The Web Ecology

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ABSTRACT
Exploring the laws of nature and the rules of human society is the grand challenge of sciences. The World Wide Web, its expanding resources, applications and users have constituted an enormous information sharing space. People's daily life and work have become increasingly relying on it. However, it is still young compared with our society and the nature. What it will be in the future? Billions of years' evolution creates the most elegant and efficient natural ecosystem. It will be ideal if the Web can eventually evolve into an artificial ecosystem that harmoniously evolves with society, economy, culture, sciences, and technologies. This paper proposes the Web ecology as the blueprint of the future interconnection environment, including its definition, scientific issues, method, and general architecture. The study of the Web ecology may lead to a new branch of sciences.

Categories and Subject Descriptors
H.1.0 [**Models and Principles**]:– *General.*

General Terms
Design, Economics, Human Factors.

Keywords
Ecology, Ecological Web, Future Interconnection Environment, Web, Web Ecology.

1. INTRODUCTION
Experienced billions of years' evolution, the huge and complex natural ecosystem has become the most elegant and efficient system. Ecology is a study of organism, natural environment and society [6]. It concerns the structure and function of ecosystem as well as the relationship between organisms and the environment.

People are familiar with the food chain or food web, and know that it can balance the population of communities in the food web. Material flow works with the food web when foods pass through individuals. Energy flow is formed when it is transformed from one form into another in the food web. Information flow goes though individuals within a community for inheritance and communication.

A healthy ecosystem works with effective energy flow, material flow and information flow cycles, by which the system can automatically keep dynamic balance on the population of all communities involved in the flow cycles, assimilate waste, self-recover a certain degree of damage, and keep harmonious and sustainable evolution. The excellent characteristics of the natural ecological environment enlighten a new way for us to develop the future Web [24].

The World Wide Web, its expanding resources, applications and users have constituted a global artificial information sharing space. Its influence on our society, economy and daily life is unprecedented in information technology. What it will be in the future? Much effort has been made towards the future Web.

The Semantic Web is an effort to extend the Web, which is expected to effectively manage Web data by creating a machine understandable Web semantics [3]. The URI (Uniform Resource Identifier), RDF (Resource Description Framework), OWL (Web Ontology Language), and Query Language for RDF (SPARQL) are its major techniques. So far, Semantic Web has formed a research community.

Grid computing is also an effort toward the future computing environment, where computing resources can be deployed and used in an optimized way. The ideal of Grid computing comes from the power grid [12]. It is more suitable for middle-scale and stable network. In contrast to the Grid, peer-to-peer (P2P) computing is more suitable for large-scale dynamic network [1], but its information sharing mechanism is rather simple and poor in semantic processing ability. Service-oriented computing and service science are receiving broad attention [13].

Benefit from the development of the Semantic Web and Grid computing, the Semantic Grid is proposed as the vision of the future generation Internet, where semantic interoperability plays the key role (www.semanticgrid.org, [9, 25]). Semantics is one of the key to implement the future interconnection environment. The effort to establish the interconnection semantics has been made to establish the understanding basis for the future interconnection environment [27].

A framework for cyberinfrastructure-based e-science was suggested [15]. A vision of cyberinfrastructure for 21st century discovery was proposed by NSF of USA in 2006.

The Knowledge Grid aims at an intelligent and sustainable Internet application environment that enables people or roles (mechanisms that facilitate interoperation among users, applications, and resources) to effectively capture, publish, share and manage explicit knowledge resources. It provides services on-demand to support innovation, cooperative teamwork, problem-

WWW 2008, April 21--25, 2008, Beijing, China.

solving and decision making. It incorporates epistemology and ontology to reflect human cognition characteristics; exploits social, ecological and economic principles; and adopts the techniques and standards developed during work toward the next-generation Web [22, 23]. The implementation of the Knowledge Grid can be based on Grid, P2P network, Web and intranet. Experienced the development from centralized to decentralized resource management, the Knowledge Grid will develop toward an intelligent interconnection environment [26].

Foreseeing further from ecological point of view, the Eco-Grid is proposed as a model of the future interconnection environment [24], which is expected to evolve with society, economy and technology harmoniously. Its architecture is proposed for managing resources in the future interconnection environment by social and economic principles and balancing the service flow, knowledge flow, information flow and material flow.

The future interconnection environment is extended to include the nature [26]. It has the following five parameters:

(1) Space — the capacity to encompass a great variety of individual resources, such as material objects, information, knowledge, services, physical space, and even a part of the natural environment.

(2) Time — the arrow of evolution and degeneration.

(3) Structure — the construction of the environment and its individuals.

(4) Relation — relationships between parameters and between individuals.

