The Knowledge Grid Environment

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The Knowledge Grid Environment is an autonomous human-machine environment evolving with science, technology, culture and society.

Pursuing the Ideal of the Knowledge Grid Environment

Human and society who create, maintain and work with the Knowledge Grid Environment are important parts of the environment. Current information technologies such as the Internet, Web, Grid, peer-to-peer, data mining, information retrieval, question-answering and artificial intelligence are helpful references but not enough for studying and realizing the Knowledge Grid Environment.

The following statements can help clarify the notion of the Knowledge Grid Environment.

- 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 Knowledge Grid Environment consists of autonomous individuals, self-organized semantic communities, an adaptive networking mechanism, an evolving semantic overlay keeping meaningful connection between individuals, flows for dynamic resource sharing, and mechanisms supporting effective resource management and providing appropriate knowledge services for problem-solving and innovation. It supports innovation and harmonious development of science, technology and culture. Main research objects are architecture and functions of the environment and its individuals, relations between individuals and between communities, and the relation between the environment and socio-economic development. It has the following characteristics:

- *Autonomy*. In microcosm, individuals in the environment autonomously acquire, create and share knowledge with others, and work according to rules of socio-economic development. In macrocosm, communities are self-organized and evolve with the interaction between individuals and autonomous knowledge sharing processes.
- *Evolution*. In microcosm, the initial structure (data model) for organizing knowledge is automatically generated and then evolved into more and more personalized one according to the growth and diversity of personal knowledge. This evolution supports efficient knowledge management and sharing. In macrocosm, the network structure of the environment can self-adapt according to the networking feature of knowledge sharing. Fig.1 depicts the architecture of an adaptive networking mechanism.
- *Multidisciplinary methodology.* The research method of the Knowledge Grid Environment needs to benefit from existing technologies and methods, to incorporate epistemology and ontology to reflect human characteristics of recognizing the environment, to make use of achievement of multiple disciplines such as management science, ecology and economy, and to absorb the technologies and methods invented in the development of the Internet and Web. Research method should be based on system methodology, philosophy, ecology, economics, and management science. Its macrocosm working principles will be inspired from natural law and social rules.

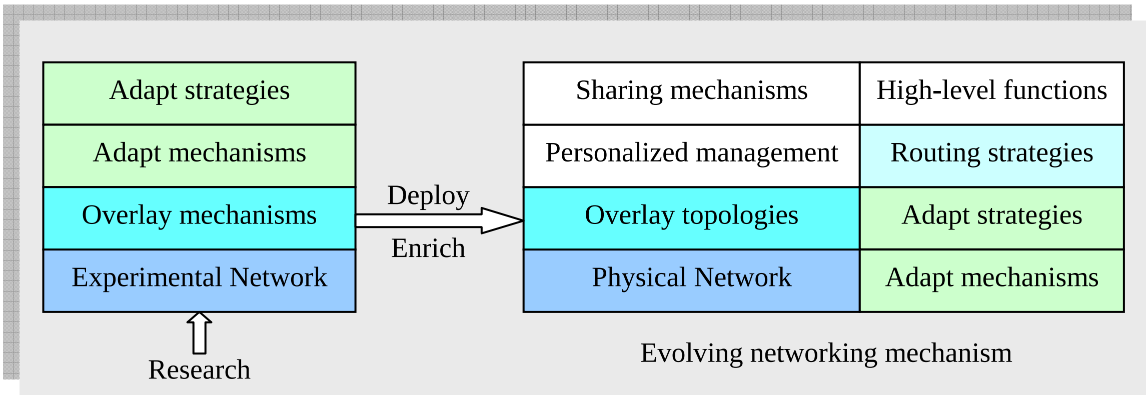

Fig.1. Evolving networking mechanism for the Knowledge Grid Environment.

China Knowledge Research Group has been pursing the ideal of Knowledge Grid Environment. A Web-based Knowledge Grid system was developed in the year 2001 for web knowledge management and retrieval. In May, 2002, the initial ideal of the Knowledge Grid was proposed [1]. In January, 2004, the ideal of Knowledge Grid was formally stated [4], and the first monograph The Knowledge Grid was published in December[5], which systematically states the methodology and technology of the Knowledge Grid. In year 2005, the series international conference SKG (International Conference on Semantics, Knowledge and Grid, www.knowledgegrid.net/) was initiated. In the end of the year 2007, the monograph 'The Web Resource Space Model' was published.

Main achievement so far includes the following aspects:

- Resource Space Model ——The semantic data model for normally organizing various resources to support efficient resource management and retrieval services [5, 12, 14].
- Semantic Link Network ——A self-organized semantic data model by using relational semantic links to organize various resources to support relational query and reasoning [5, 8]. The Resource Space Model, Semantic Link Network, database and Web languages can be integrated to form a powerful semantic platform for intelligent Web applications.
- Knowledge Flow Network——A self-organized dynamic knowledge sharing process model [5, 13].
- Methodology——Scientific issues and research method of the Knowledge Grid Environment [5].
- Decentralized Semantic Overlay——A peer-to-peer index overlay to support decentralized intelligent applications [7, 8, 10, 11].
- Interconnection Semantics——A study of the semantics in the interconnection environment.

Document is the main carrier of human knowledge. Scientists have been studying the approach to extract knowledge in documents, which is hard as knowledge is hided in text. It would be interesting to separate knowledge from document in its formation stage. This needs to create a new document model and corresponding tools for reading and writing. The Active Document Framework enables documents to actively provide with information service [3]. Applications in culture and scientific research have been studied to connect the ideal to the reality.

