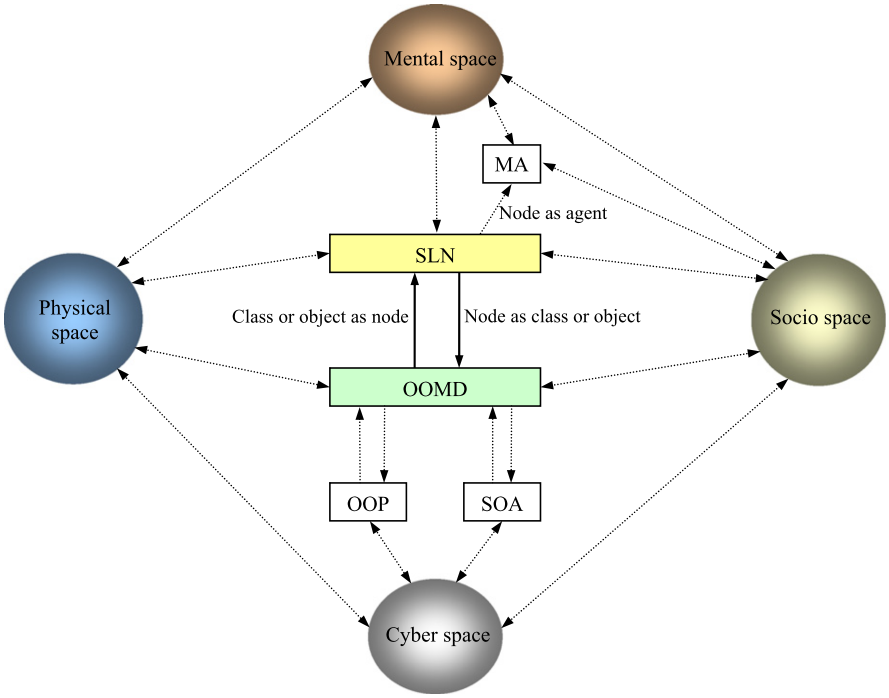



**Fig. 8.** Linking SLN to OOMD, OOP, SOA and MA for modeling functions in $CP^3SME$.

semantic links. Adding a certain number of different semantic links, different semantic covers on different topics may emerge [87,88].

Semantic images emerge with reflection, linking, reasoning and socio interactions as depicted in Fig. 9.

(1) *Emerging semantic images through co-experience.* The semantic image of an SLN emerges in the mental space when the symbols link to the sense and to existing semantic images through the physiological space and psychological space. The cyber semantic image of an SLN emerges at different abstraction levels and scales through the semantic lens.
(2) *Commonsense*. It refers to the basic classes formed through co-experience, reasoning and socio interaction processes. Commonsense of a community is the result of socio classification and regulation on attributes, objects, classes, relations, behaviors and rules. For example, professor is teacher (the professor class belongs to the teacher class), and teacher is human (the teacher class belongs to the human class). The classification hierarchy reflects social consensus on concepts. The massively collaborative online repositories such as Wikipedia (www.wikipedia.org/) and ODP (Open Directory Project, www.dmoz.org/) can be used to build the hierarchy based on the analysis of how people define and evolve the classes. The classification hierarchy can keep updating with the change of the online repositories. Different from previous symbolized commonsense representation, commonsense in $CP^3SME$ will link symbols to semantic images, e.g., linking the word 'professor' to existing relevant sense and semantic images about teaching, research, publication, project and student.
(3) *Socio interaction.* Different minds may emerge different semantic images about the same semantic link network. Interaction between individuals establishes links between the differences. Semantic images and their forms influence each other through direct or indirect interactions. Interaction incurs information flow through mental spaces and also inspires knowledge flow through the semantic images in the mental spaces. Reasoning on the semantic link networks in different spaces is based on the rules and conditions given by humans.

Potential semantic links may be derived out from SLN according to *Rules* when a semantic link $l$ indicated by the concept hierarchy is added to SLN at time $t$, i.e., $SLN(t+1) = Reason(SLN(t) \cup \{l(t)\}, Rules)$. Correspondingly, the semantic image of SLN changes with the evolution of SLN through human behaviors.

SLN is not just a labeled graph, it has the following characteristics:

(1) *Openness*. Versatile semantic nodes, semantic links and rules can be added to SLN at any time. This leads to the formation and evolution of diverse semantic communities.
(2) *Dynamicity*. Adding semantic nodes or links to SLN or removing them from SLN may have different influence on the network since different semantic nodes and links play different roles. Adding new semantic links and rules to the SLN may incur new reasoning or influence.

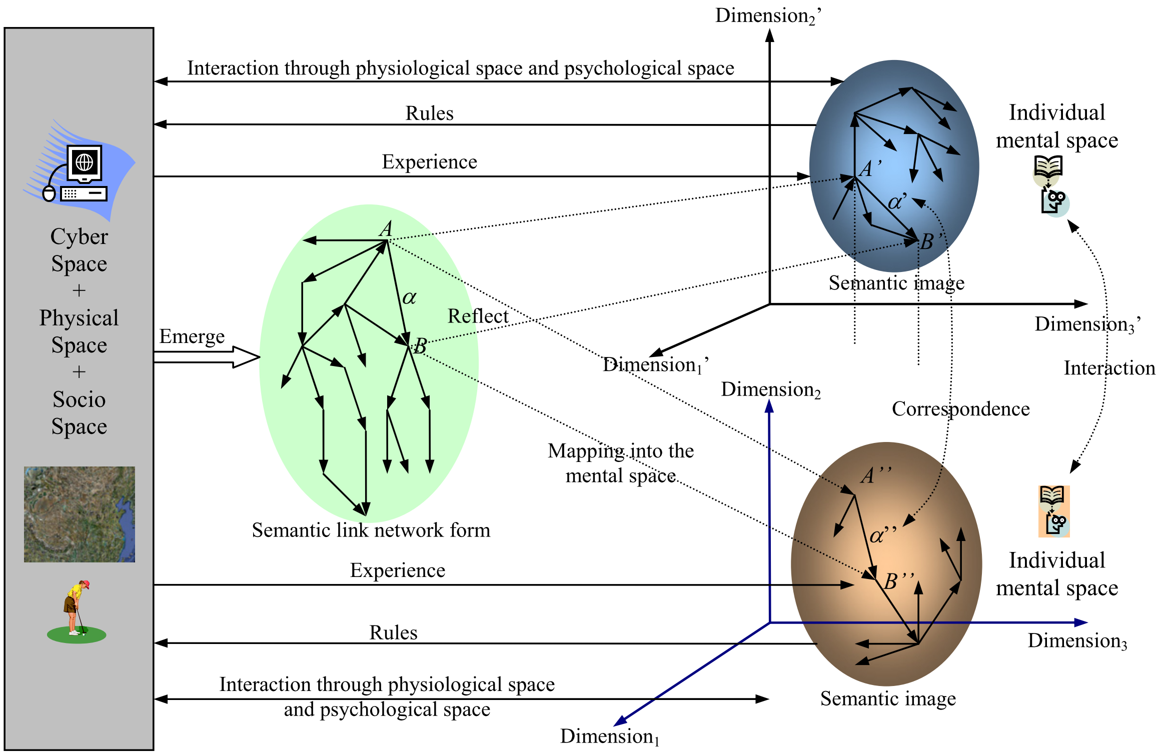



**Fig. 9.** Semantic link network: its form and semantic image. Interaction between minds is the social construction for emerging and evolving the semantic images of a semantic link network.