(5) Worth — the evaluation of the status of, and the prospects for, individuals, processes and their relationships.

The development, operation and maintenance of the environment will involve the following worlds:

(1) The physical world — nature, natural and artificial materials, physical devices and networks.

(2) The virtual world — the perceptual environment constructed mainly by vision and hearing, and possibly touch, smell and taste.

(3) The mental world — ideals, religions, morals, culture, arts, wisdom, and knowledge of sciences, springing from thought, emotion, creativity and imagination.

They will interact with each other as shown in Fig. 1 [26]. The mental world will develop both within itself and through various interactions. The virtual world starts through interaction between the physical world and the mental world, and then evolves through interaction among these worlds. The virtual world directly influences the mental world and indirectly influences the physical world through the mental world and the physical world itself.

The future interconnection environment will develop under the principles of openness, incremental development, economy, ecology, competition and cooperation, dynamic scalability, integrity and uniformity.

This paper proposes the Web ecology as the study of the future interconnection environment, including the fundamental concepts, scientific issues and methods. It does not concern the following studies: the building of a system to support the study of natural ecosystem, the study of ecology by using Web technologies, and the technologies for a particular evolution stage of the Web.

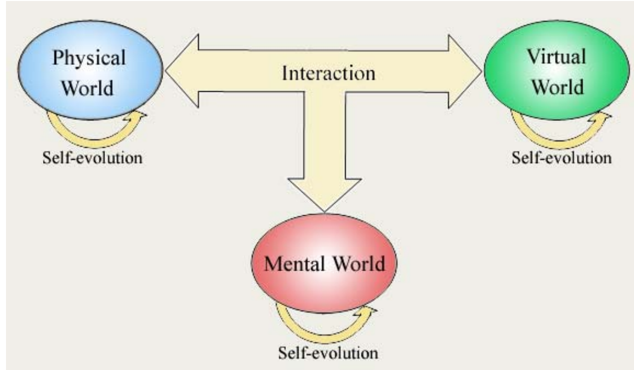

Fig. 1. Three worlds of the future interconnection environment.

2. DEFINITION, SCIENTIFIC ISSUES, AND METHOD

2.1 Definition

Web ecology studies the harmonious development of the Web, society, economy and nature as an entire environment. It concerns the architecture and function of the environment, the method and technologies for developing the environment as well as the intrinsic relationships and rules in the environment. The interconnection environment is called EcoWeb for short in the following discussion.

2.2 Scientific Issues

Web ecology studies the following fundamental scientific issues:

(1) *Individual model*. Individual organism is the most basic existing form in the EcoWeb. Research should answer what is the individual in the EcoWeb as well as its structure, function and generation mechanism.

(2) *Species and community*. Research should answer what is the species and community of the EcoWeb. Individuals sharing the same features constitute a species. A community may consist of several species.

(3) *Relationship and interaction rules between individuals and between communities*. Based on the individual model and community model, research should answer what is the symbiosis relation between communities? What is the nature of the interaction in the EcoWeb? It should be different from the interaction in the current Web and also different from the direct conversation between people. At the low level, is it similar to the interaction between organisms or between animals? At the high level, is it similar to the art languages? Research needs to answer these questions.

(4) *Competition and cooperation principles in the EcoWeb*. Competition, symbiosis and cooperation exist among individuals and among communities in the same process of evolution of the EcoWeb. What are the principles of these behaviors? Research result will suggest appropriate rules for competition and cooperation in the EcoWeb.

(5) *Model and principle of flow*, including service flow, knowledge flow, information flow and material flow. Research should answers what is the difference between

these flows and those in natural ecosystem? What are the rules of these flows? How these flows support the efficient execution of EcoWeb? Research should answer these questions.

(6) *Health of the EcoWeb*. Research should give the method to evaluate the status of the EcoWeb, judge whether it evolves in a sustainable way, and provide the way to recover from unhealthy status.

(7) *Methodology for the development and research on Web Ecology*. It suggests the research method for developing, analyzing and maintaining the EcoWeb. Incremental development is a feasible way towards the EcoWeb. Comparison between natural ecosystem and the Web at different development stages will benefit the study on the methodology for the Web Ecology.

(8) *Particular EcoWebs*. The study of domain-specific artificial ecosystems on the EcoWeb. The development of these particular EcoWebs helps people understand and study its principles.

Philosophical issues will emerge when the EcoWeb becomes an environment where people live and work with. This is because the reality will be changed from natural to artificial.

2.3 Method

The natural ecosystem objectively exists and works with natural law. Natural ecology is the human recognition of the natural ecosystem and the relationship between human society and natural ecosystem. The energy flow, information flow and material flow in natural ecosystem is governed by natural laws as shown in Fig. 2. Principles, hypotheses, and problems in natural ecology can be rethought under the digital condition in EcoWeb.