References
1. H. Zhuge, A Knowledge Grid Model and Platform for Global Knowledge Sharing. Expert Systems with Application, 22(4) (2002) 313-320.
2. H. Zhuge, Clustering Soft-Devices in Semantic Grid. *IEEE Computing in Science and Engineering*, 4 (6) (2002) 60-62.
3. Zhuge, H. Active e-Document Framework ADF: Model and Platform, *Information and Management* 2003; 20 (43) 1-11.
4. H. Zhuge, China's e-Science Knowledge Grid Environment, *IEEE Intelligent Systems*, Jan./Feb, 2004, pp.13-17.
5. H. Zhuge, The Knowledge Grid. *World Scientific Publishing Co*. Singapore, 2004.
6. H. Zhuge, The Future Interconnection Environment, *IEEE Computer*, April, (2005) 27-33.
7. H.Zhuge, X.Sun, J.Liu, E.Yao and X.Chen, A Scalable P2P Platform for the Knowledge Grid, *IEEE Transactions on Knowledge and Data Engineering*, 17 (12) (2005) 1721-1736.
8. H. Zhuge, Autonomous Semantic Link Networking Model for the Knowledge Grid. *Concurrency and Computation: Practice and Experience*, 7(19) (2007) (1065–1085).
9. H.Zhuge and X.Li, Peer-to-Peer in Metric Space and Semantic Space, *IEEE Transactions on Knowledge and Data Engineering*, 6(19) (2007) 759-771.
10. H.Zhuge, X.Chen, X.Sun and E.Yao, HRing: A Structured P2P Overlay Based on Harmonic Series, *IEEE Transactions on Parallel and Distributed Systems*, 19, (2) (2008) 145-158.
11. H.Zhuge and L.Feng, Distributed Suffix Tree Overlay for Peer-to-Peer Search, *IEEE Transactions on Knowledge and Data Engineering*, 20, (2) (2008) 276-285.
12. H.Zhuge, The Web Resource Space Model, Springer, 2007.

Web 2.0-based Knowledge Grid Environment: A Massive Interactive Knowledge Web

Grid is not the unique platform for implementing the Knowledge Grid Environment. The Web and peer-to-peer network can also be the underlying platform. Web 1.0 requires users to express content in HTML, so it is a read-only information sharing network for ordinary users. Web 2.0 is a read-and-writable information sharing network, which provides a massively interactive information sharing platform for implementing the Knowledge Grid Environment at present stage.

A Web 2.0-based Knowledge Grid Environment can have the following features:

(1) Automatically clustering massive users and large-scale annotated resources according to the use relationship between users and their annotations, the resource-mediated relationship between users, and the user-mediated relationship between annotations. These clusters represent a kind of massive selection of semantics, which can be organized by classification semantics. The Resource Space Model can be used for efficient management.

(2) Automatically accumulating relational knowledge by
- discovering semantic relations between contents, between users, and between users and meta information on contents;
- clustering texts and then constructing content classification hierarchies; and,
- discovering communities in the semantically linked network.

(3) Automatically accumulating problem-solving knowledge by establishing various question-answering mechanisms.
(4) Decentralized relational query and reasoning over the semantically linked content network.
(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) Scalable structure of resource organization, which can adapt to the evolution of community semantics due to continuous change of users and their recommended contents. Such a structure loosely couples with queries. Users do not have to know the structure of resource organization.
(8) Techniques compatible with Web standards.

The Web 2.0–based Knowledge Grid environment substantially changes the way of knowledge acquisition in traditional knowledge engineering, which is from individual experts or knowledge engineers to massive contribution of knowledge. It realizes a harmony: *one for everyone, everyone for one*.

Individuals in the Knowledge Grid Environment

The world is constituted by versatile individuals and communities. Sixty years' ago, Vannevar 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 [4]. The invention of general-purpose computer and Internet largely realized the ideal.

What is the individual of 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 the diversity of abstraction and simplify the conceptualization of complex objective world [3]. Separating data from program is an important notion in computer science, which greatly promotes the study of data structure and algorithm.

Jim Gray proposed the notion of personal memex and world memex [7]. The personal memex can record everything a person sees and hears, and 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.

Then, *what are the individual and community in the Knowledge Grid environment*? *How are their structures and functions*? *How they are generated*? *How do they evolve*? And, *how do they self-organize for tasks*?

Current search engines, spywares and crawlers are for special purposes and they do not support inheritance. The following general individual model ME (Memex Extension) shares the characteristics with the soft-device that models various passive or active network resources.

MEs are configurable, adaptive and context-aware digital organisms, modeling various types of network resources, hosting distributed network software and devices. *One ME can selectively inherit the function of another ME, and MEs can be composed into one with a richer function*.

ME model will be the advanced stage of information and knowledge. Information, knowledge and software can be unified by MEs. In macrocosm, MEs are self-organized by interacting with each other and with human to hold an evolving ME society. A competition mechanism in this society can help improve its effectiveness. In microcosm, MEs are tightly coupled to perform the integrated software via information flow and control flow. Information and functions are encapsulated within MEs. *Therefore in vision of ME, the behavior of software is the same as its structure*.

A World of ME

A ME is a network service organism that can be configured for various purposes just as installing a computer or a printer, it can actively provide with alternative services by automatically seeking requirements, and can adapt to change. A ME can not only run autonomously but also host other MEs. The configurable feature develops early special-purpose computer to general-purpose computer that can run various software.

A ME world consists of the self-organized ME society, the requirement space, and two roles: *producer* and *consumer*. The producer can input necessary content into a ME and then configuring it for new services. The consumers can enjoy the service provided by any ME in two ways: *push* and *subscribe*. MEs could actively push services to consumers, and can also accept subscription from consumers to provide with long-term services (a process of service provision). Any ME or user can play the role of producer to generate a ME or play the role of consumer to enjoy the proper service by posting their requirements or by selecting and using an appropriate ME to obtain the required services. A ME can accept the content definition from multiple providers and provide services for multiple consumers with a certain cost. Using virtual machine technology, a ME can perform any hardware across the Internet.