(3) *Self-organization*. There is no central control on the construction of SLN. Any semantic node can link to any other node according to the rules.

(4) *Autonomous reasoning*. Reasoning on semantic links is different from traditional reasoning on the production rules in knowledge-based systems due to the diversity of semantic links and rules. Reasoning can carry out locally because it is not necessary to derive out all relations to overload storage. A semantic node can participate in reasoning when necessary according to the known situation such as the neighbor semantic links and relevant rules. *SLN's complex reasoning mechanism pursues satisfied result rather than correct result*. Reasoning leads to the dependence between semantic links and the dependence between operations.

(5) *Operation order sensitive*. The result of operation may be different if different orders of operations are applied to an SLN [74]. An SLN may be changed after deleting a previously added semantic link because adding a semantic link may derive new semantic links, which may further derive other semantic links. The consequence relies on the definitions of the addition and the removal operations. Usually, $SLN \neq SLN \cup L' - L'$, and $SLN \neq SLN \cup Rule' - Rules'$, where $\cup$ and $-$ are similar to graph operations. Generally, $SLN \neq SLN \cup SLN' - SLN'$, where $SLN \cup SLN' = \langle N \cup N', L \cup L', Rules \cup Rules' \rangle$, and $SLN - SLN' = \langle N - N', L - L', Rules - Rules' \rangle$. Different from previous graph-based models, *different processes of forming an SLN may indicate different semantics*.

(6) *Complex*. A semantic node can be a semantic link network. For example, $f = m \cdot a$ 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 be a semantic node. Complex reasoning is the composition of multiple reasoning mechanisms such as relational reasoning, analogical reasoning, and inductive reasoning.

(7) *Semantic image*. The semantic image of an SLN emerges from mapping it into the semantic space and from linking it to commonsense, reasoning, evolution, and socio interaction. Semantic nodes can include rich contents so that an SLN is not only for machines to process but also for humans to operate, emerge semantic images and reasoning. A semantic node can be a class, an instance, or a semantic link network. An instance can be an image, video, audio, or text in the cyber space, can be a person or an artifact in the socio space, and can be a physical object in the physical space.

(8) *Evolving community*. Operating an SLN has different effects at different stages of evolution. At certain stage, adding a semantic link to an SLN tends to reduce its semantic communities. Removing a semantic link from an SLN tends to increase its semantic communities. The change of semantic communities in an SLN reflects its obvious movement. Visualizing the evolution process and the effects of operations helps humans to link relevant semantic images. The semantic lens enables SLN to be viewed from a particular semantic node to its semantic communities at different levels [89]. (See Fig. 9.)

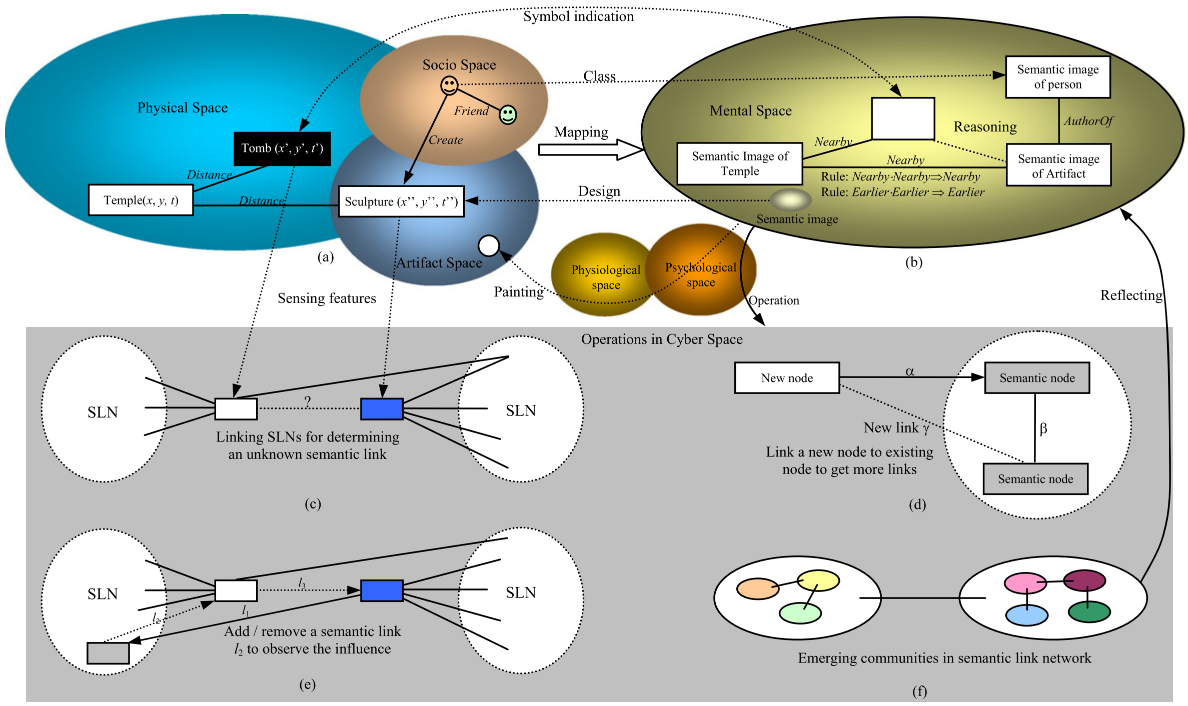



**Fig. 10.** An example of semantic linking through spaces.

### 7.3. Research issues

SLN is not only a model but also a method for semantic linking, reasoning and analyzing. The following are intrinsic causes of semantic linking:

(1) Continuous multi-dimensional classification generates the links between classes.
(2) Natural links between individuals. For example, the family relations and the food chain, although some links are indirect or implicit.
(3) Direct, indirect, conscious, or subconscious interaction between individuals.

SLN research concerns the following issues:

(1) *How to efficiently answer the query on the relations between seemly irrelevant objects or events*? For example, what is the relation between *sunspot* and *economy*? What is the relation between *climate change* and *public security*? Answering these questions needs to discover the implicit semantic links between linked objects based on uncertain reasoning.
(2) *How to recommend the best link to a node to realize its maximum performance according to such criteria as the rise of rank*.
(3) *How to develop SLN toward a self-organized semantic model to support current network applications*? *How to support efficient relational query*, *especially, query on the evolving relations*?
(4) *How to predict the evolution of SLN*? *How do semantic links and semantic nodes influence each other during evolution*?
(5) *How to enable an SLN to support automatic question answering and explanation*? *How can a query be efficiently routed in a large self-organized semantic link network through explicit or implicit semantic link paths*?
(6) *How do different communities and reasoning processes influence each other over a large SLN*?
(7) *What level of intelligence can be reached by integrating multi-dimensional classification ability, linking ability and complex reasoning ability*?

The above discussion shows that SLN is different from previous links and graph-based models in goal, model, method and research issues.

## 8. Linking, interacting and explaining through spaces

### 8.1. Linking spaces: an example

Humans create the artifact space by designing the functions of artifacts, assigning semantic indicators to artifacts to reflect meaning or idea, and linking one another by direct or indirect referencing (e.g., paintings of the same author or times). Semantic link indicates classification, reference, or rendering relations between artifacts.

