The Future Interconnection Environment

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Networks pervade nature, society, and virtual worlds, giving structure and function to a variety of resources and behaviors. Discovering the rules that govern the future interconnection environment is a major challenge.

In 1960, Marvin Minsky predicted that computers would be as smart as humans within three to eight years. Nearly half a century later, however, computing systems still cannot pass the Turing test. Despite impressive achievements in robotics, mathematical theorem proving, scientific classification, and advanced user interfaces,[1] artificial intelligence remains elusive.

Scientists and engineers have nearly realized Vannevar Bush's dream of a universal multimedia data-processing machine with the Internet and the World Wide Web. Extending this vision into the future, Microsoft researcher Jim Gray foresees the development of highly secure, highly available, self-programming, self-managing, and self-replicating computer networks.[2] Gray imagines a system, akin to Bush's memex device, that can automatically organize, index, digest, evaluate, and abstract information. However, creating intelligent networks that can program, manage, and replicate themselves is a major challenge.

The China Knowledge Grid Research Group (http://kg.ict.ac.cn), established in 2001, is exploring the operating principles of this future interconnection environment.

TOWARD A NEW COMPUTING ENVIRONMENT

The emergence of the Web provided an unprecedented AI research and application platform. By providing access to human-readable content stored in any computer connected to the Internet, it revolutionized business, scientific research, government, and public information services around the globe.

However, because machines cannot yet understand human-readable Web pages, the current Web cannot adequately support intelligent applications. Such applications require a new Internet application platform to intelligently accommodate the development, deployment, interaction, and management of globally distributed e-services based on open standards such as the Web Services Description Language.

Scientists are using symbolic reasoning, text mining, information extraction and retrieval, and other cutting-edge technologies to improve or extend the Web. For example, IBM's WebFountain (www.almaden.ibm.com/webfountain) converts online content such as Web pages, e-mail, message boards, and chat into an XML-based form and analyzes it to identify its commercial value. The proposed Semantic Web[3] aims to enmesh online content more meaningfully using ontological and logical mechanisms as well as standard markup languages like the Resource Description Framework.

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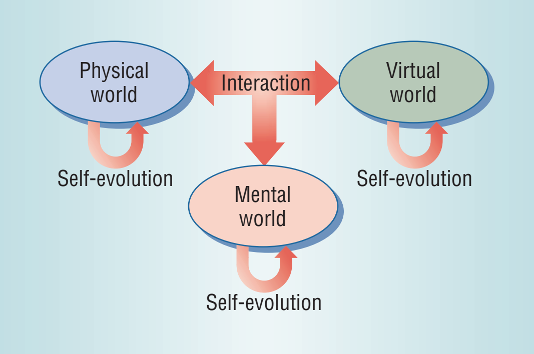

Figure 1. Future interconnection environment. The physical, virtual, and mental worlds will interact and evolve cooperatively.

In addition, the next-generation Internet2 will be hundreds of times faster and more secure than the current Internet. By providing a rich address space for advanced applications, it will push evolution of the Internet application platform, which in turn will inspire new applications.

Researchers are developing advanced functions in other types of artificial networks. For example, the Grid (www.gridforum.org) aims to share, manage, coordinate, and control distributed computing resources such as machines, networks, and data from any digital device plugged into it. The Open Grid Services Architecture (www.globus.org/ogsa) attempts to combine the Grid's advantages with those of the Semantic Web and Web services. However, OGSA is not suited to large-scale, unstable dynamic networks.

Peer-to-peer networking has emerged as a popular technology for sharing computing resources in such networks. However, while P2P networks are autonomous and scalable, they lack the required understanding, coordination, and scheduling capabilities to support advanced applications.[4]

The future interconnection environment must absorb AI and distributed systems, inherit the advantages of the Web, Semantic Web, Grid, and P2P technologies, and go beyond their scope with new principles.

