Chapter 1

The Knowledge Grid Methodology

The development of science and technology has extended human behavior and sensation, accelerated the progress of society, and enabled people to understand the physical space and themselves more profoundly. But, we still have much to find out, especially about knowledge.

What is knowledge?
How is knowledge generated?
How does knowledge evolve?
Can knowledge be inherited?
How is knowledge shared effectively?
How is knowledge stored and retrieved?
How to enable machines to obtain knowledge so that they can act intelligently?
How to create an environment to enable, facilitate, or improve knowledge creation, evolution, inheritance, sharing and service?

These are fundamental philosophic, scientific and technologic issues relevant to the Knowledge Grid methodology.

1.1 The Knowledge Space — Knowledge as a Space

Knowledge is a multi-dimensional complex space, where dimensions emerge, evolve structures (from simple to complex, or from complex to simple at higher abstraction level), and influence each other. A dimension can be viewed as a space, and a space can be viewed as a dimension. The dimensions include time, the physical space, the socio space, and the mental space. Each space includes individuals, structures, rules and statuses. The mental space reflects the other spaces, builds mental semantic images, and carries out reasoning while various individuals interact with each other. A point in the space is the reflection of a set of individuals, which share one set of projections on all dimensions.

According to the new notion, knowledge is not just in the mental space, it is reflected by the cyber space, physical space and social space, and it evolves with the interaction between individuals in various spaces. Minds can reflect, discover and link knowledge in these spaces through experiencing and thinking. Machines can help discover some rules in the cyber space by statistical approaches.

The knowledge space has the following characteristics.

(1) *There are multiple origin points*. The first one is the generation of the physical space and time. The generation of mind and society is the remarkable point of the development of human beings.
(2) *A dimension can be linear or nonlinear structure of coordinates*. A coordinate can be a tree structure. A dimension can be as simple as time or as complicated as a large-scale complex system. A dimension can be regarded as a space.
(3) *Projections of points on dimensions evolve with time*. Some points do not have projections on some dimensions at certain time. For example, some rules in the physical space have no projection on the dimension of the mental space. Therefore, these rules are currently unknown.

(4) *Projection on some dimensions may concern a complex process*. For example, the projection of a point onto the dimension of the mental space involves in a complex process of perception, learning, communication, association, and reasoning.

(5) *Knowledge transition between individuals also involves in the processes in and through multiple spaces*.

Fig. 1.1.1 depicts a knowledge space, where O_0 denotes the origin of generating the universe and time, and O_h denotes the origin of generating the mental space and the social space. The generated spaces evolve with time according to different rules.

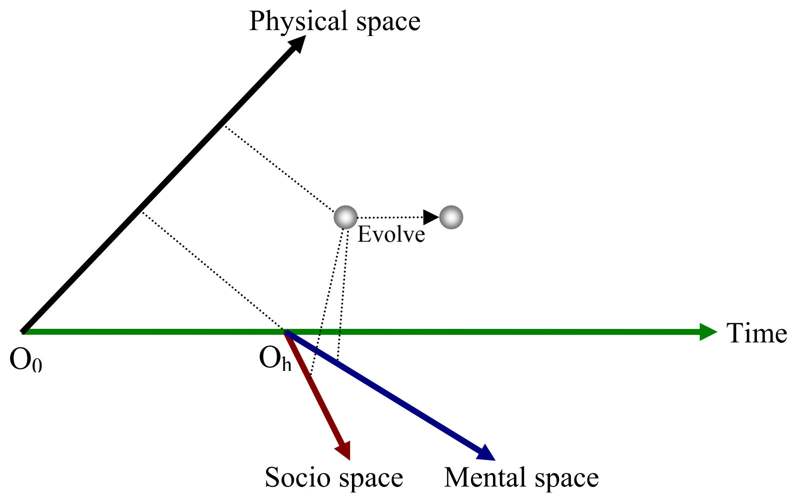

Fig. 1.1.1 A macroscopic knowledge space.

This notion of knowledge space extends the generation of knowledge not only to the origin of the mental space and the socio space but also to the origin of the physical space and time. The notion implies that knowledge is not only subjective but also objective, not only in individual mental processes but also in social processes. The links between knowledge points in and through spaces play an important role in forming and evolving the space structure.

This knowledge space notion opens new door to explore knowledge.

The generation of any space accompanies the creation of its dimensions. The evolution of spaces accompanies the expansion or shrink of dimensions. *A dimension can be viewed as a space from its coordinates*. *A space can be viewed as a dimension from its super-space*.

Fig.1.1.2 depicts the generation of new spaces through time. The socio space, mental space, psychological space, physiological space, and artifact space are generated largely at the same time, and then they evolve and influence each other continuously.

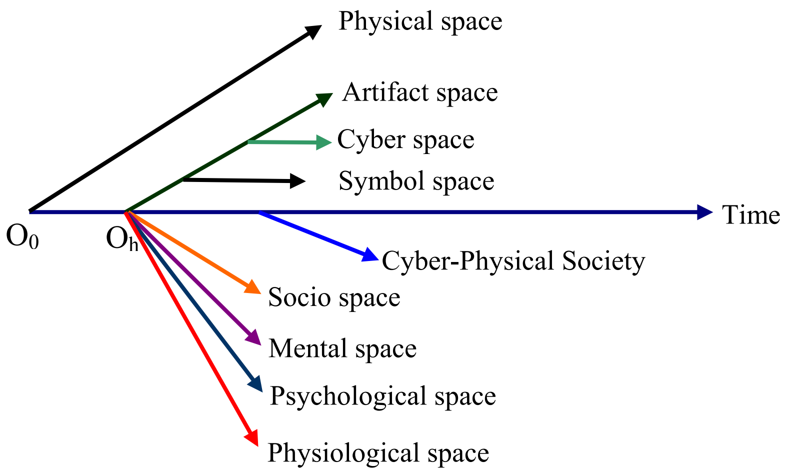

Fig.1.1.2 Generation and evolution of various spaces.

With the development of society, the artifact space keeps including new artifacts. The remarkable artifacts in the history include stone tools, iron tools, steam engines, electricity, computers, and the Internet. The cyber space is separated from the artifact space with the development of the Internet, World Wide Web and various communication devices.

The physiological space is a complex system that provides nutrition and energy for behaviors and generates the physiological motivation (e.g., generating the motivation of eating). It links self, mind and behaviors. Linking the spaces enable individuals to intelligently behave in the physical space and in the socio space. For example, it is hard for people to imagine the taste of Chinese foods without tasting them. That is, without the experience in the physical space, physiological space and psychological space, a knowledge point (a point in the knowledge space) cannot coordinate the projections into different spaces and cannot make the projection in the mental space.

These spaces can be abstracted as various networks consisting of various types of nodes and links. For example, the socio space can be abstracted as a network of human individuals and social relations, the physical space can be abstracted as a network of physical objects and relations reflecting social relations and distances or gravity in the physical space, the mental space can be abstracted as a network of concepts and semantic links (e.g., co-occur and cause-effect), and the symbol space can be abstracted as a network of symbols and the relations between symbols. There are multiple networks in the same space. Different networks obey different rules of connection. Links between individuals in different spaces (e.g., the correspondence between concepts, symbols and physical objects) connect these spaces.

The relation between mind and time was studied (B. Libet, Mind Time, Harvard University Press, 2005). Unconscious autonomous behaviors were found. From the viewpoint of cyber-physical-social intelligence, this is the effect of the physiological space. Relevant research helps understand the formation, effect and rules of knowledge and intelligence.

The physical space can contain various sub-spaces. Humans have created many artificial spaces that provide various services. One artificial space can contain the other. An artificial space belongs to both the physical space and the social space because they have both physical characteristics and social characteristics.

Some artificial spaces such as house, car, train and plane are for long-term use. Some artificial spaces such as meeting, matching and queuing are temporal for work and live. People constantly move from one space into another by making use of the functions of various spaces to fulfill various purposes in lifetime. Fig. 1.1.3 depicts the process of using some artifact spaces when traveling from home to conference hotel.

With more and more spaces being created, human behaviors are becoming more and more space-oriented, and have been extended and restricted by the capacities of various spaces.

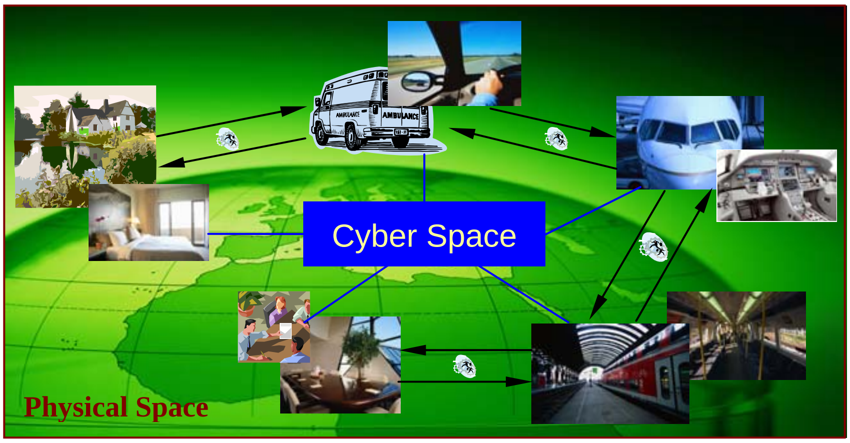

Fig. 1.1.3. The process of using various artificial spaces when traveling.

Various artificial spaces will be connected to the cyber space so that the statuses of the spaces including the statuses of physical parameters, functions, and inside individuals can be accessed and controlled under certain conditions. This is very useful for searching particular individuals with the space in some cases like security because individuals with various spaces are different from individuals or spaces. For example, person in car is different from person in plane. A hijacked plane could be remotely controlled in time through the autopilot system in the cyber space. The person who asks for help can be detected together with the space in time so that appropriate measures can be taken, because different spaces need different measures.

Newly created spaces such as new telescope and space craft could provide new means for humans to explore and reflect the physical space and therefore generating new knowledge. The process of creating spaces and using space is the process of generating and verifying knowledge.

Spaces can also be conceptual, including various mathematical theories and models as well as literature works.

The knowledge space evolves with the expansion and evolution of various artifact spaces through the interaction between the physical space and the mental space.

The cyber space will be able to reflect the temporal spaces (the status, structure and rules) for efficient retrieval. New spaces like the cyber-physical-social space will be generated with the interaction between the cyber space, physical space, psychological space, physiological space, socio space, and mental space.

Regarding knowledge as a space implies that all knowledge operations should be on the knowledge space or a point in the space, and that the space evolves with the evolution of its dimensions and various interactions between individuals (including subjects and objects) in the space. This raises new scientific problems for studying AI, especially in knowledge acquisition, reasoning, using, and explanation.

In contrast, information is objective, and it reflects the status or formation process of objects.

According to this notion of knowledge, any question and answer should enable the involved individuals to link to a set of relevant points in the knowledge space. Answers to a question at different times may be different due to the evolution of the knowledge space.

Traditional symbol representation of knowledge is limited in ability to represent knowledge effectively because the symbol space is just one dimension of the knowledge space. On the other hand, static representation is hard to reflect the evolution of the knowledge space.

To represent knowledge needs multiple types of links so that symbols can be linked not only to symbols but also to the individuals, behaviors, events and classes in multiple spaces (H.Zhuge, Semantic linking through spaces for cyber-physical-socio intelligence: A methodology, *Artificial Intelligence*, 175(2011)988-1019). Chapter 2 will further study this issue.

In the proposed models and methods, knowledge refers to the knowledge space or a point in the knowledge space.

1.2 The Cyber Space

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

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 (V. Bush, As We May Think, *The Atlantic Monthly*, 176(1)(1945)101-108). Since then, scientists have been pursuing an ideal cyber space.

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 (J. Gray, What Next?: A Dozen Information-Technology Research Goals, *Journal of ACM*, 50(1)(2003) 41-57). He raised a challenge aim of enhancing the cyber space.

The Internet and the World Wide Web are milestones of developing the cyber space. A global cyber space is forming with continuous development and fusion of the Internet and various sensory and mobile devices. People have become increasingly reliant on it for supporting modern work and life. For example, scientists are linked one another by many Web-based systems such as email, net conversation, net forums, blogs, and facebook, share their experimental data and research results through Web 2.0 or on personal or corporate websites, and retrieve technical reports and scientific papers of interest to them from online digital libraries or from less formal websites using general-purpose search engines or vertical search engines.

Web 2.0 is an interactive information sharing platform based on the Web. Social-networking sites like facebook, video-sharing sites, wikis, blogs, mashups and folksonomies are its examples. It enables users who do not know any markup language to easily publish symbols on the Web. Wikipedia has become the largest web-based multilingual encyclopedia. Its contents are contributed and freely accessible by Web users. The other characteristic is its massive effect, which accelerates the formation of online communities. Some researchers have used the Wikipedia as a collective knowledge base to improve current approaches.

Database system research will evolve with the development of the computer architecture, software architecture, and computing model. Traditional data management in a single system may be changed to the management of semantics-rich contents and services in the cyber space. One of the research issues suggested by the Claremont report (*Communications of the ACM*, 52(6)(2009)56-65) is to develop non-relational data models.

The exponential growth and intrinsic characteristics of the cyber space and its resources prevent people from effectively and efficiently sharing contents. Much effort has been put into solving this problem with but limited success. In any case it is hard for the cyber space to provide intelligent services because the representation of its resources does not support machine understandable semantics.