A ME consists of the following components as shown in Figure 2:

- *The detector* detects the current situation and requirements in the requirement space, processes the informal requirements and transforms them into more formal ones, and then seeks solutions in its resource spaces or takes appropriate actions.
- *The interface* supports interaction between MEs and between its components. It also supports the producer in defining content and offers services to others by appropriate workflows.
- *The explainer* explains requirements, information, knowledge and services according to personal knowledge and the semantic relationship between resources.
- *The built-in workflows* enable the ME to work according to the tasks assigned by configuration. They time-sensitively and adaptively operate the ME by coordinating the execution of components.
- *The reasoning mechanism* inferences according to the knowledge specified in the knowledge space — a specialization of the resource space. Knowledge herein refers to the relation automatically obtained from the relations between human and between human and resources. The explainer interprets the reasoning result and submits it to the interface for display.
- *The resource space* specifies contents by combing classification semantics and relational semantics. As a kind of resource, knowledge is organized in *a knowledge space* that supports the operation of the explainer, the detector and the coordinator. It also contains meta-knowledge for adapting the processes according to the changing situation. The resource space provides various types of knowledge for ME and supports effective management and retrieval.
- *The coordinator* synergies and adapts above components according to information/knowledge/workflows between them and the principle of mutual enhancement, co-evolvement and sustainable development. This needs an appropriate evaluation function for this coordination.

There are no central controls in the ME world, so it is completely peer-to-peer [1]. The local resource space in a ME consists of a private resource space and a sharable resource space where resources are accessible to other MEs. All sharable resource spaces constitute a peer-to-peer global resource space, which offers scalable resource location and management.

Applications initialize and add requirements to the requirement space. The party who posts a requirement needs to pay in the market mechanism and determines the initial price of the requirement. The fulfilled requirements will be removed from the requirement space. The requirement space evolves with the addition of new MEs and removal of old requirements.

The local sharable resources can be shared by merging or joining relevant local resource spaces to get the entire view where resources are uniformly classified, and can be accessed via the semantic links in the peer-to-peer semantic link network. *The sharing and dependence relations between resources establish the symbiosis relationship among MEs.*

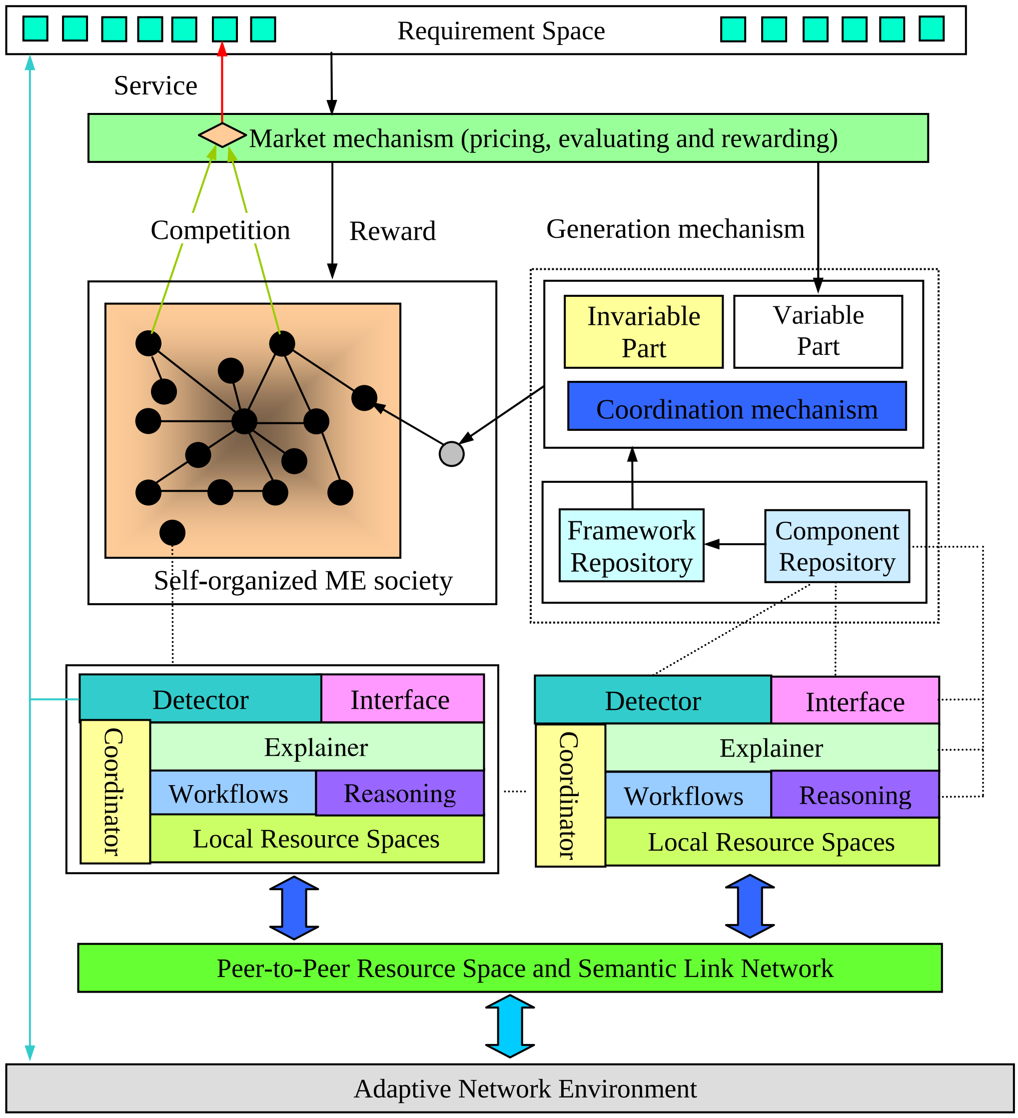

Figure 2. Architecture of the ME world.