PRINCIPLES, PARAMETERS, AND CHALLENGES

The computing environment has evolved from personal or centralized computers to distributed networks to human-computer environments. As Figure 1 shows, the future interconnection environment will be a large-scale human-machine environment that unites three worlds:

- *physical world*—nature, natural and artificial materials, physical devices, and networks;
- *virtual world*—the perceptual environment constructed mainly through vision (text, images, color, graphs, and so on) and hearing, and to some extent touch, smell, and taste; and
- *mental world*—ideals, religions, morals, culture, arts, wisdom, and scientific knowledge, which all spring from thought, emotion, creativity, and imagination.[5]

Ideally, this environment will be an autonomous, living, sustainable, and intelligent system within which society and nature evolve cooperatively. It will gather and organize resources into semantically rich forms that both machines and people can easily use. Geographically dispersed users will cooperatively accomplish tasks and solve problems by using the network to actively promote the flow of material, energy, techniques, information, knowledge, and services in this environment.

Principles

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

Openness. Making the environment open prevents stagnation. Standards are essential for open systems and must be continually updated as the environment evolves.

Incremental development. The environment will move from a small, simple scale to a large, complex one, perhaps exponentially. The number and skills of developers will likewise increase. From the applications perspective, development should balance inheritance and innovation. Smooth upgrading of the work environment and paradigms will ensure effective use of new technologies.

Economy. Benefits to participants, resources, and the environment should be distributed reasonably and fairly. The market forces participants to reasonably adjust their decisions and behaviors—both producers and consumers look for satisfaction rather than maximization because they must come to agreement. This simple mechanism avoids complex computation.

Ecology. The future interconnection environment will foster a complex ecology that explores interactions between the natural world, the virtual world, and human society.

Competition and cooperation. Resources in the environment must compete for survival, rights, and reputation. At the same time, they should cooperate with and regulate one another to support the function and value of the services they use to compete.

Dynamic scalability. Participants and resources must be able to join or leave the environment without affecting its overall function. The network and its relational and organizational layers should support this dynamic scalability.

Integrity and simplicity. The environment's beauty lies in the integrity and simplicity of the underlying structures of itself, individuals, species, and society.

Parameters

The future interconnection environment will be a sustainable and harmonious system in terms of

- *space*—the capacity to encompass a great variety of individual and shared resources including material objects, information, knowledge, services, and physical space in the natural environment;
- *time*—the processes of evolution and degeneration;
- *structure*—the environment and resources in it;
- *relation*—the relationships between and among processes and resources; and
- *worth*—the status of and prospects for resources, processes, and their relationships.

Einstein's general theory of relativity reveals that space and time are malleable entities in the physical world. On the largest scale, space is dynamic, expanding or contracting over time.

The future interconnection environment will foster the growth of knowledge, a type of resource, by supporting social activities at different levels—from the physical level to the human-machine community level—and in different disciplines. As a natural product of society, knowledge will evolve and endure throughout the life of the human race rather than the life of any individual.

Human social activities have thus far largely relied on natural-language semantics. Future social activities will instead depend on a new kind of semantics that establishes an understanding between humans and inanimate resources. This human-machine semantics will make it possible to beneficially use and safely regulate services and knowledge.

Challenges

The future interconnection environment's variety and complexity will limit the ability of a single theory to support modeling. Gaining the insights needed to resolve a number of major challenges requires going beyond traditional disciplinary boundaries.

Reorganization of versatile resources. Accurate and complete resource management requires an organized approach. The relational model ensures successful database management but is unsuitable for managing complex and semantically rich resources in a dynamic environment. A new theory is needed for organizing resources in semantically rich forms and using them under integrity constraints. The Internet2's advanced characteristics make such a theory feasible.

Reconciling normalization and self-organization. Normalization reflects stability and order, while self-organization reflects dynamic order in unstructured phenomena. The "small world" phenomenon shows a kind of stability within a scale-free network.[6] The normalization of resource organization ensures accuracy in their operations; self-organization ensures autonomy, equality, and adaptability in managing resources. One way to reconcile normalization and self-organization is to impose normalized structure at the higher levels, allow self-organization at the lower levels, and maintain mapping and consistency between levels.