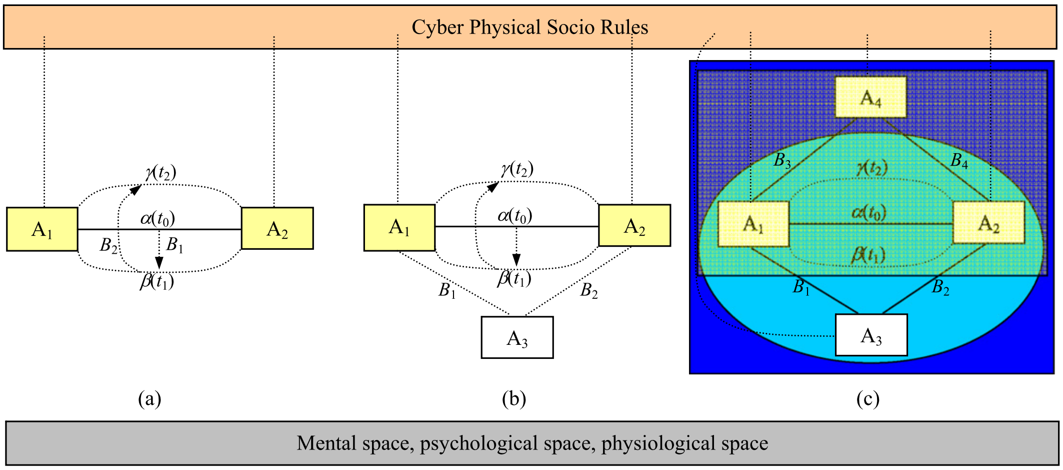



**Fig. 11.** Semantic communities evolving with interactions in the complex space. A static semantic link network is one type of form. The evolution process of a semantic link network is another type of form, which can better indicate semantics.

Humans organize artifacts according to some socio rules, e.g., co-location of different types of restaurants. Fig. 10 shows an example of linking through spaces. An artist in the socio space creates an artifact (e.g., sculpture) in the artifact space according to the semantic image emerged in the mental space, and then puts the artifact close to a physical object (e.g., hill) at latitude $x$ and longitude $y$, and at time $t$. The *Euclidean-distance* between them is two meters, and the distance between the hill and an unknown object (e.g., ancient artifact) is three meters.

The mental space, physical space, artifact space, and socio space are linked as depicted in Fig. 10 (a). The mental space reflects the physical objects and the semantic links as abstract classes and conceptual relations (e.g., the *nearby* link), and links the classes when co-experiencing in multiple spaces (Fig. 10 (b)). Reasoning may result in the inclusion of the unknown physical object (the black box) into a semantic image, deriving relevant semantic links, and linking it to other semantic images.

As depicted in Fig. 10 (c), the cyber space can visualize the semantic link networks for humans to operate according to the semantic images in mind. It can link more SLNs and discover implicit links for the reference of human operations. It can simulate the effect of operations (e.g., linking a new semantic node to an existing semantic node) according to some principles of emerging as depicted in Fig. 10 (d). It also enables humans to observe the influence by adding or removing a semantic link, as depicted in Fig. 10 (e). It can also visualize semantic communities depicted in Fig. 10 (f) and their evolution, which inspires the evolution of semantic images in the mental space.

### *8.2. Linking while interacting*

Interactions accompany the establishment of semantic links in multiple spaces:

(1) Interaction between humans establishes and evolves semantic links in the socio space, accompanying the emerging, evolving, separating, and unifying semantic images in the mental space.
(2) Interaction between humans and physical objects evolves the semantic images about the physical space in the mental space, accompanying the establishment of the semantic links between physical objects, humans, and socio events.
(3) Co-experiencing in the physical space, socio space, cyber space and artifact space establishes the semantic links through the socio space, physical space, artifact space and cyber space, and evolves the semantic images in the mental space. The cyber space creates and evolves the cyber semantic images during interactions.
(4) Creation of artifacts semantically links humans to artifacts, links semantic images to the artifacts, and link humans.

Interactions between individuals create and evolve semantic links between individuals. Interactions in different spaces follow different rules. For example, in the socio space, a mutual benefit relation (e.g., friend relation) needs satisfied interactions of multiple times, but it will be changed by just one time unfriendly interaction. Rebuilding a mutual benefit relation needs more satisfied interactions than that for creating a new one.

As shown in Fig. 11 (a), a new relation $\beta$ will be generated at time $t_1$ after behavior $B_1$, and relation $\gamma$ will be created at time $t_2$ after behavior $B_2$, indicated by: $\alpha(t_0)-B_1\rightarrow\beta(t_1)$, and $\beta(t_1)-B_2\rightarrow\gamma(t_2)$. A dynamic semantic image between individuals $A_1$ and $A_2$ is formed with interactions carrying out. Interaction can also be indirect as depicted in Fig. 11 (b): interaction between $A_1$ and $A_3$, and interaction between $A_3$ and $A_2$ can also evolve the relation between $A_1$ and $A_2$, because $A_3$ can get information about $A_1$ when it interacts with $A_2$. Some socio rules also support indirect interaction, for example, the friend of enemy may be enemy. So, the creation of a semantic link depends not only on the neighbor links and rules but also on interactions.

Different semantic communities may emerge on the same semantic link network with continuous interactions. Nodes that often interact with each other tend to form a new cluster. Fig. 11 (c) is an example of the evolution of communities: $\{A_1, A_2\}-(B_1+B_2)\rightarrow\{A_1, A_2, A_3\}-(B_3+B_4)\rightarrow\{A_1, A_2, A_4\}\longrightarrow\{A_1, A_2, A_3, A_4\}$.

*Some behaviors may have long-term effect in one space while having short-term effect in the other space*.

Communities are temporal and new communities will emerge with continuous interactions. This is different from traditional understanding of communities. CP$^3$SME should be able to recognize and make use of this kind of communities.

### 8.3. Explaining through spaces

Different spaces can answer and explain *what*, *where*, *who*, *why*, *when*, and *how* according to their respective characteristics. Linking different spaces can answer and explain the same question in different spaces.

The socio space can answer and explain the following questions: *Who are you*? *Who I am*? *How it is related to human life, socio requirement and development*? *How do individuals effectively cooperate with each other*? *Who is relevant*? *Who can help*? *Which community it belongs to? What are relevant socio rules*? *What socio resources can be used? What are the socio values and effects*? *How is the health of individual and community*? *How it is related to culture*? *How does it link to previous explanations*? *What is his/her worldview*?

The physical space can answer and explain the following questions: *How it is related to physical phenomena and laws*? *What are its physical effects? Where does it happen*? *How far is it*? *How to get it*? *Who is around*?

The physiological space can answer and explain the following questions: *Are you hungry*? *Are you tired*? *Are you pain*? *Are you happy*? *Is it tasty*? *Is it healthy*? *Do you want to sleep*?

The psychological space can answer and explain the following questions: *How people usually feel, think, speak, and behave in a given situation*?

The artifact space can answer and explain the following questions: *When and where are they created*? *Which are relevant*? *How are their values*? *Who are the authors or owners*? *Who are interested in them*? *What are its socio and cultural effects*? *What kind of model or style is adopted*?