With the development of communication facilities and Web applications, computing is developing from individual to group and social behavior, from closed to open systems, from simple and centralized to complex and distributed computing, and from static computing to dynamic and mobile services of content, computing and knowledge.

1.3 Effort toward Intelligent Interconnection Environment

Modern communication facilities such as the Internet and mobile devices provide people with unprecedented social opportunities and technical basis for promoting knowledge generation, sharing, inheritance and management. However, our increasing computing power and communication bandwidth do not of themselves improve this knowledge generation, sharing, inheritance and management. To deal with this, a new environment is needed, and the semantic ability of the facilities that project, transmit, store and evolve knowledge must be improved.

Turing described computer intelligence as a machine that can learn from experience and can alter its own instructions (A. M. Turing, Computing Machinery and Intelligence, *Mind*, 59(236)(1950)433-460). So far, machines still do not have these abilities.

Engelbart proposed a conceptual framework for the augmentation of man's intellect (D. C. Engelbart, A Conceptual Framework for the Augmentation of Man's Intellect, In Vistas in Information Handling, vol.1, Spartan Books, London, 1963). He designed the system H-LAM/T (Human using Language, Artifacts, and Methodology, in which he Trained). His aim is still significant in current artificial intelligence research.

Improving social interaction would help improve knowledge creation, evolution and sharing in our society by supporting and optimizing social activities at multiple levels (both the physical level and the mental level) *and in multiple environmental spaces* (cyber space, physical space, mental space, and socio space).

To overcome the deficiencies of the cyber space, scientists and developers are making great effort towards an intelligent interconnection environment. These efforts lie in the following categories:

The first is on the Web includes the *Semantic Web*, *Web Service*, *social Web*, *Web x.0* and *Web of things*, which aim to improve the current Web to different extents.

The second includes the *Grid computing* and *Cloud computing*, which aim at building a new computing platform over the Internet to provide advanced computing services from optimization and economy point of view.

The third is *Peer-to-Peer (P2P) computing*, which enables resource sharing in an egalitarian, large-scale and dynamic network.

The fourth is the *Mobile Web* and *Second Life*, which enable people to interact and share information cross geographical space through wireless and virtual roles. Time and space information is critical in these applications.

Recent developments indicate that all are indeed moving to closer targets.

The fifth is the Cyber-Physical Society, the Cyber-Physical Socio Environment, or the Cyber-Physical-Socio Intelligence (www.knowledgegrid.net/~h.zhuge/CPS.htm), which is to link the cyber space, physical space, socio space and mental space to extend human ability in these spaces.

Semantics is the basis for building intelligent applications on the Web. The *Semantic Web* is to support cooperation between Web resources by establishing ontological and logical mechanisms in standard markup languages like XML (eXtensible Markup Language, www.w3.org/XML), RDF (Resource Description Framework, wwww.w3.org/RDF), and OWL (Web Ontology Language, www.w3.org/TR/owl-features/) to replace HTML (HyperText Markup Language) and to allow Web pages to hold the descriptions of their contents. Research integrates the development of Web standards with such areas as data modeling, artificial intelligence, data mining and information retrieval. The linked data suggested by Tim Berners-Lee is a technique of exposing, sharing, and connecting data via URIs on the Web. It employs RDF and HTTP (Hypertext Transfer Protocol) to publish structured data on the Web and to connect data between data sources, allowing data in one data source to be linked to data in another data source.

The Web provides the opportunity for the development of traditional information technologies. Many applications have been done on the Web by using artificial intelligence and information processing technologies such as symbolic reasoning, logics (e.g., description logics), text mining, text summarization, information extraction, and information retrieval.

The *Web Service* is to provide an open platform for the development, deployment, interaction, and management of globally distributed e-services based on Web standards like UDDI (Universal Definition Discovery and Integration) and WSDL (Web Service Description Language, www.w3.org/TR/wsdl). It enables the integration of services residing and running in different places. Intelligent agent technique can be used to implement the active Web services. Service-oriented architecture (SOA) is to support the development of service-oriented applications. It has been widely accepted in software engineering. To systematically study service systems as a complex system, service science is introduced as a discipline cross computer science and management science.

The idea of *Internet of Things* and *Web of Things* is to integrate versatile things in the world into the Internet and Web so that things can be accessed via the standard Internet/Web protocols. The problem is that the things become digital Web resources like Web pages once they are represented by a certain language (Internet/Web languages) on certain aspect. Most physical characteristics will disappear. So, *the key should be the interaction between things rather than just representation or integration of things*.

Web 3.0 was suggested to incorporate some characteristics of the Web, Semantic Web and artificial intelligence. Web x.0 would be the trend of Web research community. Web science is introduced by summarizing relevant research works on the Web (T. Berners-Lee, et al., A Framework for Web Science, Now Publishers Inc, 2006).

The aim of the global *Grid* is to share, manage, coordinate, schedule, and control distributed computing resources, which could be machines, networks, data, and any types of devices. The ideal of the Grid is that any compatible device could be plugged in anywhere on the Grid and be guaranteed the required services regardless of their locations, just like the electrical power grid. Grid computing initially does not use Web technologies. The Grid architecture has become the service-oriented Open Grid Services Architecture (OGSA), in which some features of Web Service can be plainly seen (I.Foster, et al., Grid Services for Distributed System Integration, *Computer*, 35(6)(2002)37-46; I. Foster and C.Kesselman, The grid2: blueprint for a new computing infrastructure, Elsevier, 2008).

The *Peer-to-Peer* networking should work not only at the computing level but also at the semantic level. How to automatically map a semantic space into a peer-to-peer network is an important research problem that must be solved before the gap between the peer-to-peer network and high-level intelligent applications can be bridged (D. Schoder and K. Fischbach, Peer-to-Peer Prospects, *Communications of the ACM*, 46(2)(2003)27-29; H.Zhuge and X.Li, Peer-to-Peer in

Metric Space and Semantic Space, *IEEE Transactions on Knowledge and Data Engineering*, 19 (6) (2007) 759-771; H.Zhuge and X.Sun, A Virtual Ring Method for Building Small-World Structured P2P Overlays, *IEEE Transactions on Knowledge and Data Engineering*, 20 (12) (2008) 1712-1725).

The *Semantic Grid* (H.Zhuge, Semantic Grid: Scientific Issues, Infrastructure, and Methodology, *Communications of the ACM*, 48(4)(2005)117-119) attempts to incorporate the advantages of the Grid, Semantic Web and Web Service approaches. By defining standard mechanisms for creating, naming, and locating services, the Semantic Grid can incorporate peer-to-peer technology under Open Grid Service Architecture OGSA, and so it enables autonomous computing objects to cooperate in a network of equals and with scalability.

The *Cloud computing* is becoming hot in recent years. There are several different views. According to IBM's report, cloud computing is user-oriented and offers highly efficient acquisition and delivery of IT and information services. It is characterized by massive scalability, superior user experience, and Internet-driven economics. Some views refer it to both the applications delivered as services over the Internet and the hardware and system software in the data centers that provide those services. Cloud computing views infrastructure, platform and software as a service (SaaS). An obvious benefit is the reduction of cost for users. Different from Grid computing, cloud computing obtains the support from industry sector. In 2009, several UC Berkeley professors proposed their visions on cloud computing "Above the Clouds: A Berkeley View of Cloud Computing". Cloud computing can be seen as the development of client/server architecture and the implementation of McCarthy's ideal that computation may someday be organized as a public utility, which was pointed out in 1960. It would be interesting to integrate Cloud computing, Grid computing, and P2P computing to benefit from all of their advantages.

The *Mobile Web* enables users to access Web contents by mobile devices. The number of mobile Web users surpassed the number of PC-based Internet users for the first time in 2008. Besides the reliability and accessibility issues, how to map the data formats of content providers onto the specifications of mobile devices is an implementation issue. The approaches to index moving objects have been studied (D.P.Foser, C.S. Jensen, and Y.Theodoridis, Novel Approaches to the Indexing of Moving Object Trajectories, VLDB2000, pp.395-406). The mobile Web changes the information sharing paradigm. A changing physical location and the context become important factors of mobile information services. A context includes computing environment, social environment, and physical environment. Capturing context in real time and representing context is critical for context-aware applications, but machines are limited in ability to make sense on context as they only behave according to human instructions.

The *Second Life* is to establish an online interactive 3D virtual space mixing the real-world objects and virtual objects. Objects and events in the virtual world may be captured from the physical world by various sensors and mobile devices. Interaction in the mixed space may influence both the virtual world and the real world. A key technical issue is how to manage large amount of events and communications among concurrent users. The Second Life will play an important role in training and entertainment. It may form a virtual society mirroring the real society. So far, it is still at the level of man-machine interaction.

The National Science Foundation CPS Summit defines Cyber-Physical Systems as *physical and engineered systems whose operations are monitored, coordinated, controlled and integrated by a computing and communication core*. Researchers from multiple disciplines such as embedded systems and sensor networks have been actively involved in this emerging area. In the future, infrastructure will be regarded as a service (IaaS).

Different from the Cyber-Physical Systems, the Cyber-Physical Society focuses more on human and society. The integration of the physical space, cyber space and mental space was early envisaged in the *future interconnection environment* (H.Zhuge, The Future Interconnection Environment, *Computer*, 38(4)(2005)27-33) as follows: "*The physical, virtual, and mental worlds will interact and evolve* *cooperatively*". The physical world was defined as *nature, natural and artificial materials, physical devices, and networks*. The virtual digital world was defined as *the perceptual environment constructed mainly through vision (text, images, color, graphs, and so on) and hearing, and to some extent touch, smell, and taste*. The mental world was defined as *ideals, religions, morals, culture, arts, wisdom, and scientific knowledge, which all spring from thought, emotion, creativity, and imagination*.

The physical space provides the material basis for the generation and evolution of human beings and civilization. The progress of human society created the cyber space, which is linking the physical space and the other spaces to form a complex space. Human abilities will be extended in the complex space.

1.4 Challenge and Opportunity

The development of operating systems, advanced languages, and database systems were crucial events in computing history, and were also very important to the success of personal computing. The Internet and its applications are moving towards a scalable computing. But, the current Internet application platform is still far from an ideal intelligent interconnection environment.

Demanding application requirements provide researchers with many challenges and opportunities. Complex, mobile, intelligent and personalized applications require the support of completely new data models (e.g., the model based on multi-dimensional classifications H.Zhuge and Y.Xing, Probabilistic Resource Space Model for Managing Resources in Cyber-Physical Society, *IEEE Trans. on Service Computing*, http://doi.ieeecomputersociety.org/10.1109/TSC.2011.12), programming languages, operating systems and computing platform to support massively distributed sharing, coordination, deployment, parallel execution and management of dynamic services and resources, and the implementation of applications that are beyond the ability of the current Internet.

Fig. 1.4.1 depicts the evolutionary trend of computing, where WoT/IoT (Web of Things or Internet of Things), Web x.0, and Cyber Physical Systems (CPS) would extend to the phase of Cyber-Physical-Socio-Mental Environment CPSME, which contains the cyber space, physical space, socio space and mental space.

The intelligent interconnection environment (Cyber-Physical-Socio-Mental Environment) can exhibit its potential if it can be based on an advanced computing platform, which supports new resource organization models, new computing models, and new networks incorporating the Internet with information capturing, mobile, and wireless devices.

A key component of the new computing environment is the *interactive semantics* that enables interaction among services, humans, and platforms (H.Zhuge, Interactive Semantics, *Artificial Intelligence*, 174(2010)190-204). The improvement of computing architecture can improve the approach to efficiently obtain information, but it does not help understand information, neither the interaction among various resources. *The interactive semantics regards interaction as the foundation of generating semantics in society*. This proposition was then partially explained by social scientists (L.G.Dean, R.L.Kenda, S.J.Schapiro, B.Thierry, and K.N.Laland, Identification of the Social and Cognitive Processes Underlying Human Cumulative Culture, Science, 335(6072)(2012)1114-1118).

The future computing environment will evolve in a multi-dimensional space as shown in Fig.1.4.1.

A computing environment can have mappings at different dimensions. Mapping a computing environment into the physical dimension can obtain the physical characteristics, relations and measures. Mapping a computing environment into the social dimension can get the social characteristics, relations and measures.

This model puts the evolution of the computing environment into the multi-dimensional space for the first time, therefore opens a new door to studying the future computing environment.