The future interconnection environment will be a sustainable and harmonious system.

Semantic interconnection. Consistently connecting various resources in many semantic layers to support intelligent applications is a challenge. The key is to construct a computing model that applies to explicit semantics as well as tacit semantics relating to sensation and emotion. The "sense and sensibility" of autonomous resources also play an important role in semantic interconnection.[7]

Clustering and fusing. Intelligent services rely on the ability to cluster and recluster heterogeneous resources. Because current passive resource models do not support active clustering, establishing an intelligent resource model is necessary. Fusing could occur among entities or among content.

Network degeneration. Researchers have extensively studied the Web's growth and distribution[8] but have largely neglected degeneration. In the real world, however, development of anything eventually reaches a limit. It is important to determine how degeneration might impact or limit evolution of the future interconnection environment.

Abstract flow modeling. Finding rules and principles common to material, information, knowledge, and service flows and discovering their logistics is another big challenge. Meeting this challenge requires an abstract process model with optimization and control methods.

Field theory. In the future interconnection environment, as in the physical world, resources will flow from high- to low-energy nodes. This automatically requires appropriate on-demand logistics because the energy difference reflects a need for flow. However, the real-world law of energy conservation does not hold: Copying or generating data does not incur a physical cost, nor does deleting data. The basic laws and principles governing this special field require much more investigation.

Abstracting resources. Abstraction is the basis of understanding, thinking, and problem solving. It is a challenge to automatically capture semantics

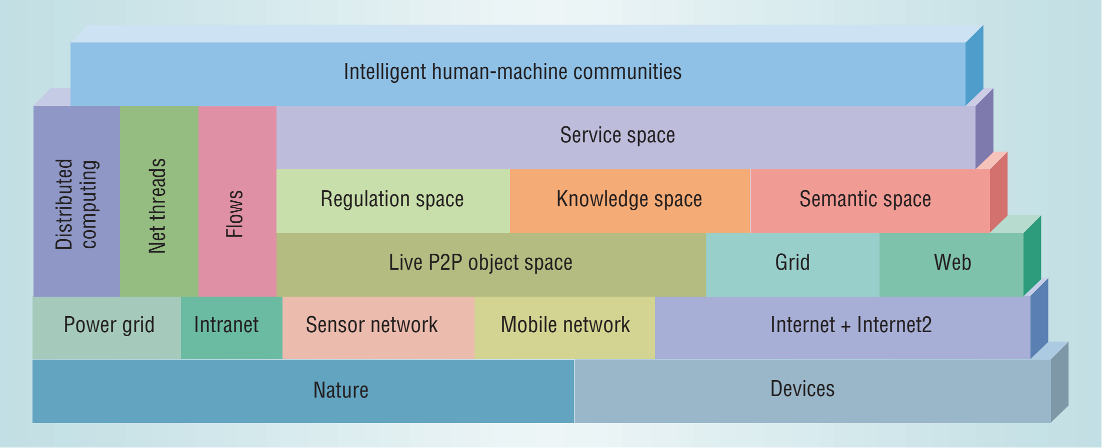

Figure 2. Future interconnection network reference architecture. Nature provides the most direct inspiration for ways to improve technology.

from resources and to reason and explain in a uniform semantic space. The environment needs a single semantic image mechanism[9] that establishes a common understanding for various resources. The mechanism's constraints and rules ensure valid resource usage in the semantic space.

Ecology. As elsewhere, resources in the future interconnection environment can be classed into species. Inheriting from existing species is the major way to form a new resource.[5] The evolution of species depends on flows between specimens. The challenge is to apply the methods and principles of natural ecology to help understand and explore the future interconnection environment ecology.