The mental space can answer and explain the following questions: *What is his/her opinion*? *What does he/she like*? *Whom he/she likes*? *How does he/she like*? *Which category it belongs to*? *What is the cause*? *What does it imply*? *What are the similar cases*? *What is the appropriate method for solving a problem*? *What is the probable effect of the method*?

The cyber space can answer and explain the following questions: *Where is its cyber semantic image*? *Why the services are recommended*? *What algorithms are used*? *How things are stored*? *How it is retrieved*? *How it is displayed*? *How to operate it*? *How is the efficiency*? *What is the cyber effect*?

Coordinating multiple spaces can answer and explain the questions that any single space cannot answer and explain, and can explain how one space influences the other spaces. For example, a physical phenomenon like earthquake in the physical space can influence the socio space, physiological space, psychological space, and cyber space. Answering the question "Where are you?" concerns the location in the physical space (explanation may concern the real-time situation about the location), the location in the cyber space (e.g., the mail box or homepage), and the location in the socio space (e.g., at a friend's home, explanation may concern the status of the friend and relevant socio networks).

Including a time dimension into the complex space can classify resources by time and answer the following questions: Where he was yesterday? Who he is with?

## 9. Complex link network and socio energy

### 9.1. Complex links

The following are some important complex links.

(1) *MCM*: *Mental Space* $\longleftarrow$ *Cyber Space* $\longrightarrow$ *Mental Space*, which is the interaction between mental spaces through the cyber space. This type of complex link can be regarded as a service that can facilitate interaction in life-time. It can extract the SLNs from interactions, and make necessary abstraction and evolution during interaction based on the modeling of mental space and the translation between languages under different cultures. It can retrieve previous interaction topics, recommend potential partners, and inspire reasoning while interacting. Multiple candidate services would be available for selection or for composition to support effective interaction according to a service description language and the interaction interest. Individuals can also select different services in the cyber space.

(2) *MCP*: *Mental Space* $\longleftarrow$ *Cyber Space* $\longrightarrow$ *Physical Space*, which facilitates the interaction between the mental space and the physical space. This type of complex link can be regarded as a service that can obtain the characteristics of the physical objects, and enables the mental space to reflect the real-time status of the physical objects. Sensors can only reflect some surface features of physical objects. For example, a photo of cup does not tell us if the cup contains coffee or tea, and it is even harder to tell us the taste. Designers are the best person to know where, how many, what types of sensors or actuators are needed, and how they are deployed to reflect the real-time status of an artifact.

(3) *MCS*: *Mental Space* $\longleftarrow$ *Cyber Space* $\longrightarrow$ *Socio Space*, which facilitates the interaction between the mental space and the socio space through the cyber space. This type of complex link can be regarded as a service that can model the mental space, recognize socio behaviors and events, and organize services according to the semantic image emerging in the mental space and socio rules.
(4) *MAC*: *Mental Space* $\longleftarrow$ *Artifact Space* $\longrightarrow$ *Cyber Space*, which facilitates the interaction between the mental space and the cyber space through the artifact space. This type of complex link enables humans to understand and influence the cyber space through versatile artifacts like robots in the artifact space. The robots linked to the cyber space can also form cyber semantic images to reflect the physical space and themselves and to share with others.

Most previous computing techniques are for improving the cyber space, for example, the Semantic Web is to create machine-understandable semantics in the cyber space, the semantic net is to express knowledge in the cyber space, and the semantic link network is to reflect socio relations and the dynamicity in the cyber space.

*Complex links not only reflect relations and network dynamicity but also transmit information, material and even energy*.

It can be denoted as: $p_i$—$l : c \rightarrow p_j$, where $p_i$ and $p_j$ are individuals or classes in one or different spaces, $l$ represents the relation between the points, and $c$ represents the type of content or material that can be transmitted from $p_i$ to $p_j$.

*Complex links will enable interactions to pass through spaces*, for example, text or image of an apple in the cyber space can be linked to the apples in a supermarket with a price or on an apple tree with the information reflecting temperature and nutrition in soil, linked to the relevant food web, and further linked to the physical concepts like gravity. Both class and individuals are concerned: One tree will be different from the other tree, and one apple will be different form the other apple.

Fig. 12 compares the hyperlink, the semantic link, and the complex link. The hyperlink enables any web page to connect to any other page. The semantic link connects semantic nodes with certain rules on relations. Different orders of operations may lead to different effects. The complex link can not only play the role of a semantic link but also facilitate interaction and transmit resources (denoted as $c_i$) according to the interests of nodes and the rules on both nodes and links in multiple spaces. They will influence the evolution of the network. Therefore, communities of different types will emerge and evolve according to different rules.

Complex link network will have the following characteristics:

(1) *Diversity*. Complex link can transmit diverse resources such as material, information, knowledge, and energy [52]. It can link various individuals in diverse spaces to support creation and well-being.
(2) *Real-time influence through spaces*. Complex link networks in socio and mental spaces concern time. A node $n_i$ with lifetime $[t_0, t_n]$, class $c$, attribute $att$, and current time $t$ is indicated by $n_i[c, att, t, (t_0, t_m)]$. A complex link $\alpha$ added to the network at time $t$ can be indicated by $\alpha[c, \tau]$ where $\tau \leqslant t$. Influence of operations and interactions will be real-time and can pass through spaces.
(3) *Cyber-physical-socio context*. A self-contained cluster of complex link network can be used as the situation of interactions. It can render richer semantics than previous forms of context in the cyber space.
(4) *Cyber-physical-socio service*. Complex links connect services in different spaces to provide *cyber-physical-socio services* for individuals. For example, complex links can link services of recommending restaurants to the favorite dish, to the best cooker, to the cooking process, to the food culture, and to the delivering service.

### 9.2. Harmony and influence measures

The difference and competition among individuals lead to the formation of various network characteristics like the centrality [91]. The physiological, psychological, socio and mental statuses of individuals play an important role in forming socio structure and socio development. The well-being of individuals is an important criterion of evaluating socio status. The well-being of an individual depends on socio interaction as well as psychological, physiological and mental statuses. People who are good at communication can live longer than those with little socio interaction as helpful interaction can help relieve mental pressure and raise immunity [38].

Previous research on links and social networks neglects an important characteristic in networks — the *harmony*. For example, the spouse relation can be either harmony or discord, over discord may lead to divorce. Therefore, the spouse relation is transformed into the divorce relation. Different from the ranks, harmony is based on healthy and satisfied interaction within a community.

*The well-being of an individual is a function of harmony and its physiological, psychological, socio and mental health*.

The influence of individual $A$ on $B$ through complex link $l$ can be measured by the *potential energy of nodes A* and *B*, the *potential energy of link l*, and the *times of effective interactions* between $A$ and $B$. *Influence can be measured according to the extent of transforming the pattern of a complex link network. The extent can be measured by the number of individuals who change their communities or obviously change the behaviors of certain number of individuals due to influence*. Socio preference influences the formation of patterns.