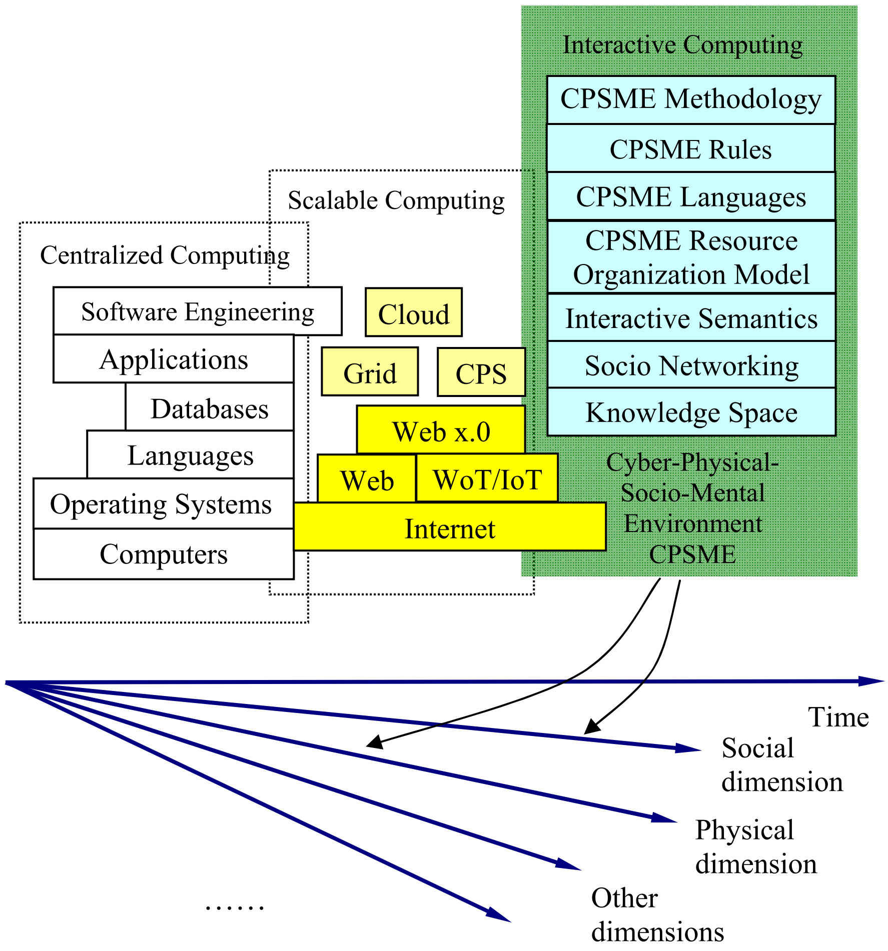

Fig. 1.4.1. Evolution of computing environments in a multi-dimensional space.

The *Cyber-Physical Society* is defined as *a multi-dimensional complex space that generates and evolves diverse subspaces to contain different types of individuals interacting with, reflecting or influencing each other directly or through the cyber, physical, socio and mental subspaces. Versatile individuals and socio roles coexist harmoniously yet evolve, provide appropriate on-demand information, knowledge and services for each other, transform from one form into another, interact with each other through various links, and self-organize according to socio value chains. It ensures healthy and meaningful life of individuals, and maintains a reasonable rate of expansion of individuals in light of overall capacity and the material, knowledge, and service flow cycles* (H.Zhuge, Semantic linking through spaces for cyber-physical-socio intelligence: A methodology, *Artificial Intelligence*, 175(2011)988-1019; H.Zhuge, Cyber Physical Society, *1st International Workshop on Cyber-Physical Society*, in conjunction with *the 6th International Conference on Semantics, Knowledge and Grids*, 2010, China).

The *cyber space* consists of various devices and digital resources, mechanisms for transforming digital resources through the devices, and various structures and algorithms for efficiently providing rich services for humans. The Web has become the largest cyber space in the world containing rich contents in various languages.

The *physical space* contains physical resources (or objects) evolving, moving and transforming from one form into another according to physical laws. Resources can be linked through such relations as distance and gravity or classified from physical structures or features.

The *socio space* includes individuals (human, agent, behaviour, event, etc), structures, and rules. Individuals are self-organized into classes according to economic, politic, or cultural statuses. Social networks can be a complex network with complex flows through complex nodes.

The *mental space* reflects various individuals in different spaces as semantic images, and operates the semantic images. The basic semantic image is concept. Concepts can be composed to form commonsense, rules, methods and theories. Chapter 2 will further discuss this issue.

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

1.5 The Knowledge Grid Environment

1.5.1 The notion

The ideal of the Knowledge Grid is to foster knowledge creation, evolution, inheritance, and sharing in a sustainable environment of humans, events, physical objects, cyber resources, machines and roles (H. Zhuge, China's e-Science Knowledge Grid Environment, *IEEE Intelligent Systems*, 19(1)(2004)13-17; H.Zhuge, The Future Interconnection Environment, *Computer*, 38 (4)(2005)27-33).

The Knowledge Grid is an environment consisting of autonomous individuals in multiple spaces, self-organized semantic communities, adaptive networking mechanisms, and evolving semantic networking mechanisms. It maintains meaningful connections between individuals, various flows for dynamic resource sharing, mechanisms for managing resources effectively, and appropriate knowledge services for problem solving and innovation. It supports innovation and harmonious development of science, technology and culture. (H. Zhuge, The Knowledge Grid Environment, *IEEE Intelligent Systems*, 23(6)(2008) 63-71).

The *Knowledge Grid methodology* is a multi-disciplinary system methodology for developing various Knowledge Grids that obeys cyber, physical and social principles, rules and laws.

Since the publication of the first edition of The Knowledge Grid in 2004, great progress has been made in the computing area. The progress will benefit Knowledge Grid research greatly. Implementation of the Knowledge Grid ideal will speed up the development of human civilization.

The following is a brief history of Knowledge Grid development.

An initial Knowledge Grid system was developed for sharing and managing various resources (documents, comments, questions, and answers) on the Web (H. Zhuge, A knowledge grid model and platform for global knowledge sharing, *Expert Systems with Applications*, 22(4)(2002)313-320). Resources are classified by multi-dimensional resource space, where a knowledge dimension classifies knowledge into the following classes: *concept*, *axiom*, *rules* and *method*. Users can accurately put resources into categories and get resources from a category according to the categories in mind. Users are responsible for determining and maintaining the categories of resources. The idea of multi-dimensional classifications was then developed into a systematic Resource Space Model for managing various resources (H.Zhuge, The Web Resource Space Model, *Springer*, 2008; H.Zhuge, Y.Xing and P.Shi, Resource Space Model, OWL and Database: Mapping and Integration, *ACM Transactions on Internet Technology*, 8/4, 2008). One distinguished characteristics of the multi-dimensional space is the ability of specialization and generations on multiple dimensions.

Then, the Knowledge Grid idea was developed to include dynamic knowledge management due to the following motivation: *knowledge is generated, shared and evolved in a flowing process rather than static symbol representation* (H. Zhuge, A knowledge flow model for peer-to-peer team knowledge sharing and management, *Expert Systems with Applications*, 23(1)(2002)23-30; H.Zhuge, Discovery of Knowledge Flow in Science, *Communications of the ACM*, 49(5)(2006)101-107). In contrast, traditional knowledge-based systems focus on the codification of knowledge, management of the statically codified knowledge in knowledge base, and provision of knowledge based on symbol reasoning.

The implementation of Knowledge Grid needs a scalable, self-organized, high-performance and decentralized semantic computing, and communication platform for supporting decentralized knowledge sharing

(H.Zhuge, et al, A Scalable P2P Platform for the Knowledge Grid, *IEEE Transactions on Knowledge and Data Engineering*, 17(12)(2005)1721-1736; H.Zhuge, Communities and Emerging Semantics in Semantic Link Network: Discovery and Learning, *IEEE Transactions on Knowledge and Data Engineering*, 21(6)(2009)785-799).

The following statements help distinguish the ideal of Knowledge Grid from others.

Knowledge Grid environment ≠ *Knowledge discovery* + *Grid computing*.
Knowledge Grid environment ≠ *Knowledge base* + *Grid computing*.
Knowledge Grid environment ≠ *Distributed data mining*.
Knowledge Grid environment ≠ *Distributed knowledge base*.

The above notion of the Knowledge Grid is essentially different from other notions of applying AI techniques (e.g., knowledge extraction, mining, and synthesis) to large data sets. Berman's idea has no essential difference from traditional AI problems (*Communications of the ACM*, 44(11)(2001)27-28). Cannataro and Talia's idea (*Communications of the ACM*, 46(1)(2003) 89–93) is similar to the distributed data mining (C.Clifton, et al., Tools for Privacy Preserving Distributed Data Mining, *ACM SKGKDD Explorations Newsletter*, 4(2)(2002)28-34).

The Knowledge Grid environment has the following distinguished characteristics.

1.5.2 *Virtual characteristic*

Many computer scientists are exploring ideal computing and resource organization models for the future interconnection environment. The editorial of the first special issue on Semantic Grid and Knowledge Grid for the *Future Generation Computer Systems* journal (20(1)(2004)1-5) described the following scenario: The future interconnection environment will be a platform-irrelevant *Virtual Grid* consisting of requirements, roles and resources. The Knowledge Grid will be such a virtual Grid, which concerns knowledge, knowledge sharing, and principle of knowledge sharing.

Humans can effectively share knowledge no matter whether computers are used or not. Actually, various human-level knowledge grids work in our society no matter whether people are aware of this or not. So, Knowledge Grid research should go beyond the scope of traditional computing area.

With machine-understandable semantics, resources in the cyber space can actively and dynamically form clusters to provide on-demand services by understanding requirements and functions. Versatile resources can be encapsulated to provide services by way of a *single semantic image*. The cyber space could intelligently assist people to accomplish complex tasks and solve problems by organizing versatile resource flow cycles through virtual roles to use appropriate cyber, physical and socio resources.

With the development of society and science, people have more profound understanding of the nature, society, and themselves than ever. So, appropriate rules and principles of the nature, society and economics should be adopted when we develop the Knowledge Grid as an intelligent interconnection environment.

1.5.3 *Social characteristic*

The Knowledge Grid has social characteristics. In the real world, people live and work in a *Socio Grid* obeying social and economic rules. The Knowledge Grid is a *socio grid environment*, where people enjoy and provide services through versatile flow cycles like control flows, material flows, energy flows, information flows and knowledge flows. People can communicate with and gain knowledge from each other through mutually understandable interactive semantics.

An artificial interconnection environment can only be effective when it works harmoniously with the physical space and the socio grids. For example, an effective e-business environment requires harmonious cooperation between information flows, knowledge flows, material flows, e-services, and social services. The e-services belong to e-business platforms. The material flows and social services belong to the physical space and social space. The information flows and knowledge flows belong to both the social space and the cyber space. Interactions between individuals in the socio grid and the cyber space are based on an interactive semantics.

In future, different artificial interconnection environments will co-exist and compete with each other for survival, rights and reputation, and will harmoniously evolve with the *cyber-physical-socio grid* (H.Zhuge and X.Shi, Eco-grid: A Harmoniously Evolved Interconnection Environment, *Communications of the ACM*, 47(9)(2004)79-83).

Social networking is regarded as one of top 11 technologies of the decade (IEEE Spectrum, Jan, 2011). Some researchers even regard social networking and relevant research as a science, which can help leverage the ability to collect and analyze data at a scale that may reveal patterns of individual and group behaviors (D. Lazer, et al. Computational social science, *Science*, 323(5915)(2009)721-723). At the current stage, the study of social networking in the cyber space can inspire research on cyber-physical-socio networking.

The ideal of the Cyber-Physical Society extends the research ground of the Knowledge Grid environment.

1.5.4 *Adaptive characteristic*

"On-demand services" is a fashionable catchphrase in the context of the future interconnection environment. But there is no limit to human demand. So, it is impossible and unreasonable to provide all participants with services on demand as long as service generation and service provision carry a significant cost and services themselves differ in quality.

Economics is concerned with three kinds of entity: *participants*, *markets* and *economic systems*. The market is an important mechanism for automatically and reasonably adjusting the decisions and behaviors of market participants, for example, agents and soft-devices (H.Zhuge, Clustering Soft-Devices in Semantic Grid, *IEEE Computing in Science and Engineering*, 4(6)(2002)60-63).

Besides the influence of the market, participants' behaviors and decisions can be adjusted by negotiation. Governments, organizations and socio rights also play important roles in influencing market participants' behaviors and decision making. Market participants, producers and consumers, look for satisfactory rather than optimal exchanges through agreement (the evaluation of "satisfactory" involves social and psychological factors). Being based on simple principles, the market mechanism adapts the interests of participants by avoiding complex computation.

The natural ecological system establishes a balance among natural species through *energy flow*, *material flow* and *information flow*. These flows in their turn influence the socio system (H. Zhuge and X. Shi, Fighting Epidemics in the Information and Knowledge Age, *Computer*, 36(10)(2003)114-116). Different species evolve together as parts of the entire ecological system.

The Knowledge Grid also supports three major roles: *producers*, *consumers* and *a market mechanism* for adapting to the behavior of different participants. It should adopt economic and ecological principles to balance the interests of knowledge producers and knowledge consumers, and adapt to knowledge evolution and expansion (H. Zhuge and W.Guo, Virtual knowledge service market for effective knowledge flow within knowledge grid, *Journal of Systems and Software*, 80(11)(2007)1833-1842).

1.5.5 *Semantic characteristic*

Semantics is the basis for people to interact with each other and with machines, and for machines to correctly understand and process various resources in the cyber space. It is generated for interaction, and evolves with complex psychological and cognitive processes. The exploitation of psychological, cognitive and philosophical issues will help study semantics.

Research on semantic information processing has a long history in the computing field (M.L. Minsky, ed., *Semantic Information Processing*, MIT Press, 1968). Knowledge representation approaches such as frame theory (Minsky, 1975), the Knowledge Representation Language KRL (D.G. Bobrow, 1979), and the Semantic Network (M.R. Quillian; H.A. Simon, 1970) are attempts to expressing semantics. Before the emergence of the Internet interchange standard XML and the Resource Description Framework RDF (www.w3.org/RDF/), the Knowledge Interchange Format KIF (www.logic.stanford.edu/kif) and Open Knowledge Base Connectivity OKBC (www.ai.sri.com/~okbc) were two standards for sharing codified knowledge.

Knowledge acquisition was the bottleneck of traditional knowledge engineering. Data mining approaches help a bit by automatically discovering some association rules in large-scale databases. These approaches can also be used to discover some links within and between texts (H.Zhuge and J.Zhang, Automatically Constructing Semantic Link Network on Documents, *Concurrency and Computation: Practice and Experience*, 61(9)(2010)1824-1841).