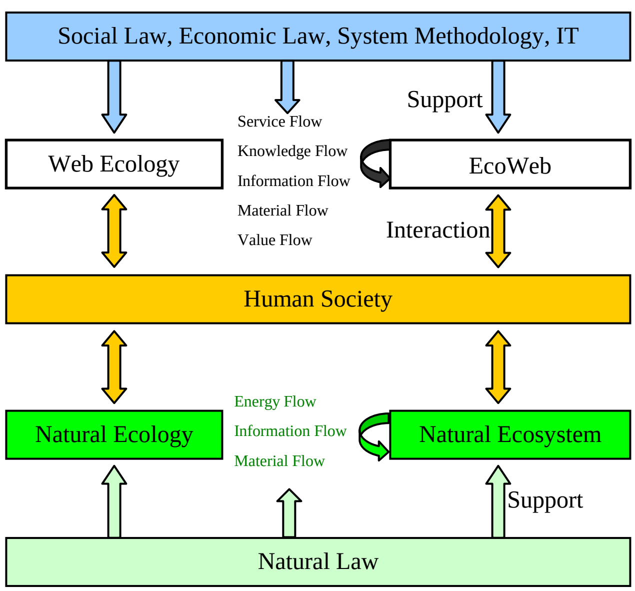

Fig. 2. Relationship among Ecological Web (EcoWeb), Web Ecology, and natural ecology. The current Web facilitates the sharing of information. The food web guarantees the harmony of natural ecosystem. The EcoWeb will facilitate the harmony of society.

As a digital society, the EcoWeb executes according to social law, economic laws and information technology. The running service flow, knowledge flow, information flow, material flow and value flow implements the function of the EcoWeb.

The EcoWeb does not exist at present, so research method of the Web Ecology is different from that of the natural ecosystem.

Fig. 3 suggests the general research method of the Web Ecology. Since the EcoWeb is a complex system, the system methodology can support research of the Web Ecology.

Studying the web hidden in society, economy and nature can help establish the fundamental rules of the EcoWeb. Some principles in the natural ecosystem and society such as the small-world [16], survival of fittest, the rich gets richer, and the indirect reciprocity can be examined to see if they are suitable in the EcoWeb [17].

Rules in social science, management science and economics can also be used for reference in research of Web Ecology and they could also help evaluate the research on the EcoWeb.

The study of Web X.0 and the development experience of IT (Information Theory and Information Technology) will help choose the way to develop the EcoWeb.

Establishing the analogy between various flows in nature (e.g., water flow) and the characteristics of the flows in EcoWeb will benefit research on the principles of the flows in EcoWeb.

Hypotheses can be proposed by surveying the natural ecology, rules in social science and economics. Since EcoWeb does not exist at present, scientific hypothesis will be very important in research of the Web Ecology.

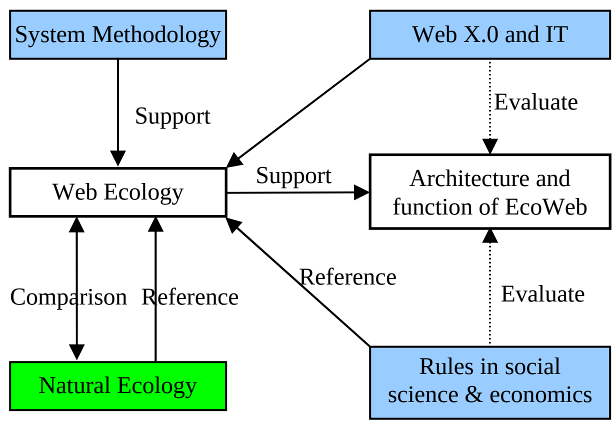

Fig. 3. Research method of Web Ecology.

3. INDIVIDUAL MODEL

The world is constituted by versatile individuals, species and communities. Just as the emergence of live on the earth, the current passive Web pages and documents will evolve into a live object in the future EcoWeb.

Sixty years' ago, V.Bush proposed the ideal of memex — a device that can store books, records and communications, and can be mechanized to be consulted with exceeding speed and flexibility [7]. The invention of general-purpose computer and Internet largely realized the ideal.

What is the individual in the computer world? Computer scientists have invented many individual models by abstraction. Object-oriented programming and development method use the notions of object and class to unify diverse abstractions and simplify the conceptualization of complex objective world [5]. Separating data from program is an important notion in computer science, which greatly promotes the study of data structure and algorithm. Agent and multi-agent technologies simulate individual and interaction between individuals [11].