A ME world can be defined by *space*, *time*, *structure*, *relation*, and *worth* φ: <*MEs*, *Flows*, *Time*, *Relations*, φ>, in which a ME is the encapsulation of processes on resource spaces under integrity constrains, i.e., *ME*=<*ResourceSpace*, *Processes*, *Constraints*> or in detail *ME*=<*ResourceSpace*, *Operations*, *Detector*, *Interface*, *Explainer*, *Workflows*, *Reasoning*, *Coordinator*, *Constraints*>. The processes realize the functions of ME by operating the detector, explainer, interface, coordinator, workflows, and reasoning mechanism. The resource spaces specify and organize information, knowledge and other resources in a normalized form. The processes defined in the ME should satisfy the constraints to ensure the process integrity: *a process outputs its result either to another process or to the resource space, and ensures that the input of a process is either from another process or from the resource space*.

To obtain the efficiency, the ME world needs a market mechanism for pricing, exchanging, evaluating and rewarding the services that MEs provided. Sometimes negotiation among MEs is needed to reach win-win solutions. MEs organize themselves according to their relationships and interactions during service process. The society evolves with the change of services, the addition of new MEs and the removal of those MEs that have not served others for a long time. MEs compete with each other to contribute service and to obtain reward (e.g., virtual money or reputation) by service evaluation and rewarding mechanism. Different from page rank distribution of the Web, the highest ranks of MEs in the society will be blocked and average out under the limitation of social regulations [2].

New MEs can be generated by getting a framework from the ME framework repository and then merging with the variable part according to the request from the market mechanism. The peer-to-peer resource space is formed by semantically linking local resource spaces in a peer-to-peer fashion.

The ME for Personal Web Information Service

The ME model can also be used to realize personal Web information service. Figure 3 depicts the architecture of ME for personal Web information services. It consists of the following components:

(1) *Crawler* —— collects Web resources satisfying personal interest from the Web.

(2) *Resource Space* —— manages the collected Web resources by classification semantics. Its structure keeps evolving with the increase of Web resources.

(3) *Semantic Link Network* —— establishes the relational semantics between Web resources.

(4) *Function set* —— includes such functions as discovering semantic communities, relational query, relational reasoning, and maintenance operations.

(5) *Detector* —— detects local capacities and other MEs on the Web for sharing and cooperation.

(6) *Interface* —— interacts with human or other MEs.

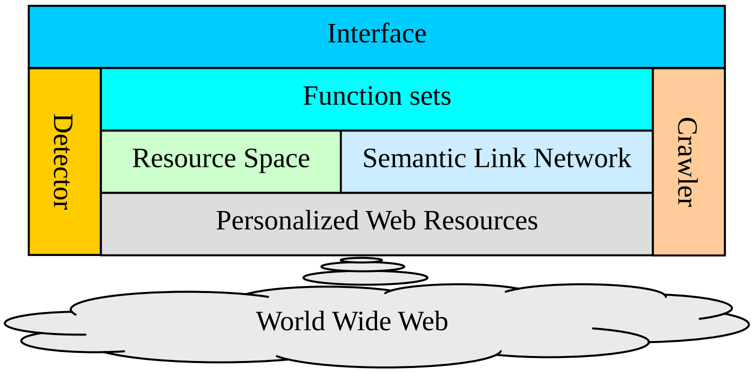

Figure 3. The ME for personal Web information services.

Compared with the current search engines, the ME has the following characteristics:

(1) *Effective and efficient personalized information services* —— it limits the scope of information search by indexing the interested Web resources in the resource space and the semantic link network. The classification semantics supports efficient and personalized management of Web resources.

(2) *Support relational query* —— it supports relational query based on the semantic link network and relational reasoning on the semantic link network.

(3) *Evolving structure* —— the structure for organizing Web resources can evolve with the change of the collected resources. This can provide up-to-date effectiveness of resource management.

(4) *Inheritable functions* —— its functions can be inherited by other MEs and new functions can be added by inheriting from other MEs.

Inheritance and Fusion

On Inheritance

Inheritance is a natural phenomenon in the biological world. The heredity information keeps the evolution of species, and the mutation of the hereditary information makes the diversity of species. In human society, social characteristics of inheritance differentiate human society from the animal world. Law and morals set the conditions for marriage and inheritance. Individuals are assigned the right to own the heritage of his/her parents. Inheritance in biology is about the principles that govern the inheritance of genes on sex chromosomes. As a special relationship, inheritance was also investigated in artificial intelligence [10]. Evolutionary computing also borrowed this idea for optimizing solutions.

Inheritance in object-oriented programming is for software reuse [9]. Inheritance constructs class hierarchy, in which a subclass can inherit the states and methods from the super-class. Subclasses can add variables and methods to the classes they inherit from the super-class. Subclasses can override the inherited methods and provide specialized implementation for those methods. One view is that inheritance can only take place between classes. A class holds the similarities among a group of objects, dictating the structure and behavior of its instances. Another view is the prototype inheritance, or object inheritance. A prototype represents the default behavior for some concepts. There are no classes in prototype-based systems. New object types are formed directly by constructing concrete and full-fledged objects. The distinction between the two types of inheritance reflects philosophical dispute concerning the representation of abstractions. Prototype-based approaches view the world by exploiting alikeness rather than classification. Previous software inheritance mechanisms are more suitable for stable and local environment. How to realize inheritance mechanism in dynamic and distributed environment challenges software engineering at the global networking age.

Inheritance is a major way to generate new MEs in the ME world. Different from previous inheritance mechanisms, ME inheritance is dynamic in nature due to continuous evolution of MEs. Children inherited from the same ME at different time could be different and they will keep evolving after being generated.