Why were the symbolic approaches, especially the KIF and OKBC of AI, and ODBC in the database area, not widely adopted in the Internet age? Thinking this question would implicate the right research method.

One cause is the success of HTML, which is easy to use both for a writer and, in cooperation with a browser, for a reader. Its main advantage is that "*anything can link to anything*" (T. Berners-Lee, J. Hendler and O. Lassila, Semantic Web, *Scientific American*, 284(5)(2001)34-43).

A second cause is that traditional AI's knowledge representation approaches try to explicate human knowledge, while the Web focuses on structuring Web contents and the links between contents, that is, it is easy to use and verify.

A third cause is that cooperation between machines (applications) has become the dominant aim in realizing intelligent Web applications, while traditional knowledge engineering focuses on cooperation between human and machine.

A fourth cause is the cross-platform requirement. Consequently, XML has been adopted as the information exchange standard of the World Wide Web.

A fifth cause is the tree structure of XML. Humans have used the same structure to organize the main contents of texts like book when large-scale symbols cannot be efficiently organized by sequential order. Users tend to adopt the way of interaction that is in line with habit. *So far, we still do not know the best form that is suitable for humans to understand*. This concerns the study of semantics.

What are the problems of semantics in the Knowledge Grid environment?

The first is the representation problem — to formally represent semantics is the basis of machine processing. Prior research into representing semantics should be a helpful reference, but in-depth understanding of semantics concerns cognitive processes. The first step of research should focus on understanding the rich semantic links between resources (some are explicit while others are implicit), on establishing an appropriate semantic computing model to efficiently operate semantic link networks, on the understanding of the process of forming and using semantics, and on seeking an approach that synthesizes the semantics expressed in different semantic spaces.

The second is the acquisition problem — to enable machines to automatically acquire semantics (reflection from various spaces). Resources in different spaces may have different forms. The first step of research should focus on the approaches to discover various classes, semantic links, and communities. The second step should look into various interactions in different spaces or through spaces.

The third is the normal organization problem — to properly organize semantics under a certain normal forms and the integrity constraints so that the correctness and efficiency of semantic operations is guaranteed.

If we can solve this problem, resources in the environment can be correctly organized and used in light of their semantic images.

The fourth is the problem of processing semantics — to refine, abstract and synthesize large-scale semantic images to provide appropriate and succinct semantic images. An example is to obtain the topological patterns and networking rules from social networks.

The fifth is the maintenance problem — to maintain consistency and reasonability between semantic images in the large-scale and dynamic semantic environment.

The sixth is the interaction problem — to trace, record and use the semantic images in the interaction processes is the way to get semantics as semantics evolves with interaction. This issue was discussed in detail in (H.Zhuge, Interactive semantics, *Artificial Intelligence*, 174(2010)190-204).

The seventh is the emerging semantics problem — to find the rules of emerging semantics. Some semantics can only emerge during interaction or during the evolution of semantic images rather than pre-defined. To find the emerging rules is a challenge issue.

The eighth is the generation and evolution of semantics — to find the rules of generating and evolving semantics. The semantic representations in previous researches are actually *forms* (semantic indicators) rather than *semantics*. *Semantics can be only emerged through the closed loop of experiencing in multiple spaces* (H.Zhuge, Semantic linking through spaces for cyber-physical-socio intelligence: A methodology, *Artificial Intelligence*, 175(2011)988-1019).

Current research on the Semantic Web is less than ideal because they do not fully address the above problems.

At a high level, the Knowledge Grid is a space of requirements, roles and services. Services are provided according to resources that are implemented on the basis of a uniform resource model. Services can actively find and advertise requirements. People can play the roles of services, and enjoy services provided by others. Requirements and services are organized into conglomerations that belong to different communities. Some services can play the broker role and be responsible for dynamically integrating services to meet varying requirements.

At a low level, a semantic space organizes and uses resources by way of a *single semantic image*, that is, various resources are mapped into a single semantic space to expose their commonality. Humans behave intelligently according to single semantic images of the environment. Although many ways based on logics and algebra tried to represent semantics, the single semantic image should be based on the most basic semantics that humans can easily understand and often use in daily life.

What is the most basic semantics?

(1) *Classification*. Classification is the basic intelligent mechanism of humans. Infants have the ability to classify things into two classes: *self* and *external things*. The nature of resources determines their categories. Humans have invented various tools such as bookshelf and drawer to manage physical resources, used taxonomy to manage knowledge in the mental space, and used file systems to manage digital files in the cyber space. Further, different classification methods can be used to classify a set of resources.
(2) *Link*. Various links connect individuals in the physical space, cyber space, and socio space to indicate certain semantics. For example, food web organizes living creatures where links represent material (food) flow, family relations and cooperation relations help organize individuals in society where links represent blood relation or friendship, and hyperlink connects Web pages to form the World Wide Web.
(3) *Reasoning*. Rules in cyber, physical, social and mental spaces regulate classifications and links. Various reasoning can carry out on classifications and links according to the rules. General reasoning also includes the influence on the statuses of nodes and links according to the rules.

The single semantic image could be based on the above basic semantics to uniformly reflect various resources, behaviors and events. As the basis of interaction, an interactive semantic base is introduced in

(H.Zhuge, Interactive semantics, *Artificial Intelligence*, 174(2010)190-204).

Normalizing the classification space and relational network can guarantee the correctness and effectiveness of resource operations. The semantic space requires a semantic browser that enables not only people but also services to exploit the semantics of a resource being browsed, to extract from the resource and reason from the extract, to explain the display, and to anticipate subsequent browsing.

A huge semantic gap exists between low-level semantics used in the cyber space and high-level semantics (or socio semantics) used by humans as shown in Fig. 1.5.5.1 Various ontology mechanisms and semantic computing models are ways to reduce the gap.

The Knowledge Grid will enable knowledge generation, evolution and service based on multi-level semantics and semantic computing models.

Current Web technologies and software tools only use some simple semantic indicators such as keywords (tags) and surface attributes (texture, color, and so on). Users have to search an enormous name space to find what they need within huge and expanding Web resources.

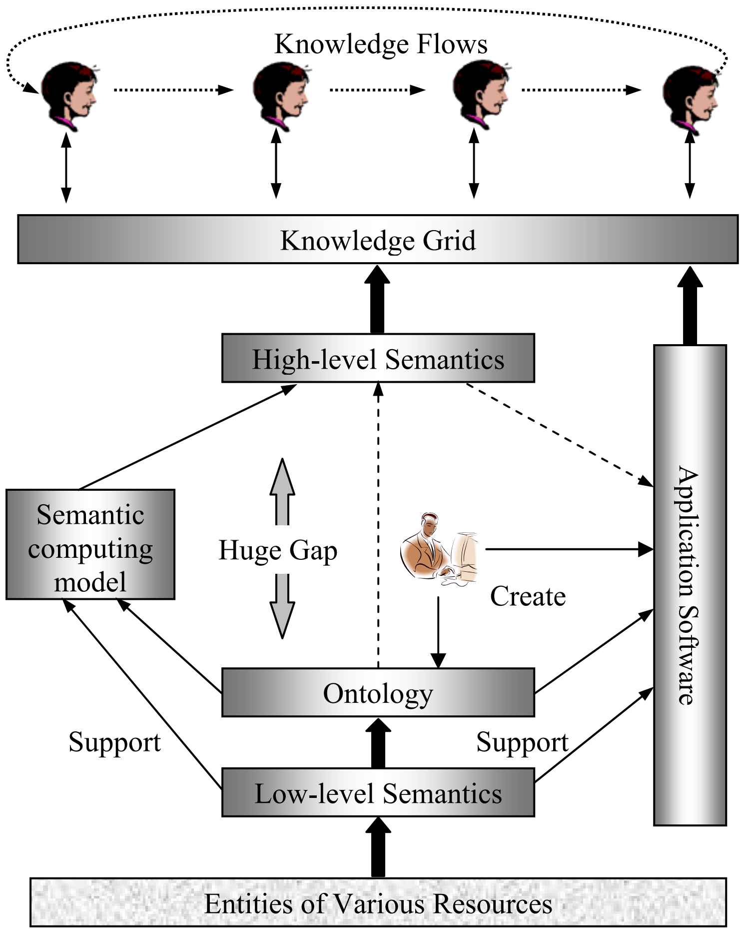

Fig. 1.5.5.1 Gap between low-level semantics and high-level semantics.

Complex cognitive and psychological processes are involved in this huge gap. Some computer scientists seek to obtain semantics by establishing domain ontology mechanisms for explaining semantics. Building tools and finding methods for creating ontology mechanisms are becoming popular in the Semantic Web area. Ontology can reflect people's consensus on semantics in the name spaces of the symbolic space to a certain extent. But it is hard to cope with the complexity of human cognitive processes.

A *semantic computing model* that could at least partly bridge this huge gap must be found. The model should go beyond the scope of traditional formal semantics, which has been extensively investigated in computer science in the past with success that is significant in theory but limited in practice. The model should balance the formal and informal and reflect human cognitive characteristics.

Semantics evolution has been accompanying socio interaction, but humans do not have profound understanding on it. Peoples in different areas have different understandings as they have been building different ontology mechanisms. Humans have created many symbol systems to represent semantics, and are pursing better semantics representation approaches to realize machine intelligence.

A key problem is: *Can semantics be correctly represented*?

Turing machines are specialized in processing symbols according to algorithms designed by humans, but they are limited in ability to understand and process socio semantics when carrying out socio interaction. This is because they do not have a semantic worldview and cannot reflect themselves.

The future intelligent interconnection environment will enable individuals to reflect themselves, effectively interact, and know socio situation through time and spaces. As it is hard to accurately represent socio semantics in a rigid, isolated and static form, the integration of a dynamic semantic link network and an evolving multi-dimensional classification space can be used as a semantic image to reflect the socio semantics (H.Zhuge, Interactive Semantics, *Artificial Intelligence*, 174(2010)190-204).

Epistemology, which has been neglected in previous efforts towards the future computing environment, plays the key role in human cognitive processes.

1.6 Epistemology and Knowledge

Epistemology is a branch of philosophy. It concerns the nature, scope and source of knowledge. Computer scientists could improve their understanding of computing by studying the history and variety of epistemology.

Empiricism sees knowledge as the product of sensory perception. Knowledge results from a kind of mapping or reflection of external objects, from our sensory organs, possibly assisted by instruments, into our brain to be used by our minds. Aristotle, Bacon, Locke and Hume are representative philosophers.

Rationalism considers knowledge to be the product of rational reflection and reasoning. Knowledge results from the organization of perceptual data on the basis of cognitive structures called *categories*. Categories include *space*, *time*, *objects* and *causality*. Rationalism is relevant to the development of mathematics. Leibniz and Kant are representative philosophers.

Pragmatism emphasizes that theory is abstracted from practice and applied to practice. It holds that knowledge consists of mental models that simplify our perception of the real world. It is assumed that a model only reflects the main characteristics of the real world. Otherwise, it would be too complicated to be of any practical use. Thus, different or even seemingly contradictory models for solving the same problem could co-exist. Problem solving is a process of developing and selecting useful models. Mathematical modeling plays an important role in scientific problem solving. Peirce is the representative philosopher.

Individual constructivism sees individual as trying to build coherence between different pieces of knowledge. In the mental construction process, knowledge that succeeded in integrating previously incoherent pieces of knowledge will be kept, and knowledge that is inconsistent with the bulk of other knowledge that the individual has will tend to be rejected.

S*ocial constructivism* regards consensus on different subjects as the ultimate criterion for judging knowledge. Truth or reality will be accorded only to those constructions on which most people of a social group agree. Karl Marx's theory of ideology can be regarded as a type of social epistemology. An ideology is a set of beliefs, a worldview, or a form of consciousness that is in some fashion false or delusive. The cause of these beliefs and their delusiveness is the social situation and interests of the believers. The theory of ideology is concerned with the truth and falsity of beliefs, so it is a kind of *classical social epistemology*. *Feminist epistemology and philosophy of science* studies the ways in which gender influences, and ought to influence, our conceptions of knowledge, the knowing subject, and practices of inquiry and justification.

Evolutionary epistemology assumes that knowledge is constructed by a subject or a group of subjects in order to adapt to their environment in the broad sense. That construction is a process going on at different levels — at biological as well as psychological or social levels. Construction happens through blind variation of existing pieces of knowledge, and the selective retention of those new combinations that somehow contribute more to the survival and reproduction of the subjects within their given environment. Knowledge is regarded as an instrument questing for survival. Evolutionary epistemology emphasizes the importance of natural selection. Selection is the generator and maintainer of the reliability of our sensory and cognitive mechanisms, as well as of the *fit* between those mechanisms and the world. Trial and error learning and the development of scientific theories can be explained as evolutionary selection processes.

An active evolutionary view is that *knowledge can actively pursue goals of its own*. It notes that knowledge can be transmitted from one individual to another, and thereby lose its dependence on any particular individual. A piece of knowledge may be successful even though its predictions may be totally wrong, as long as it is sufficiently convincing to new carriers. In this theory, the individual having knowledge has lost his primacy, and knowledge becomes a force in its own right with proper goals and ways of developing itself. This emphasizes communication and social processes in the development of knowledge, but instead of regarding knowledge as the object constructed by the social system, it rather *views social systems as constructed by knowledge processes*. Indeed, a social group can be seen as organized by members sharing the same types of knowledge. *To keep evolution sustainable, knowledge should have the characteristic of diversity*. Research on knowledge flow network is somewhat like this point of view (H.Zhuge, Discovery of Knowledge Flow in Science, *Communications of the ACM*, 49 (5) (2006) 101-107).