J.Gray proposed the notion of personal memex and world memex [14]. The personal memex could record everything a person sees and hears, and quickly retrieve any item on request. The world memex could answer questions about the given text and summarize the text as precisely and quickly as a human expert in that field. Do the same for music, art, and cinema.

The notion of soft-device was proposed to uniformly model versatile passive or active resources in the future interconnection environment [21]. They are configurable, adaptive and context-aware service organisms, modeling various types of Internet resources, hosting distributed network software and devices. One soft-device can selectively inherit the function of another soft-device, and different soft-devices can be easily composed into one with richer function. Apparently, current middleware does not satisfy above definition. The functions of current search engines like Google cannot be inherited according to requirement, so they are not soft-devices.

In macrocosm, soft-devices are self-organized by interacting with each other and with human to form an evolving self-organized society. Establishing a competition mechanism in this society can help improve its effectiveness. In microcosm, soft-devices are tightly coupled to perform the integrated software via information flow. A soft-device owns individual information and knowledge and the mechanism to use them. Therefore in vision of soft-device, the behavior of software is the same as its structure.

Information and knowledge are regarded as passive data previously. The soft-device model will be the advanced stage of information and knowledge. Information, knowledge and software can be unified by soft-devices.

Existing software, databases, applications or web services could be encapsulated as individual organisms, which can be further organized into species.

4. FLOW MODELS

The service flow, information flow, knowledge flow, value flow and material flow relevant to social activities. The study of its rules could benefit from social science, management science and economics.

4.1 Service Flow

Service flow is at the high-level of the EcoWeb. There are two motivations of generating the service flow: (1) the reliance between services, and (2) the demand from social activities. Different from static services, service flow dynamically organizes services and provides appropriate service process for demanders according to the principles of management science and economics. The study of workflow and service science will help research on the service flow [13].

4.2 Information Flow

Information transformation and transmission forms information flow. The study of information flow is to ensure the efficient transmission of information through individuals and the provision of necessary information for demanders. An effective information flow is relevant to users' interest and preference. Shannon's information theory is an important reference for the study of information flow [18].

4.3 Knowledge Flow

Knowledge itself is power. Knowledge flow is the power of a team. The original force of knowledge flow comes from human's problem-solving requirement, the intrinsic motivation of knowing the world and reputation. The study of knowledge flow is to guarantee the efficient and effective knowledge sharing across the network to promote the productivity of a virtual organization. An efficient and effective knowledge flow depends on the organization of individuals of different knowledge power, social principle and economic principle [29, 28].

4.4 Value Flow

Value flow is accompanied with exchange activities. Value flow is a product of social development, which does not exist in natural ecosystem. It pursues a maximum growth when flowing through social activities. Money flow reflects the value flow. Principles of economics will help research on the value flow. The value flow is accompanied with service flow, information flow, knowledge flow and material flow.

4.5 Material Flow

Material flow refers to the transmission of digital or real materials through individuals or in the business processes or industrial processes in EcoWeb. Effective service flow needs the cooperation of material flow logistics. Relevant research in ecology and management science will help research on the material flow.

Service flow, information flow, knowledge flow, value flow and material flow often involve in the same process. For example, the material flow will usually go with the value flow. How they influence each other? How they cooperate with each other to obtain efficiency and effectiveness? Research need to answer these questions.

4.6 Community Discovery in Dynamic Flow

Particular structure has been found in many complex networks such as the Web, citation networks, email networks, food webs, social networks and biochemical networks: nodes are often clustered into tightly-knit groups, and edges are dense within groups and loose between groups [8, 20]. Such a structure reflects the characteristic of human group behavior of sharing information [2, 4]. Research on discovery of network communities has been done as graph partitioning in graph theory, computer science, hierarchical clustering in sociology and geographical partition.

Previous community discovery approaches may not be suitable for semantics-rich web as implied semantic relations can be derived out from existing relations, and adding a node or relation could influence many nodes and even the whole network.

Flows in the EcoWeb are dynamic and content relevant. And, different types of flows follow different rules. So community discovery in the dynamic flows is an important issue to be studied.

5. FROM WEB X.0 TO ECOWEB

The current Web, i.e., Web 1.0, is mainly a read-only information sharing platform. Its characteristic is the easy usage mode and the self-organization hyperlink architecture: one page can link to any other page. Society and culture has shown some influence on forming of the Web structure. The following phenomena can be observed: people tend to read the web pages in the same language as they previously read, and a web page is likely to link to the page in the same language. Actually, the worldwide Web is local to cultures and communities.

Web 2.0 provides a decentralized massively interactive information sharing platform. By this interactive feature, society and culture will influence the evolution of the Web more significantly. Currently, Web 2.0 is still in its infancy and poor in semantics. The major characteristic of Web 2.0 seams to be the ability of massive creation and annotation of various contents.