A new ME can be generated for a definite purpose by the following operations:

- **Fusion**, denoted as ⊕, it generates new MEs by the following operation: *ME*⊕*ME'*=<*ResourceSpace*⊗*ResourceSpace'*, *Operation* ∪*Operation'*, *Processes*∪*Processes'*, *Constraints*∨*Constraints'*>, where ⊗ is the join or merge operations of two resource spaces; ∪ is the union of two operation sets; ∪ also represents the merge of two processes such that *processes*(ξ)=*processes*∪*processes'*(ξ) for any input ξ in the input field of the *process*; and, *Constraints*∨*Constraints'* is the logical OR of two constraints. *ME*⊗*ME'*=<*ResourceSpace*⊗*ResourceSpace'*, *Operation* ∩*Operation'*, *Processes*∩*Processes'*, *Constraints*∧*Constraints'*>.

- **Reduction**, it generates new MEs under constraints on the *ResourceSpace*, *Operations* and *Processes*.
- **Inheritance,** it enables a new ME to be generated by an existing ME represented as: *New.ME*→*ME*. *New.ME*= <*ResourceSpace*⊗Δ*ResourceSpace*, *Operation*∪Δ*Operation*, *Detector*∪Δ*Detector*, *Interface*∪Δ*Interface*, *Explainer*∪Δ*Explainer*, *Workflows*∪ Δ*Workflows*, *Reasoning*∪Δ*Reasoning*, *Coordinator*∪Δ*Coordinator*, *Constraints*∧*Constraints'*>. The inheritance relationship is transitive.
- **Multiple Inheritance**, it allows a new ME to inherit from two or more MEs represented as: *New*.(*ME'*⊗*ME''*) → *ME'*⊗*ME''*. *New*.(*ME'*⊗*ME''*) = <*ResourceSpace'*⊗*ResourceSpace''*⊗Δ*ResourceSpace*, *Operation'*∪*Operation''* ∪ Δ*Operation*, *Detector'*∪*Detector''* ∪ Δ*Detector*, *Interface'*∪*Interface''* ∪ Δ*Interface*, *Explainer'*∪ *Explainer''* ∪ Δ*Explainer*, *Workflows'*∪*Workflows''* ∪ Δ*Workflows*, *Reasoning'*∪ *Reasoning''*∪ Δ*Reasoning*, *Coordinator'*∪*Coordinator''* ∪ Δ*Coordinator*, *Constraints'*∧*Constraints''* ∧ Δ*Constraints*>.

A ME evolves with three dimensions: *time*, *inheritance* and *variety*. A ME can have a hierarchy of descendants, and changes itself with time due to the change of requirement and the status of itself. The change of a ME automatically induces the upgrading of its children. The changed ME could also have new children.

A ME society evolves with its social and market rules, which can be made with reference to human society, as they need to harmoniously co-exist and evolve. In the market mechanism, ME inheritance has the following social features:

- An evolving ME always tends to raise its rank, influence or reputation in the society.
- The higher rank MEs take priority in owning higher rank descendants.
- A ME always intends to maximize its profit from the market if the ME society selects the free competition mechanism to self-organize.

Self-Organization and Self-Adaptation

Self-organization has been investigated in many areas such as the formation of Web structure, Web services and agent coalition [2]. Relevant notions are J.V. Neumann's self-reproducing automata, the SYSER (SYstem of SElf-Reproduction, http://pespmc1.vub.ac.be/) and the multi-agent [5]. MEs are self-organized with the evolving service spaces and the requirement space as well as the inheritance, knowledge and information flows.

MEs compete for providing services according to the detected requirements and then get the reward. To ensure the justification in competition, a market mechanism selects MEs and logically organizes them to fulfill the requirement. A ME who provides service can also post requirements in the requirement space to acquire services from other MEs.

Information and knowledge flow coordinate MEs' behaviors. Competition in a large-scale ME world leads to unequal rank distribution among MEs. Knowing the distribution law helps make routing strategy to enhance the efficiency of information and knowledge flows. The driving force of information and knowledge flows is the interest among the involved MEs. The impact of MEs in information and knowledge flow networks is their social factor of making decisions to participate market competition.

A ME makes decisions to survive during its life cycle under the regulations in the ME world. Decisions should benefit individuals and communities involved. To maximize the benefit, a ME should adapt its functions to meet the change of the society. It needs to consider the following factors when making decisions:

- *Adaptation cost*— the time consumed for providing service to get profit and the cost for posting requirement and rewarding services provided by others.
- *Market share and trend*— the analysis for determining the opportunity for adaptation according to market information and competition.
- *Profit* — estimation of benefit according to possible market shares and adaptation cost.

Outcome of the decision is the target of adaptation — a new function. The coordinator mechanism will re-organize its functions according to the adaptation target.

Autonomous Animation of Culture

Animating Dunhuang Cave Wall-painting

Dunhuang cave wall-painting is the mixture of eastern culture and western culture. They describe ancient stories on the ancient silk-road. Feitian is a representative culture element in Dunhuang culture. Different types of Feitian appeared in different scenes representing different meaning. Figure 4 shows the process of animating Feitian wall-paintings. This animation is very useful for publicizing Dunhuang culture as it is difficult for visitors to know the meaning of the observed ancient wall-painting.

A three-dimensional resource space specifies the scene and the states of MEs. If we use relational data model to specify the scene, many tables are needed and the consistency between them needs to be maintained. The Resource Space Model can specify the content by classification semantics and provide a global view of relevant information on the scene. Semantic links are used to establish the relationship between roles, which can help determine the co-occurrence relationship between roles, scene and music, so that ME can better perform the culture. A semantic link can be built by different people sharing the same concept architecture like ACM CCS. After established, the semantic link network evolves with the interaction and can further help discover the intrinsic relations between artifacts as people are difficult to discover the relations between objects, which seemly does not exist.

Feitians in the painting are animated by MEs performing various patterns cooperatively and interacting with users upon pointed and clicked. A ME needs to display Feitian, controls its scale, monitors itself and others' locations, and realizes cooperative performance by adjusting the mode of motion. Visitors can know relevant stories, histories and references by interacting with ME.