Dynamic inheritance. A common phenomenon in the organic world, inheritance is also the key mechanism for supporting reuse in object-oriented methodology and systems. How to realize the inheritance mechanism among evolving resources in an evolving environment is another challenge. Inheritance should accord with ecological and biological principles.

Biointerface. Sensor networks are gradually making the Internet ubiquitous. Scientists are embedding sensors into animals' bodies to integrate biological and electrical data, and they are using the human body to provide energy for computing and as part of a network. These sensors will be an integral part of the future interconnection environment. However, a huge gap exists between low-level information collected from sensors and high-level information that could be automatically understood and intelligently processed.

Organic architecture. A truly dynamic network should have organic characteristics such as self-protection, self-healing, fault tolerance, dynamic adaptation, self-replication, self-motivation, and self-fueling. This requires developing a system architecture analogous to anatomical structures—including, for example, immune, nervous, digestive, and circulatory systems.

Methodology. A large-scale, dynamic, and intelligent interconnection environment will require a multidisciplinary system methodology and an epistemology for guiding the development, operation, and maintenance of the network and its applications.

ARCHITECTURE AND INTERCONNECTION RULES

Applying the incremental development principle to the future interconnection network yields the layered reference architecture in Figure 2. The bottom layer is an interface between the physical world and the virtual world. Scientists use sensor networks to collect information and various devices to control small-scale natural environments—for example, to make rain.[10] Nature most directly inspires technological improvements, as evidenced by genetic computing, neuronal computing, swarm intelligence, and biomolecular computing.

The *live P2P object space* contains abstract representations of various environmental resources, and each object within it has a life span. *Net threads* carry running applications. Objects in the *regulation space* manage resources autonomously. The *knowledge* and *semantic spaces* overlay the live P2P object space and support the *service space*. Services can find requirements advertised by roles and resources. People in *intelligent human-machine communities* work, entertain, contribute, and enjoy services according to regulations and social principles. A person's role can move from one community to another through *flows* of material, information, knowledge, and services that link communities and exploit computing resources.

Object space growth

The live P2P object space is a relational network with live resource nodes connected by semantic links. The network is said to be alive because every node has a life span that lasts from "birth" (addition to the network) to "death" (removal from the network). Rules that govern network growth must consider the addition and removal of both nodes and links.

As a case study, investigators in the China Knowledge Grid Research Group compared the Web's hyperlink distribution with two models of the link distribution of the live semantic network—a stochastic growth model and a directed evolving

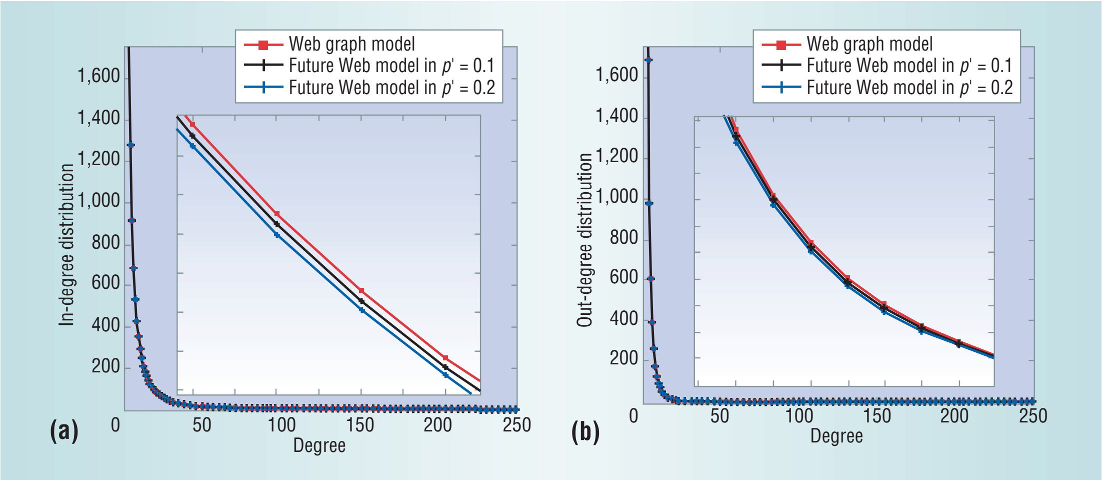

Figure 3. Live P2P object space growth. (a) In-degree and (b) out-degree distribution of live semantic network links using a stochastic growth model and a directed evolving graph model compared with Web data.

graph model—and obtained the same scale-free distribution rule from each.