The Web 1.0 uses the dominant technology: HTTP protocol, HTML-based web page design, and the URL web page locating mechanism. Search engines are the complementary technology of Web 1.0. From Web 2.0, the Web will enter an era of diverse technologies and usage modes.

Web 3.0 would be a semantics-rich Web based on Web 1.0 and Web 2.0. Web 1.0 provides human understandable contents and Web 2.0 facilitates the interaction. Research on Semantic Web will help establish Web 3.0 research community.

The evolvement of software neglects the lower version. Functions of the new version completely cover the functions of old versions. So people tend to pursue the latest version.

The characteristic of the Web evolution is that the old versions will still be effective and co-evolve with the new versions. People of different communities would prefer different versions.

Web 4.0 would be a massive knowledge Web/Grid, which has the following features:

(1) Massive users who are willing to explain Web resources due to certain incentive models.

(2) Automatic accumulation of relational knowledge by
- discovering semantic relations between contents, between people and between people and meta information on contents;
- cluster texts and then constructing content classification hierarchies;
- discovering communities in the semantically linked network; and,
- analogical reasoning and inductive reasoning.

(3) Accumulating problem-solving knowledge by various question-answering mechanisms.

(4) Decentralized relational query and reasoning over the semantically linked contents.

(5) The mechanism of using relational knowledge to explain contents, using problem-solving knowledge to explain content and relational knowledge, and using relational knowledge to complete the problem-solving knowledge.

(6) Automatic evolution of relational knowledge with massive information sharing behaviors.

(7) Query loosely couples with the structure of resource organization.

(8) Architecture for resource organization is scalable and can adapt to change of resources.

The final form of the Web X.0 will be EcoWeb, which will co-evolve with our culture and society. During evolution, fragmenting the uniform Web architecture and technology into communities will be unavoidable according to the diversity requirement of the ecology. The facture of the Web by no means go back to information isolation. It is a higher level of the development spiral. Fragments will become communities connected with each other by semantic links. So the architecture of the EcoWeb will be a decentralized system consisting of communities of various types.

6. THE ARCHITECTURE

6.1 The Decentralized Evolution Model

The natural ecosystem consists of evolving local ecosystems. In this decentralized system, different species efficiently make use of resources in a local ecosystem accompany with energy flow, material flow and information flow.

Fig. 4 depicts the decentralized evolution model of the EcoWeb. Diverse technologies will co-exist to support different communities. Diverse technologies support communities and will evolve with the communities. There will be no direct interaction between communities. One community influences the other communities by social and economic principles and policies. Different communities may adopt different social systems. Each community consists of individuals and evolving species, which compete and help each other for reputation or interest.

An individual can only get what it needs within community and it needs to provide services for others within the community. Every individual is not only a consumer but also a producer. Those intelligent individual can play the role of decomposer to decompose a resource into pieces and reconstruct them into meaningful resources, which may be useful for other individuals. The economy and culture are localized to community.

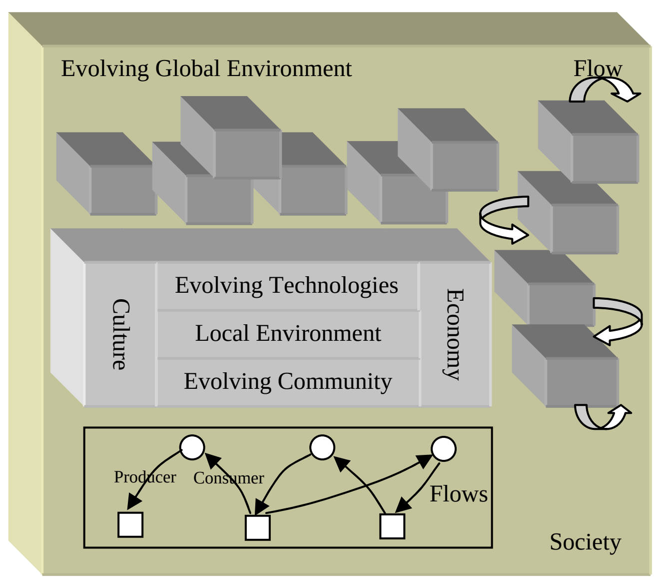

Fig. 4. The decentralized evolution model. This decentralized architecture supports the diversity of culture and technology.

A semantics-rich platform is important for supporting advanced functions of the EcoWeb. Recent research progress of the Semantic Web research community and the database research community shows increasing communications between the two communities. Closer cooperation between the two communities will provide better solutions for establishing a semantics-rich platform.