### 9.3. Socio energy

An individual $x$ in society has *potential energy* $E_p(x)$ due to its centrality in complex link network and interaction. *The potential energy of a community can be measured by its population, structure and interaction. The potential energy of*

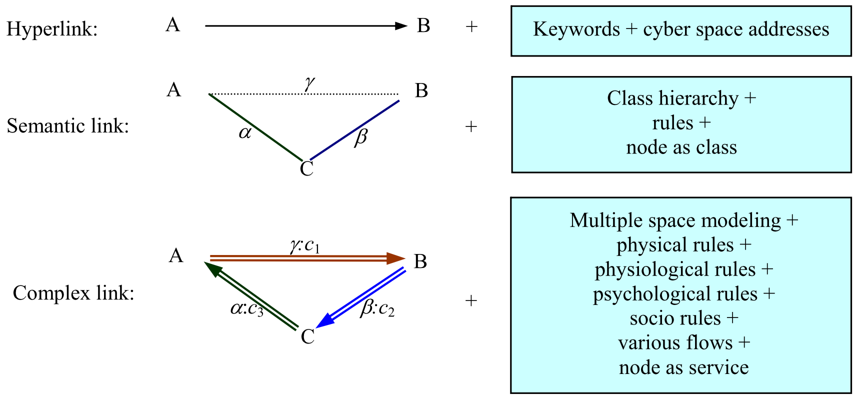



**Fig. 12.** From hyperlink to the semantic link and to the complex link.

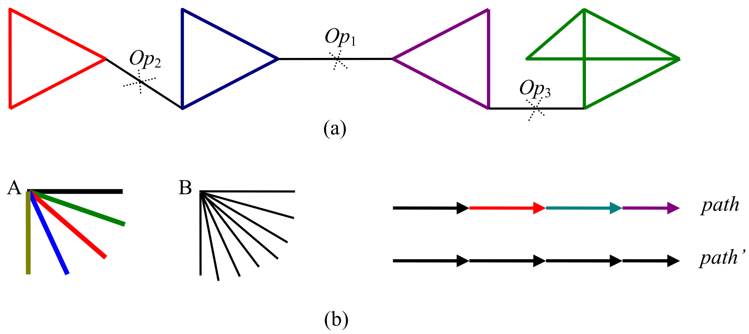



**Fig. 13.** (a) Socio energy. (b) The priority of emerging. The colored lines represent different types of links. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

*an event can be measured by the number of involved individuals and the emerging rules of individuals in the complex link network.*

Physical motion, socio behavior, and cyber operation has *motion energy*. An operation's motion energy reflects the influence of the operation. The following is a motion energy measure of operation based on the number of individuals who have changed their communities influenced by the operation and the total number of individuals as follows: $E_p(\mathit{operation}) = \mathit{Number\ of\ individuals\ who\ have\ changed\ their\ communities/Total\ number\ of\ individuals}$.

The motion energy in CP$^3$SME originates from thoughts in the mental space. A great thought may transform a society. The up portion of Fig. 13 is a simple example of the motion energy of removing links. The motion energy of operation is sensitive to the operation order. For the following operation orders: $Op_1 \to Op_2 \to Op_3$ or $Op_1 \to Op_3 \to Op_2$, we have $E_m(Op_1) > E_m(Op_3) > E_m(Op_2)$. For the following operation orders: $Op_3 \to Op_2 \to Op_1$ or $Op_3 \to Op_1 \to Op_2$, we have $E_m(Op_3) > E_m(Op_1) = E_m(Op_2)$.

The potential energy and the motion energy co-exist and influence each other through various networks in the CP$^3$SME.

The low portion of Fig. 13 shows the following principles of emerging.

(1) *The node with rich types of links takes the priority to emerge*. The node with richer types of links takes the higher priority to emerge than that with less or single type of links. This is because the node with richer types of links offers higher probability to the new link to derive out more links so that communities have higher probability to be enriched or changed. The new link has higher probability to connect the same type of link for transmitting materials or contents. It is the reasoning rules on links and nodes who determine the emerging preference rather than the ranks of nodes or links. For example, a person with only one type of link like family link will be more probably isolated in society, so a node who wants to raise socio status should not link to an isolated node.
(2) *The path with single type of links takes the higher emerging priority than that with more types of links when understanding or explaining the path*. For complex links, the path with the same type of links enables more types of information or materials to pass through.
(3) The *outstanding principle* and the *relevance emerging principle* were introduced in [89].

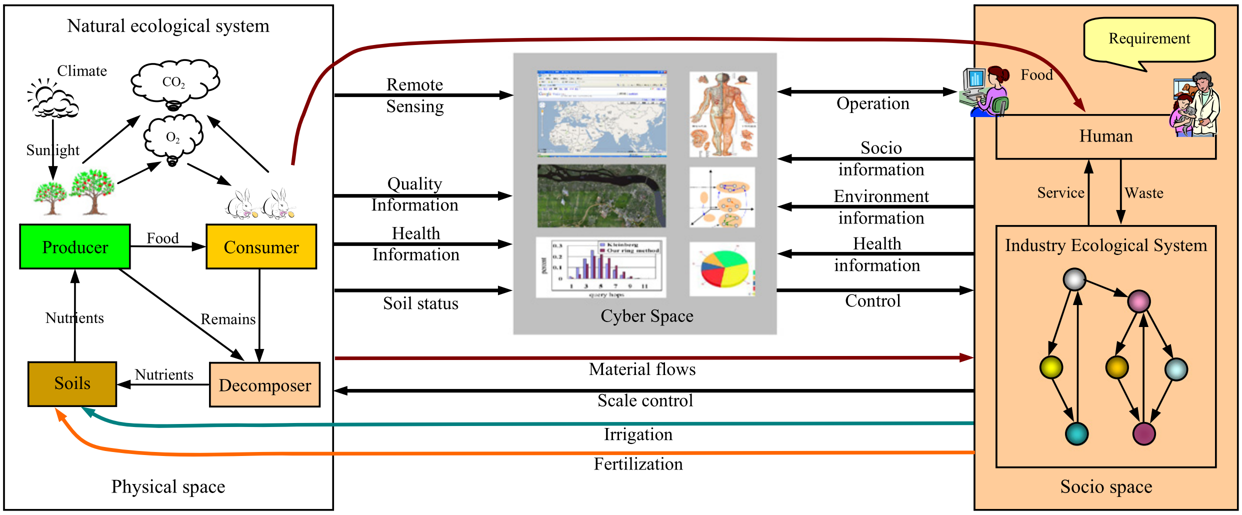



**Fig. 14.** A cyber-physical-socio-ecological environment. The closed loops of complex linking within space and through spaces make full use of material, energy and information.

## 10. Closed loops of complex link

Complex link can be chained and closed for improving the performance of behaviors in multiple spaces. The closed loops of complex link within $CP^3SME$ concern macro- and micro-closed loops.