Figure 3 shows the in- and out-degree distribution, respectively, of data obtained using the two models along with the Web data.[11] The models' loss of links and nodes accounts for the gap in results: the faster the removal, the larger the disparity. Further, the magnitude of the curve's slope for the investigated models is always smaller than that of the Web graph model. The number of links indicates a node's wealth: Rich nodes have more links than poor ones. Preferential attachment leads to a "rich get richer" phenomenon that increases the gap between rich and poor nodes.

Damping effect

Experience indicates that rich nodes will last longer than poor ones, but a cap on wealth tends to average out life spans. A simulation that blocked nodes from acquiring further in-links once they reached a certain level resulted in the distribution shown in Figure 4a, which is no longer a power law. Instead, the tail rises a little near the limit, suggesting that relatively rich nodes shared the blocked wealth.[11]

This *damping effect* also exists in many real-world networks, causing them to move from prosperity to degeneration. For example, in epidemic dissemination networks, nodes join when they become infected and leave when they recover or die. Figure 4b shows the damping effect of antibody development and community self-protection measures on the spread of the severe acute respiratory syndrome (SARS) epidemic in China in 2003.

In the future interconnection environment, resources will likewise compete under a damping effect. Because rich nodes emit more information, knowledge, and services, poor nodes will find it easier to get rich. Some social and natural rules will also apply to the interconnection environment.

Compression and expansion

Figure 5 presents a time-space model of the future interconnection environment. Compression and expansion pull and push development like the ebb and flow of tides. Compression intensifies competition among technologies (for example, the Internet, the Internet2, the Web, the Grid, and P2P networking), pushing some out and helping to generate new ones (such as the Semantic Grid and the Knowledge Grid), which leads to expansion.

The extent of expansion and compression influences sustainability. Achievements in sustainable development of the natural ecosystem provide insight into the future interconnection environment's sustainability.[12]

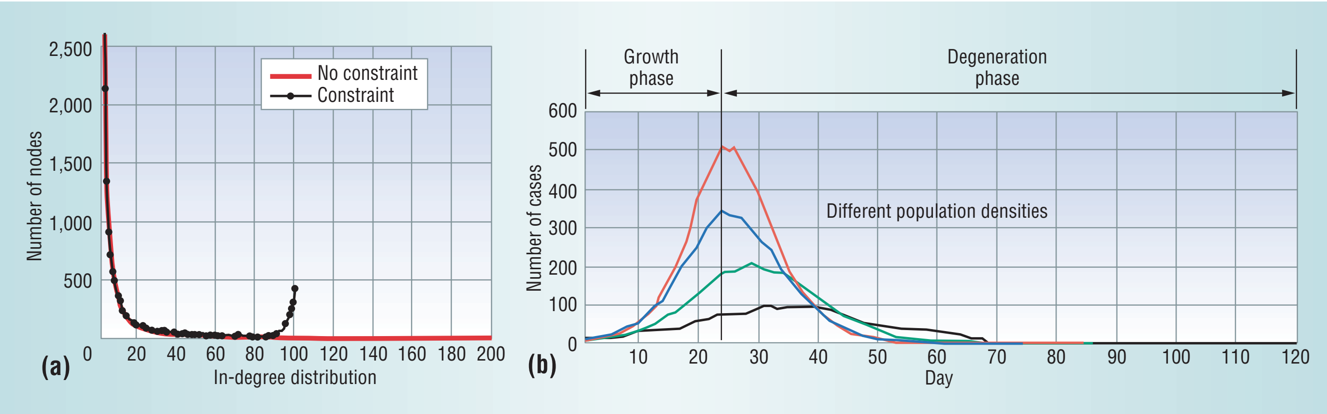

Figure 4. Damping effect. (a) In-degree link distribution under constraint. (b) SARS epidemic dissemination network.