Since traditional P2P networks are poor in semantic processing ability [1, 19], effort has been made on establishing various semantic overlays [30, 31, 32]. The semantic overlay P2P network is to support autonomous management of resources and intelligent up-level applications. Relevant technologies could be used as the underlying infrastructure for the EcoWeb. A reference architecture for the future interconnection environment is suggested in [26].

To increase the diversity, the following section introduces some technologies that can be used to semantically organize resources.

6.2 The Semantic Link Network Model

Various explicit and implicit semantic relations in the world constitute a semantic link network, which can be formalized into a semantic data model.

The Semantic Link Network SLN is an autonomous semantic data model for the future semantics-rich Web [23]. It consists of semantic nodes (abstract concept, instances, a schema of data set, or an identity of complex object), semantic links between nodes, and a set of relational reasoning rules like $\alpha\cdot\beta\Rightarrow\gamma$ (i.e., semantic relation α and semantic relation β imply semantic relation γ).

As shown in Fig. 5, the Semantic Link Network model includes the following aspects:

(1) *Semantic Space*. The semantics of semantic nodes and semantic links are specified by the classification trees and reasoning rules in the semantic space. The first-level of the classification trees regulate the commonsense, the second-level regulates the domain commonsense like ACM CCS. Users can use their own keywords to tag semantic nodes and semantic links by extending the classification. The frequently used user-defined tags can be regarded as commonsense by linking them to existing classes, but other user-defined tags should be given detailed explanations.

(2) *Metric Space*. The metric space determines the *importance* of a Semantic Link Network. The importance of a semantic link is in positive proportion to three factors: (a) the importance of its two ending nodes; (b) its occurrence in the Semantic Link Network; and, (c) the times it participates in semantic reasoning. The importance of a semantic node is in positive proportion to the importance of its neighbor nodes. The metric space also determines the *probability* over the Semantic Link Network. The probability of a semantic link is in positive proportion to the probability of its premise links if there is an appropriate reasoning rule. The probability of a node is determined by the probability it belongs to a classification.

(3) *Abstract Semantic Link Network* consists of abstract concepts and abstract semantic links. An abstract semantic link network can be regarded as the schema of the SLN where each semantic node and semantic link is defined by a field: a class in the classification trees.

(4) *Instance Semantic Link Network* consists of instance nodes and instance semantic links. Several instance Semantic Link Networks can be generalized as an abstract Semantic Link Network.

The Semantic Link Network has the following main characteristics:

(1) It inherits the characteristics of the Web.
(2) It is easy to use, without any special training on its use.
(3) It is self-organized: any node can semantically link to any other node.
(4) It is a loosely coupled semantic data model. New nodes can be freely added to the network by establishing the semantic link(s) with existing semantic nodes and the new node.
(5) It supports relational query based on semantic links and semantic link reasoning.

The inter-influenced reasoning rules constitute semantic closures over semantic reasoning rules. These semantic closures can help regionalization of semantic reasoning.

Semantic communities will be formed in SLN due to its semantic self-organization feature. Different from previous graph-based community discovery, the semantic communities is specific to semantics and reasoning rules. So they are useful in realizing relational requires.

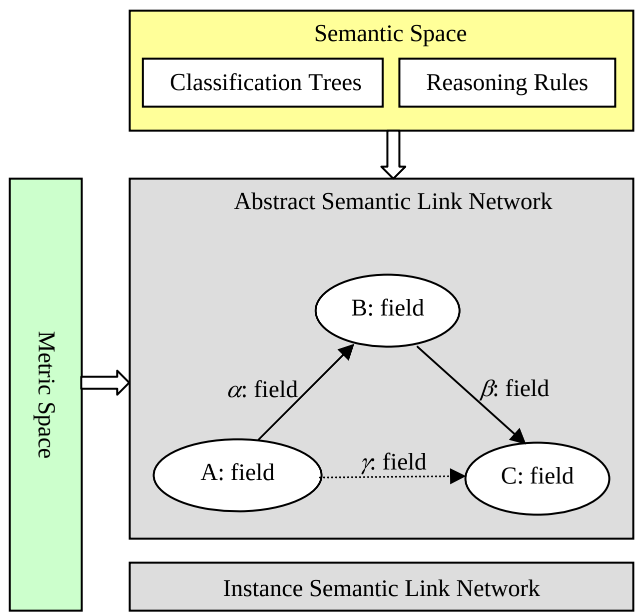

Fig.5. The Semantic Link Network, a self-organized semantic data model for the future Web.

6.3 The Web Resource Space Model

Classification is the most basic way to know the real world and manage real-world objects. Normalizing the classification can form a classification-based semantic data model.