The following references can help readers know more about epistemology:

(1) F. Heylighen (1993), Epistemology Introduction, in: F. Heylighen, C. Joslyn and V. Turchin (editors): *Principia Cybernetica Web*, http://pespmc1.vub.ac.be/epistemology.html.
(2) P.D. Klein, (1998). Epistemology. In E. Craig (ed.), *Routledge Encyclopedia of Philosophy*. London: Routledge. http://www.rep.routledge.com/article/P059.
(3) E. Anderson, Feminist Epistemology and Philosophy of Science, *Stanford Encyclopedia of Philosophy*, http://plato.stanford.edu/entries/feminism-epistemology/.

(4) M. Brady and W. Harms, Evolutionary Epistemology, *Stanford Encyclopedia of Philosophy*, http://plato.stanford.edu/entries/epistemology-evolutionary/.
(5) R. Feldman, *Stanford Encyclopedia of Philosophy* article, Naturalized Epistemology.
(6) A. Goldman, Social Epistemology, *Stanford Encyclopedia of Philosophy*, http://plato.stanford.edu/entries/epistemology-social/.

1.7 Ontology

Ontology — another branch of philosophy — is the science of what is, and of the kinds and structures of the objects, properties and relations in every area of reality. Ontology in this sense is often used in such a way as to be synonymous with metaphysics. In simple terms, it seeks to classify entities. A scientific field has its own preferred ontology, defined by the field's vocabulary and by the canonical formulations of its theories.

Traditional ontologists tend to model scientific ontologies by producing theories, organizing them, and clarifying their foundations. Ontologists are concerned not only with the world as studied by sciences, but also with the domains of practical activities such as law, medicine, engineering, and commerce. They seek to apply the tools of ontology to solving problems that arise in these domains.

In the field of information processing, different groups of data-gatherers have their own idiosyncratic terms and concepts that guide how they represent the information they receive. When an attempt is made to put information together from different groups, methods must be found to resolve terminological and conceptual incompatibilities. At first, such incompatibilities were resolved case by case. Then, people gradually came to realize that providing once and for all common backbone taxonomy of entities relevant to an application domain would have significant advantages over resolving incompatibilities case by case.

This common backbone taxonomy is called an *ontology mechanism* by information scientists.

In the context of knowledge sharing and reuse, an ontology mechanism establishes a terminology for members of a community of interest. These members can be humans, application software, or automated agents. Ontology can be represented as a formal vocabulary organized in taxonomic hierarchies of classes, whose semantics is independent of both user and context.

1.8 System Methodology

Previous efforts toward the future interconnection environment have not yet made use of the principles and methods of system methodology.

Darwin's theory of evolution holds time to be an "arrow" of evolution. The subjects of the evolutionary process evolve as time progresses, so the overall process is irreversible, just like time. Life evolves from simple to complex, from a single-celled ameba to a multi-celled human being.

The second law of thermodynamics (R.J.E. Clausius and L. Boltzmann) tells us of a degenerate arrow: all processes manifest a tendency toward decay and disintegration, with a net increase in what is called the *entropy*, or state of randomness or disorder, of the overall system.

The theory of dissipative structure was created against the background of the collision between the two arrows.

1.8.1 *The theory of dissipative structure*

A system with dissipative structure is an open system that exists far from thermodynamic equilibrium, efficiently dissipates the heat generated to sustain it, and has the capacity to change to higher levels of orderliness.

According to Prigogine's theory, systems contain subsystems that continually fluctuate. At times a single fluctuation or a combination of them may become so magnified by positive feedback that it shatters the existing organization. At such revolutionary moments, it is impossible to determine in advance whether the system will disintegrate into chaos or leap to a new, more differentiated, higher level of order. The latter case is called a dissipative structure, so termed because it needs more energy to sustain itself than the simpler structure it replaces and is limited in growth by the amount of heat it is able to dissipate.

According to the theory of dissipative structure, the exponential growth of Web resources tends to disorder. The current efforts towards the future Web are trying to establish a new kind of order — *the order of diverse resources*. But how such an order can be prevented from becoming disordered again is a critical issue that needs to be considered as we work towards the future interconnection environment.

Here is an interesting question: *Can we design a dissipative structure for the future interconnection environment or the Cyber-Physical Society*?

1.8.2 *Synergetic theory*

Synergetics is a theory of pattern formation in complex systems. It tries to explain structures that develop spontaneously in nature. Readers can obtain more information from H. Haken's works (*Synergetics, An Introduction: Nonequilibrium Phase-Transitions and Self-Organization in Physics, Chemistry and Biology*, Springer, 1977; *Synergetics of Cognition*, Springer-Verlag, 1990 (with M.Stadler); *Principles of Brain Functioning: A Synergetic Approach to Brain Activity, Behavior, and Cognition*, Springer-Verlag, 1995).

The purpose of introducing the relevant concepts here is to provoke constructive thought about their possible influence on the future interconnection environment.

How order emerges out of chaos is not well defined, so synergetics employs the ideas of probability (to describe uncertainty) and information (to describe approximation). Entropy is a central concept relating physics to information theory. Synergetics concerns the following three key concepts: compression of the degrees of freedom of a complex system into dynamic patterns that can be expressed as a collective variable; behavioral attractors of changing stabilities; and the appearance of new forms as nonequilibrium phase transitions.

Systems at instability points are driven by a *slaving principle*: *long-lasting quantities can enslave short-lasting quantities* (that is, they can act as order parameters). Close to instability, stable motions (or “modes”) are enslaved by unstable modes and can be ignored, thereby reducing the degrees of freedom of the system. The macroscopic behavior of the system is determined by the unstable modes. The dynamic equations of the system reflect the interplay between stochastic forces (“chance”) and deterministic forces (“necessity”).

Synergetics deals with self-organization, how collections of parts can produce structures. Synergetics applies to systems driven far from equilibrium, where the classic concepts of thermodynamics are no longer adequate. Order can arise from chaos and can be maintained by flows of energy or matter.

Synergetics has wide applications in physics, chemistry, sociology and biology (population dynamics, evolution, and morphogenesis). Completely different systems exhibit surprising analogies as they pass through instability. Biological systems are unique in that they exhibit interplay between structure and function that is embodied in structure and latent in form.

The ideas introduced above imply that synergetics can help us explore the intrinsic self-organization principle of the future interconnection environment and its resources (for example, how can the components such as services form a well behaved structure to provide an appropriate service, and how can individuals in social networks appropriately cooperate to achieve ideal performance), and find better approaches to solve existing problems in processing information and knowledge.

1.8.3 *The hypercycle — a principle of natural self-organization*

A living system has three features: *self-reproduction*, *metabolism*, and *evolution*.

A *hypercycle* is a system that consists of self-reproducing macro-molecular species that are linked cyclically by catalysis. It is interesting to investigate pre-biotic evolution since it might explain how molecular species having a small number of molecules could evolve into entities with a great amount of genetic information.

The idea of the hypercycle, introduced by Eigen in 1971, has been experimentally and theoretically verified by Gebinoga in 1995. The purpose of introducing here the concept of the hypercycle is to provoke some rethinking about work towards the future intelligent interconnection environment.

The following example explains the concept of the hypercycle. Living cells contain both nucleic acids and proteins, and molecules of the two classes interact. Genetic information controls the production of polypeptide chains, that is, proteins. Data encoded in nucleic acids ensure that certain proteins can be produced. Information about proteins helps the replication of nucleic acids and enables information transmission. A system of nucleic acids and proteins helping to replicate each other is an important basis for evolution as evolution can occur only when the state information can be obtained, maintained and extended.

M. Eigen and P. Schuster consider hypercycles to be predecessors of protocells (primitive unicellular biological organisms). As quasispecies, hypercycles have also been mathematically analyzed in detail.

The self-reproducing automaton was investigated early on by John von Neumann.

A similar system of catalytically interacting macromolecules called a *syser* is comprised of a polynucleotide matrix and several proteins. There are two obligatory proteins: the replication enzyme and the translation enzyme. A *syser* can also include some structural proteins and additional enzymes. The polynucleotide matrix encodes the composition of proteins, and the replication enzyme controls the matrix replication process. The translation enzyme controls the protein synthesis according to the data encoded in the matrix. Structural proteins and additional enzymes can provide optional functions. Different *sysers* should be inserted into different organisms for effective competition.

Compared to hypercycles, *sysers* are more like simple biological organisms. The concept of *sysers* makes it possible to analyze evolutionary stages starting from a mini-*syser*, which contains only a matrix and replication and translation enzymes. An adaptive *syser* includes a simple molecular control system, which “turns on” and “turns off” synthesis by some enzyme in response to change in the external medium.

Readers can know more about the hypercycle from M. Eigen and P. Schuster’ work (*The Hypercycle: A principle of natural self-organization*, Springer, Berlin, 1979).

The notion of a *soft-device*, an uniform resource model of the future interconnection environment, is introduced in “Clustering Soft-Devices in Semantic Grid” (H.Zhuge, *IEEE Computing in Science and Engineering*, 4(6)(2002)60-63) and envisions that the future interconnection environment will be a world of versatile soft-devices and roles. Ideal soft-devices have the same function as *sysers*.

Hypercycle theory will give us some useful notions for when we explore the organization mode of the future intelligent interconnection environment. For example, the future intelligent interconnection environment can be imagined as a living system or environment, which consists of resource species in the form of soft-devices (or active services) and versatile flow cycles. Resources could be dynamically organized into diverse flows such as knowledge flows, information flows, and service flows to provide users or applications with on-demand services. Once a requirement is confirmed, all relevant flows could be formed automatically (H.Zhuge and X.Shi, Eco-Grid: A Harmoniously Evolved Interconnection Environment, *Communications of the ACM*, 47(9)(2004)79-83).

The future intelligent interconnection environment can be imagined as a quasihuman body, which has knowledge and intelligence and operates with special hypercycles. It can cooperate with people in a humanized way and provide appropriate, up-to-date, on-demand and just-in-time services.

1.8.4 *General Principles and Strategies*

The Knowledge Grid methodology should adopt the principles and rules of social science, economics, psychology, physiology, biology, ecology and physics, and inherit the fundamental ideas, views, rules and principles of system science.

General Principles

(1) *Integrity and uniformity principle* — The idea of integrity requires us to resolve the issue of correctness (for example, the correctness of operations). The idea of uniformity requires us to resolve the issue of simplicity, that is, to simplify a system. The integrity theory of the relational database model is a good example of integrity and it could give us useful ideas for developing the theory and system of a Knowledge Grid, especially in managing its resources.

(2) *The hierarchical principle* — H.A. Simon unveils the hierarchical principle of artificial systems in his book (*The Sciences of the Artificial*, Cambridge, MA: The MIT Press, 1969). The construction

of a Knowledge Grid should follow this principle. Furthermore, different levels of a system could work in different spaces. Consistency and harmony should be maintained between multiple spaces.

(3) *The open principle* — This principle would keep the Knowledge Grid away from the equilibrium state. Standards are a critical criterion for open systems. The Knowledge Grid could make use of the standards generated with the development of the current platforms such as the Internet, Web, Grid, and Cloud.

(4) *The self-organization principle* — Resources including systems themselves can actively collaborate with each other according to some principles (for example, the economic principles) and common regulations.

(5) *The principle of competition and cooperation* — Resources including systems (multiple systems or environments could coexist) evolve through competition and cooperation so that competitive resources or systems could play a more important role.

(6) *The optimization principle* — Optimization means making a system more effective. Material flow, information flow, knowledge flow and service flow can be optimized to achieve efficiency in logistic processes.

(7) *The principle of sustainable development* — Sustainable development requires individuals and communities, the interconnection environment and its human-machine interfaces, the human-machine society, and even the natural environment to harmoniously coexist and co-evolve.

(8) *Symmetry and self-similarity*. Symmetry 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.

General Strategies

The following strategies could help develop the Knowledge Grid as an intelligent interconnection environment.

The fusion of inheritance and innovation — the Knowledge Grid environment should absorb the advantages of the current efforts such as Web x.0, Grid, Cloud, Semantic Web, and Web Services. The Web applications should be able to work in the new environment. Smooth development would enable the environment to exploit research on the Web.

The fusion of centralization and decentralization — Advantage should be taken of both centralization and decentralization. On the one hand, an ideal system should be able to dynamically cluster and fuse relevant resources to provide complete and on-demand services for applications. On the other hand, it should be able to deploy the appropriate resources onto the appropriate locations to achieve optimized computing.

The fusion of abstraction and specialization — On the one hand, we need to abstract a variety of resources to investigate common rules, and on the other hand, to investigate the special rules of different resources to properly integrate and couple resources.

The fusion of mobility and correctness — On the one hand, the Knowledge Grid should support mobile applications to meet the needs of ubiquitous applications. On the other hand, we should guarantee the quality of services and the means of verification.

The fusion of symbolic and non-symbolic approaches — Current ontology only uses the symbolic approach, which is very similar to traditional knowledge base construction. The combination of the symbolic approach and the non-symbolic approach like the connectionist approach would help find better solutions for intelligent applications.

The incremental strategy — As a worldwide interconnection environment, the Knowledge Grid will undergo a development process similar to that of the World Wide Web — from simple to complex, from immature to mature, from a small community to a large-scale human-machine-nature environment with an exponential expansion of developers, users, services, and demands. So, the Knowledge Grid development methodology should support an incremental strategy.