The first step of animation is to determine the roles in the painting, its location in cave, and its meaning according to the documents about cave. The designers configure the MEs with the general rules and constraints on the motion of roles. The animation can be carried out by the following two ways:

- given a script to regulate the performance of MEs; and,
- given the description of the final state and allow the participated MEs to perform arbitrarily according to some basic rules (e.g., evenly distribution, symmetry, and avoiding overlap) and their knowledge and understanding on the scene they are exhibiting.

To improve performance, domain experts evaluate the performance according to meaningfulness and beauty criteria, and then feed their suggestions back as supplemented rules and constraints, which are learned by MEs as experience. Each ME performs and detects the performing pattern to see whether it can be explained in existing semantic space and whether it is simple.

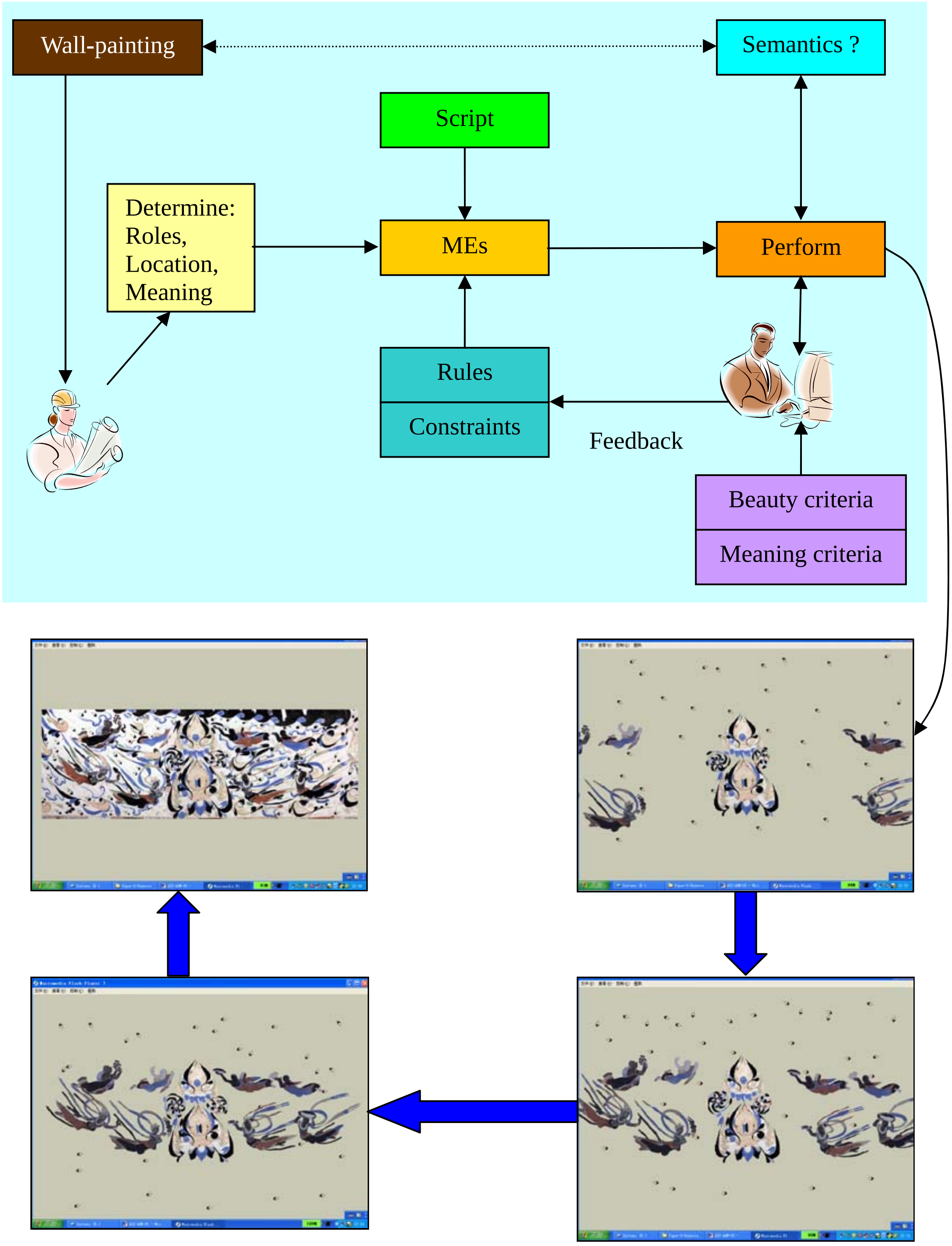

Figure 4. Animation process of Dunhuang wall-paintings.

New MEs can be generated by inheriting from one existing ME. Such dynamic inheritance relationship structures the ME society, establishes the basis for culture evolution, and can facilitate the generation of animation elements. Artifact MEs provide applications and designers with components to animate wall-painting. Figure 5 shows the environment for autonomous animation of Feitian wall-painting. The left-hand interface allows user to interfere the location of individual Feitian by clicking and drawing. In the right-hand interface, Fetians perform freely according to the performance rules and the detection of the distribution of Feitians in screen.

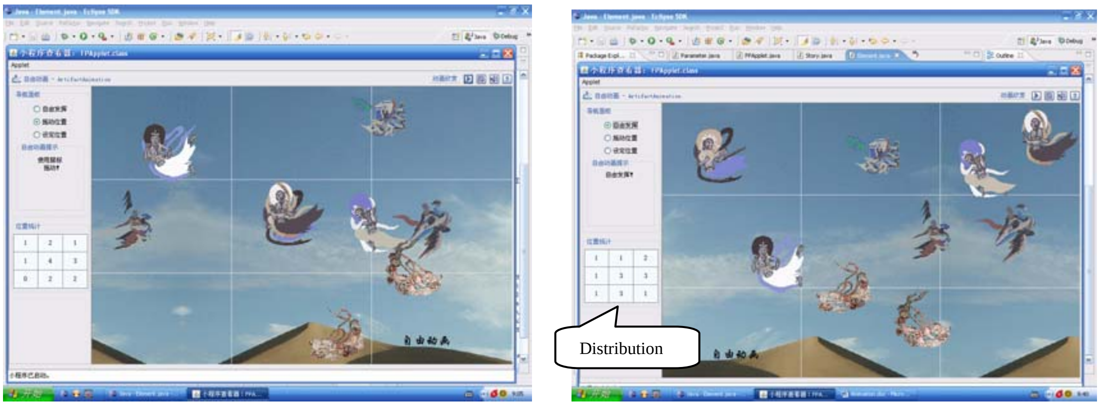

Figure 5. Autonomous animation of Feitian arts.