The Web Resource Space Model is a semantic data model for specifying, storing, managing and locating contents of Web resources by normalizing the classification [29]. An *n*-dimensional resource space represents *n* kinds of classification method. Selecting one coordinate at every dimension can uniquely locate a point — a set of resources of the same category.

A resource space focuses on contents, so resources in a point can take any form.

A resource space is a multi-dimensional classification space where dimensions are discrete and every coordinate can be a coordinate tree, where low-level coordinates finely classify their parent coordinates. The intrinsic characteristics of the Resource Space Model determine its research value since it is not an ordinary distance space with linear dimensions. A point in the space can be a set of resources, a set of semantic links, or a resource space.

A resource space can be normalized to ensure the correctness of managing resources by setting constraints on axis and between axes. The normal forms of the Resource Space Model are to realize this type of normalization [23, 29].

People have many ways to organize and mange real-world objects. Relation and classification are two most basic ways. The SLN and RSM are two models making use of these basic ways.

The Semantic Link Network represents self-organization and the Resource Space Model represents normalization. The semantic links can establish ties between resources and between spaces, and the resource space model can be used to normalize the classification trees. So the Semantic Link Network, Resource Space Model, and traditional relational database model [10] can be integrated to provide a stronger semantic data model for the future web.

6.4 IMAGINE-1

IMAGINE-1 is proposed as an evolving, self-organized, self-managed and dynamic scalable human-machine environment [26], based on the following components:

(1) Semantic-based organization of resources on P2P networks;

(2) Decentralized resource monitoring, scheduling and management in applications; and,

(3) The development of high-level applications with an advanced architecture and application framework.

Its architecture has three distinctive characteristics:

(1) A general and scalable platform that supports the development of applications in different domains.

(2) A virtual environment that simultaneously supports research and development of itself and of domain applications.

(3) Integrating research and development laboratories with a real application platform so that experimental applications can be tested in a real environment with user participation.

It will implement an embedded resource management platform on a P2P network to support self-organization and self-management of applications, so that sophisticated applications can be developed to provide scalable services on large-scale networks.

China Knowledge Grid Research Group is developing the Web Resource Space Model 2.0, which incorporates the Web 2.0, Web Resource Space Model, Semantic Link Network, semantic peer-to-peer network, semantic community discovery, and the platform IMAGINE-1. It promises a scalable, autonomous, adaptable, automated, normalized, loosely coupled, decentralized and evolving platform.

7. BENEFIT OF THE WEB ECOLOGY RESEARCH

Carrying out research on Web Ecology can bring benefit in the following aspects:

(1) A basic scientific research. Web ecology would be a new branch of science.

(2) Methodology thinking. EcoWeb will be a future integration of artificial system and society rather than objective existing, so research methodology will be valuable in science.

(3) Ecological thinking. Research on Web Ecology will help ecologists rethink their research scope and research objects. Research on Web Ecology will be a significant reference to research on natural ecology.

(4) Social thinking. The EcoWeb will influence human society more directly and substantially than the current web. How will it influence people of different communities? Human's reading scope is very limited compared with the expanding resources. How to form a healthy local ecology around people is an interesting research issue. Research on Web Ecology will help make policies for harmonious development of society. Research can also help make policy for sustainable development of the Web. The development of technology should be in line with the development of human being in such aspects as knowledge, skill, culture and art.

(5) Computer science thinking. A global ecosystem consists of local ecosystems. One local ecosystem influences others by material flow and climate. This localization is formed with local characteristics such as climate, land and water. The energy limitation of individuals also determines the limited scale of the food web and also influences the localization of the ecosystem. The computer science is largely based on Turing Machine and algorithm. But Turing Machine is not suitable for all requirements or not the unique solution. Computer scientists can learn from natural ecosystem to create a new computing model (ecological computing?) by exploring the intrinsic principles in natural ecosystem.

(6) Current Web research thinking. Web Ecology research will form helpful reference to the research on the web and semantic web.

8. CONCLUSION

The current Web facilitates the global sharing of information by simple usage mode and the Web technologies such as the HTML and HTTP. The future Web will be a decentralized digital ecological environment consisting of diverse local communities holding diverse societies, economic systems, cultures, sciences and technologies and co-evolving with them.

The food web contributes to the harmony of the natural ecosystem such that any resource can be made full use of. The EcoWeb will enhance the harmony of our society.

Artificial intelligent concerns human wisdom. The Web Ecology concerns the relationship between human and the environment they live and work.

The Web Ecology will be a multi-disciplinary science on research, planning, development and evolution of the future EcoWeb. Policy should be made to push its development.

ACKNOWLEDGEMENT

The research work is supported by the National Basic Research Program of China (973 project no. 2003CB317001) and the National Science Foundation of China (Grant no.70773109). We thank all team members of China Knowledge Grid Research Group for their help and cooperation.