### 10.1. Macro-closed loop

The closed loops of material flow and energy flow can achieve harmonious ecological effect [28]. The $CP^3SME$ will include more types of closed loops such as information flow, service flow, material flow, and knowledge flow cycles. Fig. 14 depicts a cyber-physical-socio-ecological environment. The material flows, information flows, and control flows within space and between spaces form closed loops within the environment. The material flows include the flows of various materials required by the socio space, irrigation or fertilization. The following are some characteristics of this environment:

(1) *The cyber space can reflect more of the physical space and socio space by using the advanced sensors, actuators, interactive interfaces, and link situation in different spaces to provide cyber-physical-socio services*. For example, the scale of farming can link to the requirements of society.
(2) *Multi-dimensional real-time status about individuals and communities in the physical space and the socio space can be captured*. For example, the status of crops concerns nutrient dimension, health dimension, function dimension, economic dimension, and time dimension.
(3) *The cyber-physical-socio effects of various behaviors are available so that appropriate decisions can be made to ensure harmonious development of various spaces.* For example, climate change in the physical space may influence agriculture, which may influence the society.
(4) *The mental space will develop new functions as it will emerge and evolve new semantic images when reflecting multiple spaces simultaneously*. For example, humans can view complex link networks in the socio space and relevant real-time events in the physical space while reading or writing in the cyber space. While drinking tea, humans can know the characteristics of the tea and its production process from the touch table, enjoy the tea-cultural performance in the physical space, verify the quality of the tea through the equipments linked to the touch table, and, access the soil status of the tea trees in the physical space.
(5) *Complex linking different spaces enables one space to make use of material, energy and information in the other space*. For example, linking the agricultural ecological system to the industrial ecological system enables some industrial waste to be used as the fertilizer of crops, and enables the agricultural products to be the raw materials of some industries.

Influence through spaces can also form closed loops. Changes in the physical space such as the increase of roads and buildings 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 cyber space will influence interaction between humans, which will influence the mental space. Changing semantic images in the mental space will influence behaviors in the physical space, cyber space and the socio space.

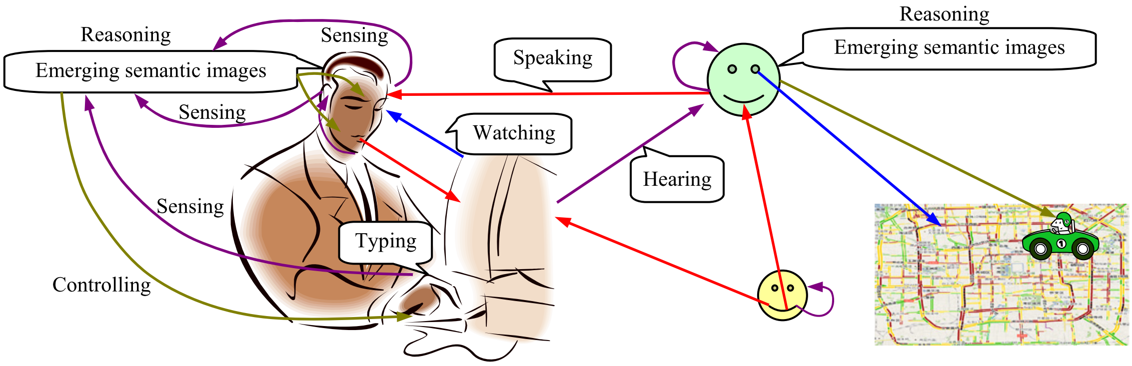



**Fig. 15.** Micro-closed loops. Emerging and enriching semantic images while closing the loops of sensing, controlling, behaving and reasoning through multiple channels. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

### 10.2. Micro-closed loop

*Humans can not only sense from multiple channels but also form close loops through sensing, behaving, emerging semantic images, and reasoning*. Behaving through one type of channel (e.g., writing) accompanies sensing through another type of channel (e.g., vision). Practice (e.g., dictation) helps establish the links between the behaviors through different channels and between behaviors and semantic images. This is why blind people cannot write in the normal natural languages. Interactions among various individuals extend the closed loops.

Fig. 15 depicts the closed loops of sensing, behaving and emerging semantic images through multiple channels. The red arrows denote sensing and the yellow arrows denote controlling. *How to optimize the closed loop to raise the efficiency of cognition is an important issue*.

A semantic image synthesizes the sense, behavior, and language. It will be enriched with the execution of the closed loops. *How do sense, behavior, language and reasoning interact with and influence each other is the foundation of cognition and is a challenge issue of sciences, technologies and socio development. The closed loop of complex link is a basic mechanism of the interaction and influence.* Relevant research concerns multi-disciplinary innovation.

### 10.3. Cyber-physical-socio innovation

CP$^3$SME also provides a new innovation environment. As shown in Fig. 16, thoughts are inspired by the requirements raised in the socio space and the co-experiences in the physical space, socio space, artifact space, physiological space, and psychological space. Humans emerge semantic images in mind, use languages to indicate semantic image, use sketch to describe semantic image, develop a sketch toward a design, and model a design in the cyber space or in the artifact space as a prototype. A prototype can be refined through reflection and reference in the physical space, artifact space, and socio space as well as through reasoning processes in the mental space. The final design can lead to the artifacts in the artifact space through a manufacture process. *This indicates a new design paradigm that enables designers and users to co-experience during the whole design process*.

The real-time status of an artifact (e.g., bridge) and the influence from the socio space and the physical space can be reflected in the cyber space through various sensors during the whole process of innovation and design. Appropriate on-demand services can be provided when sub-healthy status is detected. The end-of-use artifact will be decomposed into materials that can be reused for composing new artifacts [67]. *The closed loop of various flows through the spaces form a sustainable innovation environment*.

## 11. The interactive co-computing environment

Turing machine is the model of computing and studying the extent of computing. All digital computers are Turing machines. Much efforts have been made to extend Turing machines [15,65]. Traditional intelligent systems rely on humans to define a problem, and then design a computing process to solve the problem by machine languages. This is not in line with the characteristics of human intelligence. A fundamental difference between machine and human is that humans can co-experience in multiple spaces and emerge semantic images and motivations according to psychological, physiological and socio requirements.

The CP$^3$SME will be a massive interactive environment, where various interactions play more important role than algorithms [70]. Interactions are the source and driven force of the formation and evolution of all the spaces. It is important for ensuring effective interaction since interactions not only create links but also evolve semantic images.

Traditional artificial intelligence research is based on representation. To pursue accurate representation of human knowledge is questionable [89]. In the CP$^3$SME, co-experiencing in multiple spaces, forming and improving the closed loops of

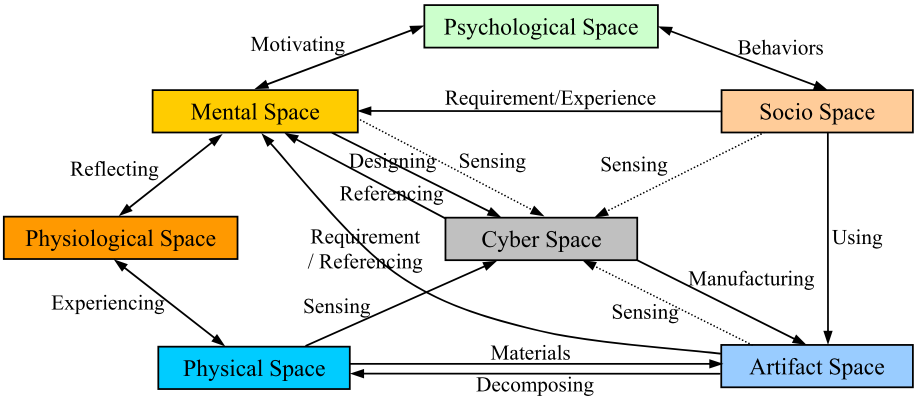



**Fig. 16.** Innovation and design in CP$^3$SME.

various links and flows through sensing, classifying, emerging, computing, communicating, interacting, controlling, behaving, and reasoning form the basis of the cyber-physical-socio intelligence.