Adoption of new computing models — The functions of new computing models will go beyond the abilities of the Turing machines. It is hard for any single model to yield an ideal solution. An ideal computing model should incorporate the advantages of various models or be a set of collaborative models. The new computing model should support massive interactions in the future interconnection environment and the computing processes that are not predesigned. (H.Zhuge, Semantic linking through spaces for cyber-physical-socio intelligence: A methodology, *Artificial Intelligence*, 175(2011) 988-1019).

Cross-disciplinary research — Compared to the physical, mental and social spaces, the artificial interconnection environment is at a very primitive stage. The principles and rules of physical, mental and social spaces will inspire us to establish the principles and rules of the ideal Knowledge Grid environment.

1.9 Dynamic Knowledge Management

Early in 1880, the American engineer F.W. Taylor investigated workers' efficiency, and formulated a scientific management method for raising productivity by standardizing operations and work. He published his authoritative book *The Principles of Scientific Management* in 1911. With increasing industrial productivity and social development, scientific management methods nowadays pay increasing attention to production processes and even social changes, psychological factors, environmental impact, and so on.

With the development of information technology, enterprises more and more become knowledge organizations, which lead to great changes in decision processes, management methods and working conditions. P.F. Drucker pointed out that the existing knowledge organizations, such as the symphony orchestra, can inspire us to develop new management approaches to knowledge organizations (*Harvard Business Review on Knowledge Management*, Boston, MA: Harvard Business School Press, 1998). However, much team work has become decentralized with the development of Internet and mobile communication devices.

After all, a large-scale orchestra can perform very well with just one conductor. Organizational learning and knowledge innovation become the key competitive abilities of a knowledge organization (I. Nonaka, A dynamic theory of organizational knowledge creation, *Organization Science*, 5(1)(1994)14-37). Nowadays, how to establish a high-performance self-organized knowledge innovation team becomes a key research issue.

Knowledge flow was studied from management point of view (A.K. Gupta and V.Govindarajan, Knowledge flows and the structure of control within multinational corporations, *Academy of management review*, 1991; M.E. Nissen, An extended model for knowledge-flow dynamics, *Communications of the Association for Information Systems*, 8(2002)251-266). An epistemological dimension is used to classify knowledge into explicit knowledge and tacit knowledge. An ontological dimension is used to describe knowledge that is shared between members of an organization. Knowledge flow within dimensions is of four types: 1) social flow, in which knowledge moves from creation by an individual to acceptance by the organization; 2) externalization flow, in which knowledge moves from tacit form to explicit; 3) combination flow, in which the knowledge of small teams is combined and coordinated to generate the knowledge of a large team; and 4) internalization flow, in which explicit knowledge of the organization becomes tacit.

Traditional knowledge engineering requires knowledge engineers to acquire knowledge from domain experts, codify knowledge and then store knowledge in knowledge base so as to support knowledge sharing and question-answering based on possible reasoning. This kind of knowledge is statically stored like digital resource in library.

Knowledge sharing in society is dynamic. People may get different answers when asking one question at different times. This is because knowledge evolves in the sharing process. Knowledge sharing has diverse forms, for example, in broadcasting or peer-to-peer.

The knowledge flow notion in computing area was stated firstly as follows:

Knowledge flow is invisible, but it works with any cooperative team no matter whether people intentionally make use of it or not. Team members are linked with various types of "knowledge transmission belts" like the production line. Any team member can put knowledge onto a proper belt, which then automatically conveys the knowledge to the team member who requires it. Any team member can get the required knowledge from the belt linked to him/her when performing his/her task. These belts together with the team members constitute a knowledge flow network. People can raise the effectiveness of teamwork by properly designing the network and controlling its execution process (H. Zhuge, A knowledge flow model for peer-to-peer team knowledge sharing and management, *Expert Systems with Applications*, 23(1)(2002)23-30).

This knowledge transmission belt can be regarded as a kind of super link that can pass through knowledge flow (H.Zhuge, Semantic linking through spaces for cyber-physical-socio intelligence: A methodology, *Artificial Intelligence*, 175(2011)988-1019).

A peer-to-peer knowledge flow refers to the propagation of external and explicit knowledge that can be formalized, transmitted via communication media, and stored in computing machinery. The planning of a knowledge flow network seeks to formalize and optimize knowledge flows (H.Zhuge, Knowledge flow network planning and simulation, *Decision Support Systems*, 42(2) (2006)571-592).

Knowledge flows will pass through socio networks like the citation networks of scientific publications to form communities and reputations (H.Zhuge, Discovering Knowledge Flows in Science, *Communications of the ACM*, 49(5)(2006)101-107).

A knowledge flow network is in itself a kind of organizational knowledge that is more relevant to the roles of the organization and less focused on individuals. It is more concerned with the content of knowledge and with effective knowledge sharing in distributed cooperative teams especially the geographically distributed virtual organization.

Knowledge sharing in the Knowledge Grid environment needs a kind of mechanism to reflect human cognition. Different people may see a different epistemology in the same object or event. Epistemological mechanisms help humans and agents understand, generate and describe new knowledge when they share resources. An easy way to implement an epistemological mechanism would be to develop an epistemological appendage, generated and used in conjunction with the original resources.

Some researchers are interested in mining Web usage logs. These logs record data about the Web's users. The researchers are striving to use the results of mining Web usage logs to support personalized Web services. However, the Web logs only reflect a small portion of users' behavior, and they are unable to capture users' actual intentions, thinking or understanding, even if the lifetime logs could be recorded.

A personalized epistemological appendage together with domain ontology could improve the current Web's keyword-based approaches and ontology-only approaches. The appendage could be in form of a complex semantic space integrating classification, semantic link, and reasoning (H.Zhuge, Complex Semantic Space, Keynote at *the 20th IEEE International Conference on Collaboration Technologies and Infrastructures*, Paris, France, June 27th-29th, 2011).

Determining the dimensions of knowledge within an organization is important for managing knowledge in the organization. The dimensions of abstract knowledge can include the following three dimensions: the *knowledge category* dimension (e.g., disciplines), the *knowledge level* dimension (e.g., concept, rule, method, and theory), and the *knowledge host* dimension (knowledge may be specific to individual and community).

1.10 The Knowledge Grid as a Research Area

1.10.1 Research Scope

It is helpful to know what are *not* the major concerns of the Knowledge Grid research. Traditional natural language processing, information retrieval, recognition of human speech and handwriting, and formal semantics are not the major concern of the Knowledge Grid. Security and scientific computing are not its key issues. The Knowledge Grid will go beyond the traditional Web, Grid, cloud, information retrieval, filtering, mining and question answering (H. Zhuge, China's e-Science Knowledge Grid Environment, *IEEE Intelligent Systems*, 19(1)(2004)13-17).

Efforts towards the future interconnection environment supply the Knowledge Grid with several candidate techniques and implementation platforms.

The Grid computing is not the only platform for realizing the Knowledge Grid, but the ideal, method and techniques of the Grid computing could be helpful references.

The meaning of the term *grid* in the Knowledge Grid is broader than it is in Grid computing. Actually, people have a long history of using the word “grid” in drawing and mapping, geodetic surveying, and mathematics. The word was borrowed from the power grid to refer to clustered computing power when the concept of Grid computing appeared in 1995.

As depicted in Fig. 1.10.1.1, the Knowledge Grid emerges and evolves with the interaction between different spaces (dimensions), which also evolve.

Humans use knowledge to design the power Grid, which makes use of natural resources to generate and transmit electricity for society. The principle of the power Grid inspires the Grid computing. The development of Grid computing accelerates the emergence of the smart Grid. A cyber-physical-socio innovation closed loop will be formed if the Knowledge Grid can be integrated with the smart grid to extend the ideal of the Grid and to enrich human knowledge.

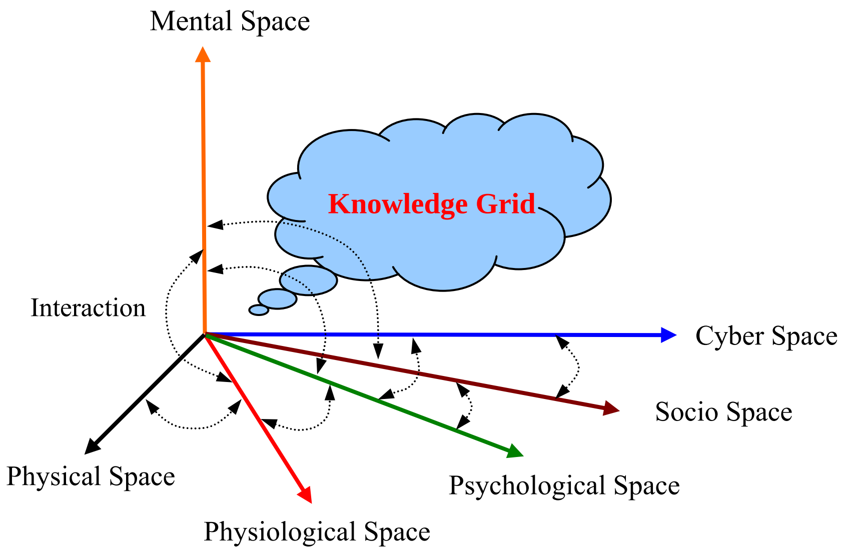

Fig.1.10.1.1 Dimensions of the Knowledge Grid and interactions between dimensions.

In the long run, a Knowledge Grid environment should be a large-scale, autonomous, living, sustainable and intelligent network where the mental space, psychological space, social space, and physical space can develop together, functioning and evolving cooperatively. It would collect useful resources from the environment, transform and organize them into semantically rich forms that could be used easily by both machine and human. Geographically dispersed people and resources could work together to accomplish tasks and solve problems by using the network to actively promote the flow of material, energy, technique, information, knowledge and service through roles and machines, improving both the natural and the artificial environments.

Intelligence, Grid, peer-to-peer and environment represent humanity's four aspirations for the future working and living environment. The intelligence reflects humanity's pursuit of recognizing themselves, society and the nature. The Grid reflects humanity's pursuit of optimization and systemization. The peer-to-peer reflects humanity's pursuit of freedom and equality. The environment reflects humanity's pursuit of understanding the nature and its harmony.

1.10.2 Parameters

As a large-scale dynamic human-machine-nature system, a Knowledge Grid environment will be a complex space characterized by the following five parameters:

(1) *Space* — the capacity to hold a great variety of versatile individuals.
(2) *Time* — the arrow of evolution, which generates and evolves with the space.
(3) *Structure* — the construction of the environment and individuals in the environment.
(4) *Relation* — the abstract structure, distance, interaction or influence among parameters and among individuals in different spaces.
(5) *Measurement* — the evaluation of the status of, and the prospects for, individuals, processes and their relations.

Einstein's general theory of relativity reveals the relations between space and time in the physical space: space and time are malleable entities. On the largest scales, space is naturally dynamic, expanding or contracting over time.

A Knowledge Grid environment will foster the growth of knowledge by supporting behaviors in different spaces. As a product of complex space, knowledge evolves and endures throughout the life of the race and the life of individuals to wave and evolve social networks in various spaces.

Human social activities generate and develop the semantics of natural languages. Cyber-physical-socio-mental behaviors will need to be based on a kind of cyber-physical-socio semantics, and need to establish an "understanding" between inanimate resources and humans. Such semantics will be needed so that resources, services and knowledge in the Knowledge Grid can be beneficially used and protectively regulated by humans.

1.10.3 Distinctive characteristics of the Knowledge Grid

The Knowledge Grid has the following distinctive characteristics in knowledge generation, sharing, evolution and service.

(1) *Reflecting knowledge*. It will record individuals' behaviors, detect events in the cyber, physical, and social spaces, and make summarization, abstraction and reasoning. Intelligent individuals are responsible for transforming knowledge from one form into the other and developing individuals' knowledge.

(2) *Intelligently clustering and fusing distributed knowledge*. In the Knowledge Grid environment, related knowledge distributed around the world could intelligently cluster together and fuse to provide appropriate on-demand knowledge services with underlying reasoning and explanation. So, knowledge providers should include some meta-knowledge (knowledge about knowledge), and could use a kind of uniform model to encapsulate the provided knowledge and meta-knowledge to realize active and clustered knowledge services.

(3) *Single semantic entry point access to worldwide knowledge*. In the Knowledge Grid environment, people could access knowledge distributed around the world from a single semantic access entry point without needing to know where the required knowledge is.

(4) *Single semantic image*. The Knowledge Grid environment could enable people to share knowledge and to enjoy reasoning services in a single semantic space where there are no barriers to mutual understanding and pervasive knowledge sharing.
(5) *Worldwide complete knowledge service*. The Knowledge Grid could gather knowledge from all regions of the world and provide succinct and complete knowledge relevant to the solution of particular problems. To achieve this goal, we need to create new knowledge organization and service models.
(6) *Dynamic evolution of knowledge*. In the Knowledge Grid environment, knowledge would not be just statically stored, but would evolve to keep up-to-date with sharing and innovation. The Knowledge Grid can show how knowledge evolves from macroscopic to microscopic and how behaviors influence the evolution.