Culture Representation and Inheritance

The MEs can actively communicate with each other and with human users once activated. Figure 6 shows an example of the artifact MEs, where the roles in the painting can perform like actors accompanied with music and explain themselves upon being clicked. Users can click the left-hand bottom buttons to know the explanation of the scene, to query the local resource space, and search the Web to acquire more relevant information. The search results will be clustered and stored in local resource spaces for future use.

The scene of a wall painting can be regarded as a ME composed by multiple MEs. The inheritance relationship between scenes indicates the inheritance relationship between cultures of different dynasties.

A scene ME can be described by a semantic space and a set of operations. The semantic space consists of the orthogonal multi-dimensional semantic space and the related semantic links: *SemanticSpace*= <{<*Author*, *Dynasty*, *Actors*, *Content*, *Cave*, *ResourceType*, *ArtifactType*>, <*LinkToScenes*, *LinkToResources*, *LinkToStory*, *LinkToReality*, *LinkToKnowledge*, *SemanticRelationship*>}, where the resource type can be text, image, video and audio. The artifact type refers to building, color statue and wall painting. The operations include <*Move* (from <x_1, y_1, x_2, y_2> to <x_1', y_1', x_2', y_2'>)>, *Explanation*(*resource*), *RotateAt*(<*x*, *y*>), *ZoomIn*(<*x*, *y*, *rate*>), *ZoomOut*(<*x*, *y*, *rate*>), and *focus*(<*x*, *y*, *Radius*>).

Cultural Inheritance. Culture is represented by culture elements and architecture. Culture inheritance focuses on these features. For two sets of features that describe scenes *A* and *A*': *A*=<{*Color*, *Style*, *Layout*, *Architecture*, *Skill*}, *Time*> and *A*'=<{*Color*', *Style*', *Layout*', *Architecture*', *Skill*'}, *Time*'>. If the *Color*, *Style*, *Layout*, and *Architecture* are similar to *Color*', *Style*', *Layout*', and *Architecture*' respectively, and *A*' is created after *A* (i.e., *Time*'>*Time*), then we can say that *A*' is the cultural inheritance from *A*.

The key to determine the culture inheritance relationship is to find similarities between corresponding features of artifacts across generations. The following rules help make the determination:

- For color: Color *X* appears in *A* for describing *Y* also appears in *B* for describing *Y*.
- For style: Shape *X* is similar to *Y* if they are geometrically similar to each other.
- For layout: Layout *X* is similar to *Y* if there exists an isomorphism between them.
- For architecture: Structure *X* is similar to *Y* if there exists an isomorphism between them.
- For skill: Skill *X* is similar to *Y* if they implement similar structure or layout.