An interactive co-computing environment model incorporating machine computing, human reasoning and socio interaction is depicted in Fig. 17. The *co-computing process* concerns the following behaviors:

(1) Interaction requirements are raised in the physiological space, psychological space, socio space, and mental spaces from time to time.
(2) The designer defines the function $f$ of one computing machine, which can accept question from the user or from the other machine $f'$ and then give answer, or ask $f'$ or user questions.
(3) Minds reflect forms, emerge or enrich semantic images, generate motivation, and carry out reasoning.
(4) Forms and semantic images co-evolve.
(5) The cyber space builds cyber semantic images during direct and indirect interactions so that it knows the past and present interactions.
(6) Functions emerge from time to time with linking machines, services and humans as well as executing various flows such as information flow, knowledge flow, material flow, energy flow, and workflow in the environment [73,80].

Turing machine is a closed system as its computing components and computing process is pre-defined and fixed, which cannot be changed by input and output. In contrast, humans can continually receive input from the environment and adjust behaviors when thinking and behaving. The CP$^3$SME is an open system since machines may be linked to existing machines from time to time or disconnected the current links according to the real-time requirement and rules in multiple spaces. *The important thing is that the process of interaction is not predefined*. Even for a single machine, its work process depends on real-time interactions and its semantic images. The cyber semantic image plays an important role in supporting effective interaction. Individuals in different spaces evolve with the development of the environment. The interactive environment operates for ensuring harmonious development of individuals and the environment.

The interactive co-computing environment concerns the following scientific issues.

(1) *Methodology*. Many current technologies are based on or about past, e.g., software and hardware are pre-designed, information retrieval is to get past data, and knowledge discovery is based on past data. The CP$^3$SME concerns not only the past but also present and future. Real-time situation in multiple spaces will be available at anytime and any place with the generation and evolution of spaces. The new methodology should accelerate the progress of science and technology, break the boundaries of existing disciplines, and be more insightful and predictable on the influence on various spaces. The aim is a harmoniously evolved and sustainable environment.
(2) *Ability extension in complex space*. An idea will be linked to sketch, to design, to the production processes, and further to the closed loops in the environment. This concerns the modeling of the spaces, the mapping between spaces, the mechanism of influence, and the rules of linking and flows through links.
(3) *On-demand services through spaces*. Services are provided on demand through logistics of materials, services, information and knowledge according to socio rules. The logistic processes will leave semantic images in the environment and can be adapted according to the change of requirements.
(4) *Cyber-physical-socio laws*. Laws of competition, symbiosis and cooperation among individuals and among communities in the evolution process of the environment need to be explored.
(5) *Principles of interaction*, *transformation and flows*. Research concerns: the principles that individuals in different spaces interact with each other; the transformation of forms; the coordination of information, knowledge, service, material and

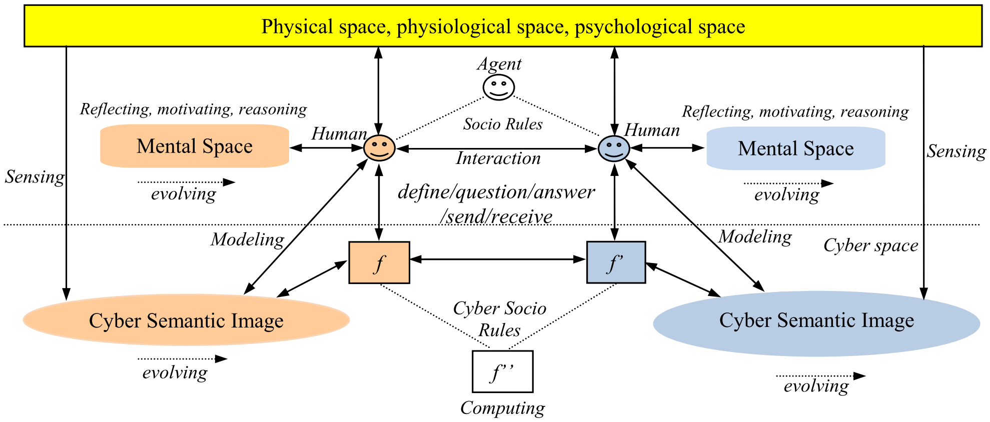



**Fig. 17.** The interactive co-computing environment model. Various interactions link humans, mental space, physical space, physiological space, psychological space, and cyber space. The two-way arrows denote the following interactions: define and adjust functions, ask or answer questions, as well as send and receive situation. The dotted lines denote the possible interactions according to socio rules. The ultimate goal of the environment is the well-being of individuals and communities as well as the sustainable development of the environment.

energy flows; and, the principles, laws and methods of interaction, influence, reasoning and explanation in the complex space.

(6) *Reflexive, self-organized and self-adaptive architecture*. The CP$^3$SME needs a reflexive, self-organized, and adaptive architecture that can preserve semantic images of itself and versatile individuals in lifetime and manage significant behaviors, events and processes (e.g., in daily life, learning, creation and business). The architecture can also link socio activities and processes, physical individuals, thoughts as well as physiological, psychological and mental statuses to create a complex intelligent environment for well-being.

(7) *Rules of effective interaction among sense, language, semantics and reasoning*. The CP$^3$SME concerns not only machine intelligence, human intelligence and social intelligence as emphasized in the interactive semantics but also the closed loops in the environment. *How to raise the effectiveness of the closed loops by reducing redundant interactions is an important issue*. In addition, a harmonious human-machine interactive interface is an important aspect of integrating machine intelligence, human intelligence and socio intelligence.

## 12. Philosophical perspective

The study of social relations can trace back to the age of Laozi (576 BC), Confucius (551–479 BC), Thales (624 BC–546 BC), and Socrates (469 BC–399 BC). The formal definition of general relation traces to the invention of set theory in 1874.

Laozi respected the nature rather than action as he thought that unnatural act will break natural balance. His philosophical idea emphasizes the unification of human and the nature. He is the first person who proposes the ideal of harmonious development of human being and the nature. Confucius emphasized social relations such as morality, correctness, justice and sincerity. He argued that particular duties arise from one's particular situation in relation to others, and that the individual stands simultaneously in multiple relations with different people. This is in line with the discussed principles of emerging. These are early ideas on social regulations and emerging semantics. Their ideas are significant to explore socio relations and the harmony in CP$^3$SME.

Thales explained natural phenomena via a rational explanation with reference to natural processes. Socrates emphasized the importance of friendship and community in human life. Plato believed that the world we observe is not the real one, but only a shadow of the real world. Kant believed that passive experience is not the beginning of understanding, and that there are some categories that human beings actively use to make sense of the world. *These ideas are in line with the method of modeling the mental space and semantic image* — integrating the multi-dimensional classification space and the semantic link network [82,87].

Wittgenstein concerned the relationship between propositions and the world. He regarded language as a series of interchangeable language-games in which the meaning of words is derived from their public use. This idea is in line with the statistical approaches and the interactive semantics [89].

Relevant to Plato's notion, Popper classified the universe into three interactive worlds: physical world, subjective mental world, and objective knowledge world. His notion does not include the cyber space which has extended the form of reflection, interaction and existence. Different from his static classification, *the evolving space model proposed in this paper emphasizes the dynamicity and diversity of the spaces*. For example, the symbol space evolves differently from the physical space, mental space, and cyber space.