1.10.4 The Knowledge Grid's general research issues

The Knowledge Grid has the following general research issues:

(1) *Effective organization of various resources. Self-organization and autonomy will be the major feature of this resource organization.* The structure of a Knowledge Grid system is very important just like a child's learning ability is based on its innate mental structure (J.McCarthy, The Well-Designed Child, *Artificial Intelligence*, 172(2008)2003-2014). The first edition of this book introduced a Semantic Link Network and Resource Space Model as the basic structure for managing resources in the Knowledge Grid. This edition will enhance the two models and integrate them into a single semantic image.
(2) *Theories, models, methods and mechanisms for supporting knowledge reflection and representation.* The Knowledge Grid should be able to help people or virtual roles effectively reflect, and conveniently share knowledge in a machine-processable form that could directly, or after transformation, be understood by humans. An open set of semantic primitives should be built to help

knowledge representation. These primitives should be able to represent multi-granular knowledge. Reflecting knowledge has two meanings: one is when people learn from each other directly, or from the resources published by others, and then publish new knowledge on the Knowledge Grid; and, the other is when the Knowledge Grid gets knowledge from numeric, textual or image resources by discovery, induction, analogy, deduction, synthesis, and so on.

(3) *Knowledge display and creation*. These come mainly through an intelligent user interface (for example, a semantic browser) that enables people to share knowledge with each other in a visual way. The interface should implement the distinctive characteristics of the Knowledge Grid and be able to inspire people's discovery of knowledge through analogy and induction. The development of interface accompanies all development stage of computing systems.

(4) *Propagation and management of knowledge within virtual organizations*. This could eliminate redundant communication between team members to achieve effective knowledge management in a cooperative virtual team in the cyber-physical society. Knowledge flow management is a way to achieve knowledge sharing in a virtual team.

(5) *Knowledge organization, evaluation, refinement and derivation*. Knowledge should be linked and organized according to certain normal forms to obtain high retrieval efficiency and ensure the correctness of operations. The Knowledge Grid should be able to eliminate redundant knowledge and refine knowledge so that useful knowledge can be increased. It can also derive new knowledge from existing well-represented knowledge, from case histories, and from raw knowledge.

(6) *Knowledge integration*. Integrating knowledge at different levels and in different domains could support cross-domain analogies, problem solving, and scientific discovery.

(7) *Abstraction*. It is a challenge to automatically capture semantics from a variety of resources, to make abstractions, and to reason and explain in a semantic space. The semantic constraints and rules of

abstraction ensure the validity of resource usage at the semantic level.

(8) *Scalable network platform*. The Knowledge Grid should enable a user, a machine or a local network to freely join in and leave without affecting its performance and services. It is a challenging task to organize and integrate knowledge within a dynamic network platform.

(9) *Interactive semantics.* Semantics is the fundamental issue of computer science and information science. How to enable machines to have the ability to process semantics is a challenge issue. Semantics can be classified into two categories: *social semantics* and *natural semantics*. Social semantics is hard to be accurately represented and the correctness cannot be proved, but it can be explained and indicated. Natural language processing, text analysis and statistical method do not attack the core of semantics study as socio interaction is more fundamental then symbol language. Humans can effectively interact with each other before the emerging of symbol language. Animals can effectively interact with each other without using symbol language. The new notions such as *interactive semantics*, *semantic worldview*, *semantic images*, *semantic lens* and *the process of explaining semantic image* were proposed (H.Zhuge, Interactive Semantics, *Artificial Intelligence*, 174(2010)190-204). Interactive semantics consists of interactive system and the semantic images of individuals, communities and the system rather than the static representation. Semantic images evolve with the evolution of the system such that systems, communities, and individuals can have *selfness*. The semantic lens can help individuals to observe semantics from different facets, scales and abstraction levels across time. Individuals can understand and interact with each other based on the semantic worldview, semantic base and semantic image. The study of interactive semantics will be a new direction of studying semantics.

1.10.5 Differences between the Web and the Knowledge Grid

Here we use examples to make a brief comparison between the Web and the Knowledge Grid. With the Web, people with an illness can use search engines to retrieve relevant medical information, and browse hospital or health websites to find suitable hospitals and doctors, depending on what URLs they can remember. As there are more than a thousand million health websites, people are often annoyed by the large amount of useless content in a search result and by the time consumed in browsing through many websites. They may be further confused by the various opinions of different doctors. They may also worry about whether the result of their searching is based on up-to-date knowledge. Entering related symptoms, they can usually only obtain results for separate symptoms. Further, the whole searching process may overlook some experts, especially those who specialize in uncommon diseases.

Such searches will be improved by the Knowledge Grid, which can accurately and completely locate all relevant knowledge, cluster and synthesize the search result and then actively present it to users according to their illness profiles and the locations of hospitals and doctors. The users can get an explanation of the search result with underlying reasoning based on the clustered knowledge. The relationship between the symptoms of a disease will be considered during reasoning. The search results can adapt to change in illness profiles. Knowledge provided by different doctors worldwide will be refined, checked, fused and evaluated as to usefulness, consistency and time-effectiveness.

In the Knowledge Grid, new knowledge can be derived from: existing knowledge, patients' feedback, and mining in medical textbooks, papers, online contents, and other related sources such as contents captured from patients' daily life through smart homes. Ill people can also choose to provide symptoms of their disease through a single semantic entry point when accessing the Knowledge Grid to obtain instant consulting services. The result may include several candidate treatments selected by considering such factors as cost, waiting time, skill level, real-time transportation, and so on. In emergent case, the appropriate hospital, the route and vehicle from home to hospital will be recommended according to the real-time hospital situation (about patients, doctors, equipments, et. al.) and traffic situation. Family members are able to know the real-time status of the patient through mobile devices and sensors.

Similar advantages of the Knowledge Grid also exist in scientific research, business, education and other application domains.

1.10.6 The technological basis of the Knowledge Grid

The Knowledge Grid is not pie in the sky. It is based on existing methods and technologies such as the Web, Cloud, Grid, Semantic Web, Web Services, Sensor Network, mobile communications, Peer-to-Peer, AI, modeling, information processing technologies (for example, data and text mining, information filtering, extraction, fusion and retrieval), and system methodology as shown in Fig. 1.10.6.1.

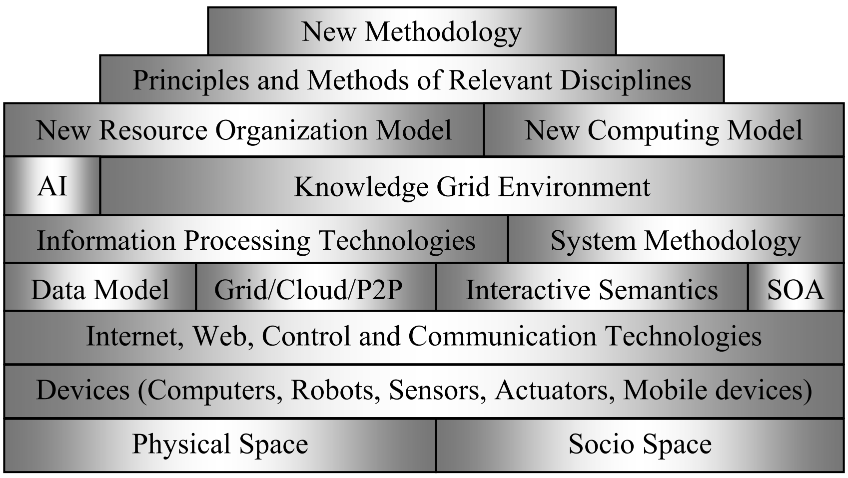

Fig. 1.10.6.1. The methods and technologies of the Knowledge Grid environment.

The adoption of a new system methodology, a new resource organization model, a new computing model, and the principles of relevant disciplines will further challenge the current software methodology. The implementation of the ideal Knowledge Grid requires a new methodology that can cope with resources in different spaces through cyber-physical-socio processes, and support competition and sustainable development according to the cyber, physical, socio principles and rules.

1.10.7 A new dream

Gray summed up computing history in his 1999 Turing Award Lecture: the dream of Charles Babbage (1791-1871, the father of the computer) has been largely realized, and the dream of Vannevar Bush has almost become reality, but it is still difficult for computer systems to pass the Turing Test — computing systems still do not have human intelligence although significant progress has been made. Gray extended Babbage's dream to the following: *computers should be highly secure and available, and they should be able to program, manage, and replicate themselves*.

Scientists have made significant progress towards establishing highly secure and available systems — the major goal of the Grid and cloud computing. But so far, we are still far from the goal of self-programming, self-managing and self-replicating. Gray extended Bush's Memex vision to an ideal that automatically organizes indexes, digests, evaluates, and summarizes information, and indeed scientists in the information processing area are making efforts towards this goal. He proposed three more Turing Tests: prosthetic hearing, speech, and vision (*Journal of the ACM*, 50(1) (2003)41-57).

The word *meme* was used to indicate any evolving thing (human, behavior, idea, tune, clothing, design, culture, science, and even meme itself) that spreads from one individual to the other within a culture in (R. Dawkins, The Selfish Gene, Oxford University Press, 1976). Memes are transmitted from individual to individual and compete (or cooperate) with other memes occupying the same space. Genes replicate themselves, and each type competes with other types and may or may not compete with other species' genes in the same space. Different from genes, memes do not necessarily need a concrete medium to transfer.

Carrying out experimental research on finding various memes in cultures and sciences will be very interesting.

What modern society needs from the future computing environment has gone far beyond the scope of the Turing Test and other automatic machine intelligence problems such as self-programming. Computing has evolved from mainframe computers to personal computers, to locally networked computers, to the Internet, and to the Cyber-Physical Society (or Cyber-Physical-Socio-Mental Environment when the mental space is considered). People now primarily use computers interactively on a large scale, so that the *dynamics*, *evolution*, *cooperation*, *fusion*, *sustainability*, and *socio effects* of computer use have become major concerns.

Fig. 1.10.7.1 shows the evolution of the man-machine environment, where interaction evolves from machine semantics to social semantics and to multiple semantic spaces. The Knowledge Grid is the platform that supports the large-scale knowledge sharing and management in the Cyber-Physical-Socio-Mental Environment.

Communication in human society is carried out in multiple semantic spaces, such as the emotional, cultural, artistic, scientific, and that of daily life, which establish the basis for mutual understanding. Loosely or tightly coupled rules could be used to coordinate between these semantic spaces. Traditional research on natural language processing only focuses on one space — the text space, where some information has inevitably been lost in the reading and writing processes. This is one reason why different people have different understandings of the same text. So, it is impossible to realize the dream of automatically processing natural language if only text analysis is used.

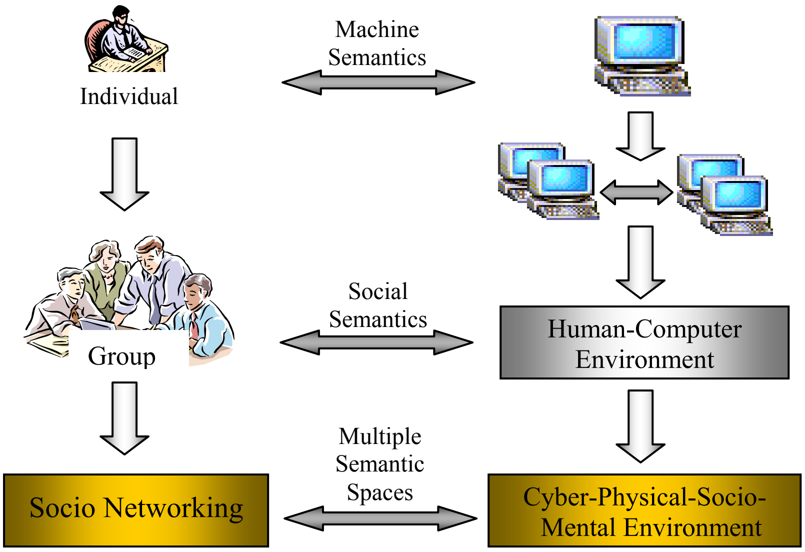

Fig. 1.10.7.1. The evolution of the man-machine environment.

We need an incremental strategy to develop the Knowledge Grid. A worldwide Knowledge Grid is a long-term target. A preliminary stage developing a medium-sized Knowledge Grid based on an institution's intranet would be an appropriate step in the long march towards the long-term target. It could support more effective knowledge management within institutions of various kinds. Institutional Knowledge Grids could then become components of the worldwide Knowledge Grid.

A *Micro Knowledge Grid* could be the basic component of a medium-sized Knowledge Grid and thus the basic component of the worldwide Knowledge Grid. It would be useful in helping individual knowledge management — managing knowledge not only in the cyber space (indicated in natural language texts, photos, and videos) but also in the other spaces. A personal Knowledge Grid should keep evolving with the development of his/her career and characteristics so as to provide appropriate knowledge services at right time.

A personal Knowledge Grid could be a lifetime artificial companion with a powerful conversation interface (Y. Wilks, Is There Progress on Talking Sensibly to Machines? *Science*, 5852(318)927-928).

A worldwide Knowledge Grid Environment should be more powerful than the sum of its components.

A Knowledge Grid Environment should support more semantic spaces than just one symbol space. Knowledge sharing in a Knowledge Grid Environment depends on correct understanding of the semantics of its resources and processes. But these semantics are not the same as the traditional formal semantics. These should be a kind of interactive semantics, which supports sensing, fusion, mapping, reasoning, abstraction, and transformation between semantic spaces. The semantics of the Knowledge Grid should be easily understood by humans and readily processed by machines.

The internal structures of resources that indicate the same semantics could be completely different. So, finding effective ways (for example, markup languages) to express the internal structure will be much more complex than finding ways to express the external semantics — the semantic links between resources. Since no object in the world exists in isolation, the semantics of a resource could be determined or roughly reflected by the semantics of the resources related to it and the links between them. This is one cause of studying the semantic link network.