9. REFERENCES

[1] Androutsellis-Theotokis, S. and Spinellis, D. A Survey of Peer-to-Peer Content Distribution Technologies. ACM Computing Surveys, 36(4) (2004) 335-371.

[2] Barabási, A.L. and Albert, R. Emergence of Scaling in Random Networks. Science, 286, (1999) 509-512.

[3] Berners-Lee, J Hendler, O Lassila, The Semantic Web, Scientific American, 2001.

[4] Berners-Lee T., et al., A Framework for Web Science, Foundations and Trends in Web Science, 2006, 1-130.

[5] Booch, G. Object Oriented Design with Applications, Redwood City, Calif.: Benjamin/Cummings Pub. Co., 1991.

[6] Bronfenbrenner, U., The Ecology of Human Development: Experiments by Nature and Design, Harvard University,1979.

[7] Bush, V. As We May Think, Atlantic Monthly, July, 1945.

[8] Girvan, M. and Newman, M. Community Structure in Social and Biological Networks. Proceedings of National Academy of Sciences of the United States of America, (2002) 8271-8276.

[9] De Roure, D. Jennings, N.R. Shadbolt, N.R., The Semantic Grid: Past, Present, and Future, Proceedings of the IEEE, 93(3), (2005), 669-681.

[10] Codd, E. F. A Relational Model of Data for Large Shared Data Banks. Communications of the ACM, 13 (6) (1970) 377-387.

[11] Ferber, J. Multi-Agent Systems: an Introduction to Distributed Artificial Intelligence, Harlow: Addison Wesley Longman, 1999.

[12] Foster, I. Internet Computing and the Emerging Grid, Nature, Dec., 2000.

[13] Foster, I. Service-Oriented Science, Science, 308(5723) (2005) 814-817.

[14] Gray, J. What Next?: A Dozen Information-Technology Research Goals, Journal of ACM, 50(1), (2003) 41-57.

[15] Hey, T. and Trefethen, A. E., Cyberinfrastructure for e-Science, Science, 308 (5723) (2005)817-821.

[16] Kleinberg, J. Navigation in a Small World. Nature, 406, 2000, p.845.

[17] Nowak, M.A., and Sigmund, K.: Evolution of Indirect Reciprocity, Nature, 427(27), (2005) 1291-1298.

[18] Shannon, C.E. and Weiner W., The Mathematical Theory of Communication. University of Illinois Press, 1963.

[19] Stoica, I. et. al. Chord: A Scalable Peer-to-Peer Lookup Service for Internet Applications. Proc. ACM SIGCOMM, Aug. 2001, pp. 149 – 160.

[20] Wilkinson, D. M. and Huberman, B.A., A Method for Finding Communities of Related Genes. Proceedings of National Academy of Sciences of the United States of America, (101) (2004) 5241-5248.

[21] Zhuge, H., Clustering Soft-Devices in Semantic Grid. IEEE Computing in Science and Engineering, 4 (6) (2002) 60-62.

[22] Zhuge, H., China's e-Science Knowledge Grid Environment, IEEE Intelligent Systems, Jan./Feb, 2004, pp.13-17.

[23] Zhuge, H., The Knowledge Grid. World Scientific Publishing Co. Singapore, 2004.

[24] Zhuge, H. and Shi, X. Toward the Eco-Grid: a Harmoniously Evolved Interconnection Environment. Communications of the ACM, 47(9), (2004), 78-83.

[25] Zhuge H., Semantic Grid: Scientific Issues, Infrastructure, and Methodology. Communications of the ACM, 48(4), (2005)117-119.

[26] Zhuge, H., The Future Interconnection Environment, IEEE Computer, April, (2005) 27-33.

[27] Zhuge, H., The Open and Autonomous Interconnection Semantics. In Proc. ICEC 2006, 105-115.

[28] Zhuge, H., Discovery of Knowledge Flow in Science, Communications of the ACM, 49(5) (2006), 101-107.

[29] Zhuge, H., The Web Resource Space Model, Springer, 2007.

[30] Zhuge, H. and Li, X., Peer-to-Peer in Metric Space and Semantic Space, IEEE Transactions on Knowledge and Data Engineering, 6(19) (2007), 759-771.

[31] Zhuge, H. et al., HRing: A Structured P2P Overlay Based on Harmonic Series, IEEE Transactions on Parallel and Distributed Systems, 19, (2) (2008) 145-158.

[32] Zhuge H. and Feng, L., Distributed Suffix Tree Overlay for Peer-to-Peer Search, IEEE Transactions on Knowledge and Data Engineering, 20, (2) (2008), 276-285.