Since the formation of modern science, many scientists such as Newton, Maxwell and Einstein have made great effort to explore the uniformity of the world. For example, Maxwell created the electromagnetic theory by unveiling the uniformity of electricity, magnetism and light. But it is hard to create a uniform theory to explain all spaces [35]. *$CP^3$SME purses the uniformity, while respecting diversity, dynamicity, harmony and sustainability*.

At the early stage of AI, philosophical problems of AI are concerned [48,51]. For example, Minsky regarded minds as the collections of vast number of semi-autonomous, intricately connected agents, and gave an explanation of how minds relate to such functions as motivation, language, memory, learning, intentions, and metaphors. Different agents can be based on different processes with different purposes, ways to represent knowledge, and approaches to produce results. A society of agents can together perform more complex functions than any single agent could. He modeled the function of mind from the view of computer architecture. On the contrary, Dreyfus argued that human expertise depends on unconscious instinct rather than conscious symbol manipulation and on having a *feel* for the situation rather than explicit symbolic knowledge [19]. *Gödel's incompleteness theorem early showed that a formal system cannot prove all true statements.* This actually limits the ability of machines.

The terminology "ontology" was borrowed by computer scientists to solve the semantics problem. Many domain ontology mechanisms have been developed. Ontology engineering and ontology mapping are topics in the semantic web area. It is worth pointing out that these ontological mechanisms are symbols that can only help indicate semantics rather than semantics itself. Ontological mechanisms may help establish consensus in specific areas. Various encyclopedias are to establish consensus by collecting multiple definitions. Cultural and experience influence the way and effectiveness of using various forms to indicate semantics. Multiple forms from different spaces can help indicate semantics, and the first language is more effective in indicating semantics than using the second language due to culture difference. Psychological research indicates that brain uses different regions to process the first language and non first languages. The epistemology has been emphasized in the effort to solve the semantics problem [77]. This implies that the current approaches to the semantic web, machine translation, and text understanding through processing symbols in the cyber space is questionable in essence.

Rationalism and empiricism have different viewpoints on the formation of worldview and knowledge. Empiricists like John Locke (1632–1704) regard sense experience as the starting point of knowledge. Perception starts the processes that generate beliefs. Rationalists argue that the ultimate starting point for knowledge is not the senses but reason. Human beings rely on innate fundamental concepts or categories in minds such as space and time to organize and interpret sense experience. Humans can actively link experiences according to cause and effect, which are categories that are hard to be generated from experience. Social constructionism like Berger and Luckmann argue that knowledge including commonsense derives from and evolves through social interactions [3]. *The $CP^3$SME methodology argues that experience, reason and social construction contribute to the formation of mind from different facets and scales*.

*Semantic linking through spaces extends experience, reason and social construction to more spaces*. Semantics emerges and evolves with various interactions through multiple spaces. Reasoning will be complex and will pass through spaces. New philosophical issues will arise in $CP^3$SME research as the world people live and the way people interact with each other have been changed greatly with the generation and evolution of various spaces. The scientific pursuit of the $CP^3$SME brings challenging philosophical issues.

*Form and semantics constitute a dimension of the $CP^3$SME*. All things in other spaces can be viewed as forms from the mental space. Features and structure are forms. An apple in the physical space we observed is form, its image in the cyber space is form, its weight and price in the socio space are forms, the word "apple" in the symbol space is form, and the brain signal reflection is also form. One form can be constructed by several forms. Only the mental space has the ability to emerge and explain socio semantics since the mental space has been reflecting various spaces and carrying out reasoning in lifetime. One form may be used to indicate different semantics by different individuals, and different forms may be used to indicate the same semantics.

*Semantic images emerge and evolve with continuous reflection and reasoning while co-experiencing in various spaces*. The generation and evolution of spaces can be regarded as a continuous classification process. So, classification, link, rule and reasoning are the basic form of the $CP^3$SME.

The following are some principles on form, semantics and interaction:

(1) *Operations on forms get forms*. This indicates that semantics cannot be got by operating forms, and that machines are limited in ability to generate social semantics by processing symbols without the participation of mental space, physiological space and psychological space. The explanation of computing results also relies on cooperation of multiple spaces.
(2) *Emerging semantic images through experience and reason*. Semantic images emerge and evolve when forms are sensed, classified, linked, and reasoned according to the existing semantic images in the mental space.
(3) *Differences in emerging semantics*. Different semantic images may emerge when a form is sensed by different individuals because they have different experience.
(4) *Richness in emerging semantics*. Forms in more spaces provide richer experience for indicating semantic images. A semantic link network of forms can help individuals emerge semantic images. For example, a semantic link network of words and images can render semantic image better than just one word.
(5) *Similarity in emerging semantic images*. Two individual mental spaces can emerge similar semantic images about one form, and the similarity can be increased through an interaction process. Usually such an interaction process just needs several questioning and answering steps.

(6) *A little interaction goes a long way*. A little interaction helps a lot in understanding since interactions enable individuals to co-experience in multiple spaces. This implies an approach to improving the current research in many areas such as the semantic web, natural language processing, and text understanding by adding a little interaction.

## 13. Summary

How the ideal environment human beings live and work is like, what are its distinguished characteristics and basic laws, and what is the basis of future intelligence are fundamental scientific issues. The $CP^3SME$ is a complex space, where diverse spaces emerge, evolve, compete and cooperate with each other. It aims at an ideal environment for human beings to live and work, and concerns diversity, dynamicity, harmony and sustainability. Linking within and through spaces, emerging semantic images, and reasoning at different levels and facets are basic motions of the environment.

The following are four levels of pursuits of semantic linking.

(1) Extending the hyperlink network to support some preliminary intelligence such as guided browsing, query implicit relations, question answering and explanation by introducing a semantic space and reasoning mechanisms such as relational reasoning, analogical reasoning, inductive reasoning, and complex reasoning.
(2) Establishing a self-organized semantic networking model to support basic socio intelligence with some distinguished features such as self-organized peer-to-peer linking and high-performance routing, semantic communities and emerging principles, pervasive and effect-aware linking, and link recommendation.
(3) Realizing semantic lens by integrating with the multi-dimensional classification space [89].
(4) Exploring the general linking methodology. This concerns new philosophical thinking, interactive computing model, nature of the complex linking such as dynamicity, symmetry and rules of various flows, the methods for improving various closed loops, and the methods for coordinating spaces, controlling and predicting evolution.

Machine intelligence, human intelligence, and socio intelligence are extended in the complex space by linking within and through spaces, forming and improving the closed loops of complex links and flows through sensing, classifying, emerging, computing, communicating, interacting, controlling, behaving, and reasoning. The methodology of linking through spaces for cyber-physical-socio intelligence includes new models, principles, mechanisms, scientific issues, and philosophical explanation.

The ideal of Bush has been realized with the development of the Web and various advanced Web applications. The ideal of Gray's personal memex and world memex will be realized in the near future with the development of the next-generation Web. But it is still hard to realize Turing's ideal on intelligent machine.

Exploring the $CP^3SME$ will go beyond Turing's ideal since traditional machines and the cyber space are limited in ability to realize the $CP^3SME$ and cyber-physical-socio intelligence. In $CP^3SME$, research objects and conditions of many disciplines will be changed. Methodologies in respective disciplines are not suitable for researching and developing the environment. A multi-disciplinary methodology will lead to breakthrough in sciences, technologies, engineering and philosophy.

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