A Knowledge Grid can also cooperate and harmoniously co-evolve with other systems like the society. The research aims are to understand ourselves and the law of the society as well as to support decision, wellness, and teamwork. Any effort violating this aim will be insignificance.

Symbolic systems are elegant computing models. Artificial intelligence was regarded as evidenced by the behavior of working symbolic systems. However, symbolic systems have their own particular scope of ability. Non-symbolic systems also have their particular scope of ability. The Knowledge Grid environment should combine the approach of symbolic systems with the approach of non-symbolic systems (this still needs much work).

Billions of years of natural evolution have created a natural environment and an intelligent species that has evolved into human society.

If we draw an analogy between the future interconnection environment and the world of nature, a challenging question arises: what is the field theory of the Knowledge Grid environment? As its basic material, the various resources in the interconnection environment exist in a special field, where resources flow from higher intensity nodes to lower intensity nodes. Social energy is introduced to measure the potential and motion energy in social network (H.Zhuge, Semantic linking through spaces for cyber-physical-socio intelligence: A methodology, *Artificial Intelligence*, 175(2011)988-1019). But the duplication and generation of resources does not cause the loss of any other resource, and the flow of resources also does not mean the loss of any resource. This means that the law of energy conservation in the physical space does not hold in the abstract knowledge space. The laws and principles in this special field will become the basic theory of the future Knowledge Grid environment.

If we draw an analogy between the Knowledge Grid environment and human society, challenging questions arises:

What is the economics of the future intelligent interconnection environment? Economics is an artificial virtual system that helps raise the efficiency of society and realize human aspirations. Continually, we can ask the following questions: *What is the market? What are the prices of services in the Knowledge Grid environment*?

If we draw an analogy between the Knowledge Grid environment and the human physiological system, some further challenging questions arise:

(1) *What is the circulatory system of the future intelligent interconnection environment*? This question impels us to

investigate and establish models for material, information, knowledge and service flows.

(2) *What is the immune system of the future intelligent interconnection environment*? This question impels us to investigate the principles of resource clustering and security.

(3) *What is the digestive system*? This question impels us to investigate the principles of generation and understanding of various resources.

(4) *What is the nervous system*? This question impels us to investigate the principles of the control flow within the Knowledge Grid environment.

(5) *What is the ecology*? *What are the rules of evolution*? *Will the environment degrade and its species diversity decrease*? To answer these questions requires us to carry out research relating ecology to a cyber-physical-socio-mental ecosystem.

(6) *What are the sustainable development principles and the rules of the future interconnection environment that could evolve harmoniously with human society*? This question impels us to explore the relationship among society, economy, culture and the Knowledge Grid environment.

So far, we can assert that both the notion and the ideal of the Knowledge Grid Environment are understandable, useful and challenging. The methodology of the Knowledge Grid Environment should also include the testable and incremental aspects that Gray mentioned in his Turing Award Lecture.

The incremental aspect would make our short-term target modest. The major characteristics of the Knowledge Grid will be realized by a medium-sized Knowledge Grid in some application area, such as e-science and e-learning, based on the Web x.0, Web of Things, P2P, Cloud, and Grid technologies.

As for the testable aspect, we can use the following basic criteria to evaluate whether it is a Knowledge Grid environment or a knowledge based system within the prior art:

(1) *The cost of knowledge*, including acquisition, reasoning, provision, and maintenance.
(2) *The effectiveness of knowledge services*, for example, the response time.
(3) *The quality of knowledge services*, for example, users' degree of satisfaction with the services.
(4) *The improvement of knowledge services*, for example, whether the services can be improved during use. The improvement means two aspects: the way of service and the development of knowledge.
(5) *The involvement of multiple spaces*. The Knowledge Grid can link symbols to multiple spaces when interacting with humans, while traditional knowledge base systems are only in the cyber space.

On average, a Knowledge Grid should perform better than other systems in 70% of tests.

1.10.8 Beyond the vision of Turing and Bush

Turing described computer intelligence as a machine that can learn from experience and can alter its own instructions. Bush not only envisioned the multi-media but also the information system, Internet and Web. It seems that almost all previous research works in the computing area are to realize their dreams. To go beyond their vision is a grand challenge.

The Cyber-Physical-Socio-Mental Environment is a vision that goes beyond the vision of Turing and Bush.

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

The cyber space, physical space, socio space, and mental space will evolve and cooperate with each other in the complex space. Scientific issues will go beyond the cyber space.

Fundamental research concerns the origin and essence of material, life, intelligence and society. These issues obviously go beyond the visions of Turing and Bush.

Different spaces can explain specifically on *what*, *where*, *why*, *when*, and *how* (H.Zhuge, Semantic linking through spaces for cyber-physical-socio intelligence: A methodology, *Artificial Intelligence*, 175(2011)988-1019).

(1) *The socio space can explain*: How do individuals effectively cooperate? What are relevant socio rules? What are the socio effects and socio value?
(2) *The physical space can explain*: How is it related to physical phenomena and laws? Where and when does it happen? What are its physical effects?
(3) *The mental space can explain*: Which category does it belong to? What is the cause? What does it imply? What are the similar cases? What is the appropriate method to solve a problem? What is the probable effect of the method?
(4) *The cyber space can explain*: What is the cyber effect? What services it can provide with?

Sciences and technologies specific to a single space will converge to a general theory and methodology for studying and developing the new environment. The following are some revolution aspects:

(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 language representations to reasons in multiple spaces, to relevant research,

and to applications. Scientific thoughts will efficiently influence society through the links between spaces.

(2) *Education*. Students can learn natural and socio laws not only from linguistic and mathematical description in textbooks but also from the linked physical and socio phenomena through times. Learning resources can be self-organized according to students' real-time interest and psychological statuses. Knowledge is created, enhanced, and rebuilt through interaction between coherent motions in different spaces.

(3) *Engineering*. Artifacts can be linked to the ideas, to the design, to the manufacturers, and to the manufacturing processes. The statuses of engineering can also 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 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. Recommendation or evaluation will be explained from historical and cultural point of view.

(5) *Society and life*. Society will be safer and life quality will be higher as 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.

(6) *Intercultural collaboration*. It will help people with different cultural backgrounds collaborate effectively by transforming symbols, 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.

The Cyber-Physical-Socio-Mental Environment has dual nature: the real space containing real individuals, and a virtual space containing the structure, rules, reasons and status of individuals. The virtual space will change when the real space significantly changes.

A simple Knowledge Grid framework consists of the following three levels to support self-organization and normalization in organizing decentralized resources:

(1) High level — the knowledge flows, which work in minds and pass through minds and socio networks for creating and sharing knowledge with the help of the cyber space.
(2) Middle level — the complex semantic space integrating diverse models, including the Semantic Link Network and the Resource Space Model, which will be introduced in the following chapters.
(3) Low level — the decentralized sense, link, organization, synthesis, and storage of knowledge in the cyber space.

The methodology of the Knowledge Grid environment is for guiding human individuals to carry out continuous research and development. It does not follow any single methodology. It incorporates diverse methodologies, including *empiricism*, *rationalism*, *pragmatism*, *individual constructivism*, *social constructivism* and *evolutionism*:

(1) *From empiricism point of view*. The Knowledge Grid methodology argues that knowledge as a complex space evolves and it is enriched in structure and individuals through human behaviors in multiple spaces, and that the cyber space can reflect and extend human behaviors and experience, e.g., in remote sensing and discovering rules in large-scale data set. Experimental science belongs to empiricism as scientists' judgments rely on experiment results.
(2) *From rationalism point of view*. The Knowledge Grid methodology emphasizes rational thinking, reasoning, and the development of systematic theory during research. The categories of space, time, objects and causality are used in constructing knowledge space in research process.
(3) *From pragmatism point of view*. The Knowledge Grid methodology emphasizes human requirements, well-being and harmonious development of individual, society and nature. It

emphasizes both formal models and informal models when developing models. It emphasizes the relation between theory and practice while respecting the differences between them and the independent development.

(4) *From individual constructivism point of view*. The Knowledge Grid methodology argues that individuals contribute and influence knowledge evolution and indication. Symbols and models are created, evaluated, and used by individuals. It also emphasizes that individuals are not isolated, and they interact with each other to evolve knowledge in the social space.

(5) *From social constructivism point of view*. The Knowledge Grid methodology argues that social space is one dimension of knowledge. Social semantic link networks are waved along time and semantics emerges and evolves with the evolution of the network. The social space provides the resources, regulations, cooperation, recognition and culture for individuals.

(6) *From evolutionism point of view*. The Knowledge Grid methodology argues that individuals (humans and resources), spaces, environments, theories, models, and methods co-evolve with time.

The Knowledge Grid (KG) Methodology adopts previous knowledge theories and methodologies as its dimensions when developing its multi-dimensional methodology as shown in Fig. 1.10.8.1. A point in the space has a projection on each dimension. Thought can transfer between dimensions.

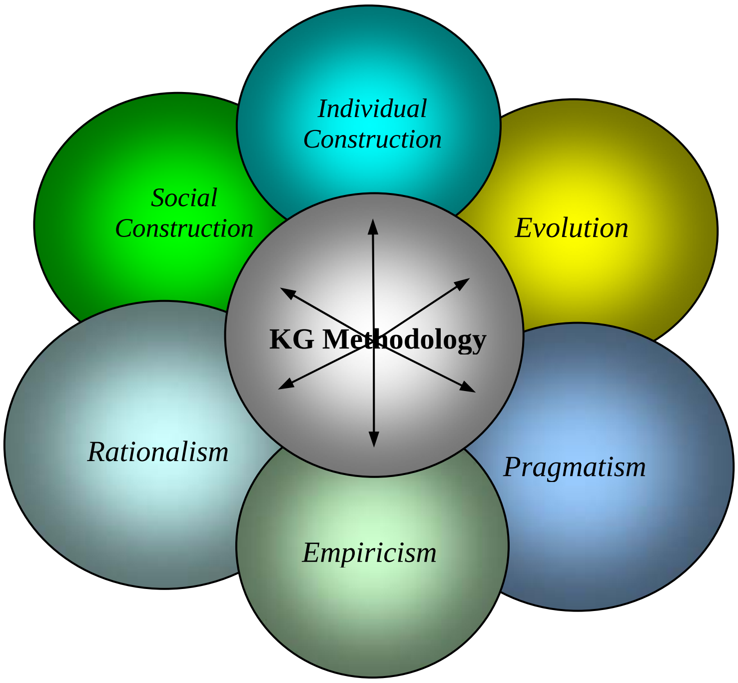

Fig. 1.10.8.1. The Knowledge Grid Methodology.

A semantic link network of this book's chapters is depicted in Fig. 1.10.8.2.

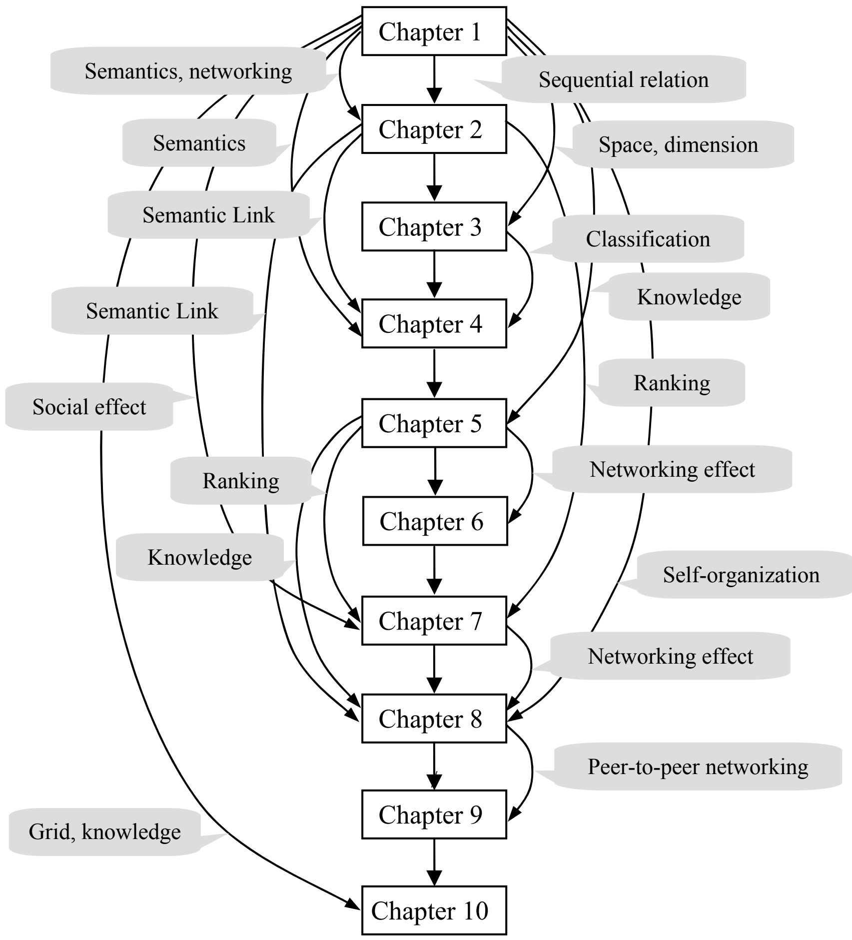

Fig. 1.10.8.2 A semantic link network of chapters.

The following chapters present detailed research and practice — some attempts to fulfill the ideal of the Knowledge Grid environment.

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