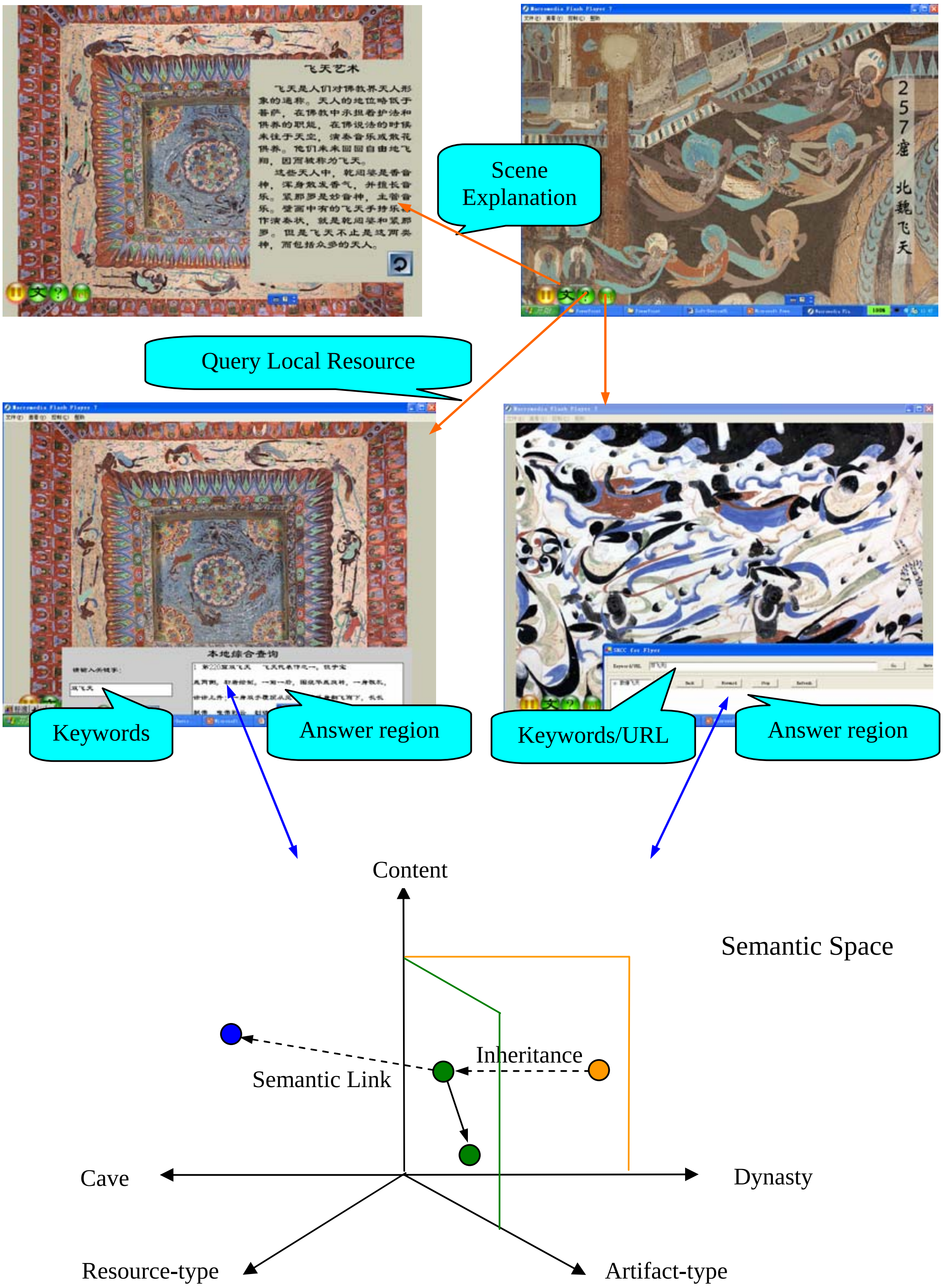

Figure 6. Artifact MEs can interact with users to explain content. The content retrieved from the Web will be processed, clustered and then stored in the resource space to support efficient retrieval.

The interaction between subjects in the society and their artifacts forms the following cultural networks:

- *Reference network of artifacts* — a network formed by observing the nature and artifacts, writing documents on artifacts (usually include descriptions and photos of artifacts) or citing the documents on the artifact. The number of citations and readers determines the reputation of a node in the network.
- *Semantic link network of artifacts* — a network of semantic relationships between meta-information of artifacts. The attributes of an artifact can be inferred by relevant semantic links and the semantics of relevant artifacts.
- *Value network of artifacts* — The interaction between artifacts and between human and artifacts constitute the value network of artifacts. The following factors influence the value of an artifact: the values of relevant artifacts (e.g., artifacts of co-authors, the same author, and the same dynasty) as well as the authorities and numbers of comment and citing.

Physically isolated artifacts interconnect with each other via relevant documents and knowledge. So culture exists in and evolves with a semantic network of artifacts and a network of interacting subjects. The two networks interact with each other by subjects' making and exhibiting behaviors. Subjects also write documents to explain artifacts. Cultural inheritance carries out by acquiring and fusing knowledge during observing, reading and understanding artifacts and relevant documents, and then using knowledge to create new artifacts and documents. So cultural inheritance implies cultural evolution and accompanies knowledge inheritance. Knowledge inheritance involves in fusing existing knowledge with new knowledge.

The world of MEs can adopt a kind of market selection mechanism to interpret the fitness in culture selection during the evolution of culture. For example, the times of the occurrence of culture features with the development of dynasties can be taken as the selection criteria.

Work of animating Dunhuang Feitian wall-paintings can help people understand the forms, content and creation of culture in real world over time and how people can benefit from them, and can inspire thinking on the culture in the Knowledge Grid Environment—carriers, forms, creation and evolution.

Effective knowledge sharing between human via a knowledge base system was the major concern of traditional knowledge engineering. Human (knowledge engineers) had to codify human (experts') knowledge and then stored them in the knowledge base system for providing consulting service for human (users). The future Knowledge Grid Environment will realize knowledge sharing between human and knowledge carrier as well as between knowledge carriers.

As configurable, adaptive and context-aware organism carrying knowledge in the Knowledge Grid Environment, MEs organize themselves to perform tasks according to social and economical principles to ensure its simplicity, diversity and effectiveness. New MEs can be generated in the evolving environment by inheritance. The ME model is also a knowledge model that can actively detect problems and fuse with and inherit from others' knowledge to obtain reputation in providing knowledge services. The implementation of ME and the interaction between MEs can benefit from the service-oriented infrastructure [6, 8].

To realize the ideal of the Knowledge Grid Environment needs a long-term research. Further research should be done on autonomous infrastructure for the environment, economical principle of knowledge sharing, ecological principle of knowledge innovation, knowledge flow network for knowledge sharing in dynamic environment, and culture development in the environment.

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References

1. H. Balakrishnan, et al. Looking Up Data in P2P Systems. *Communications of the ACM*, 46 (2) (2003) 43-48.
2. A.L. Barabási, and R. Albert, Emergence of Scaling in Random Networks. *Science*, 286, (1999) 509-512.
3. G. Booch, Object Oriented Design with Applications, *Redwood City, Calif.: Benjamin/Cummings Pub. Co.*, 1991.
4. V. Bush, As We May Think, *Atlantic Monthly*, July, 1945.
5. J. Ferber, Multi-Agent Systems: an Introduction to Distributed Artificial Intelligence, Harlow: Addison Wesley Longman, 1999.
6. I. Foster, Service-Oriented Science, *Science*, 308(5723)(2005) 814-817.
7. J.Gray, What Next?: A Dozen Information-Technology Research Goals, Journal of ACM, 50(1), (2003) 41-57.
8. T. Hey, and A. E. Trefethen**,** Cyberinfrastructure for e-Science, *Science*, 308 (5723) (2005)817-821.
9. A. Taivalsaari, On the Notion of Inheritance. *ACM Computing Surveys*, 28, 3 (1996) 438-479.
10. L. Morgenstern, Inheritance Comes of Age: Applying Non-monotonic Techniques to Problems in Industry. *Artificial Intelligence*. 103 (1998) 1-34.
11. J.E. Smith, and R. Nair, The Architecture of Virtual Machines, *IEEE Computer*, 38 (5) (2005) 32-38.

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