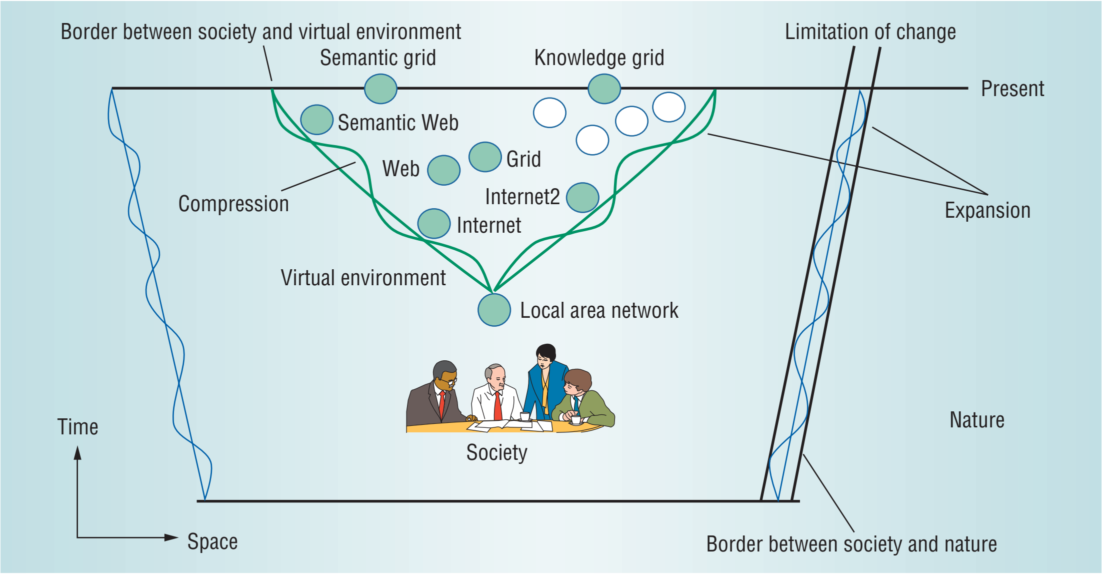

Figure 5. Time-space model. Compression and expansion pull and push development of the future interconnection environment like the ebb and flow of tides.

Various resources compete with one another in the interconnection environment for survival.[5] Some become dominant in the competition, as in the Web's "rich get richer" phenomenon.[8]

Compression and expansion change both the space and self-organization behavior. Social expansion and compression influences virtual environment development, which eventually will fuse with and keep pace with social development.

The border between society and the virtual environment will evolve from screens and keyboards to various mobile devices, sensors, and biointerfaces.

EVOLVING E-SCIENCE ENVIRONMENT

The China Knowledge Grid Research Group is developing the e-Science Knowledge Grid Environment as an experimental microcosm of the future interconnection environment.[9] This evolving, dynamic, self-organizing, self-managing, and scalable system is designed to support the development of diverse distributed and intelligent information, knowledge, and computing services.

The architecture, shown in Figure 6, includes five main components:

- *Imagine-Framework*—the core component that supports overall system development. This basic application development framework organizes and manages resources in a decentralized and autonomous way on a P2P network. It contains a class library, algorithm library, and template library for developing and managing high-level applications.
- *Imagine-Run*—an embedded platform that will support runtime management of the underlying P2P network and high-level applications, including network maintenance, application deployment, configuration, and execution control.
- *Imagine-Research*—a virtual network laboratory that will support monitoring, debugging, configuring, testing, and verification to hasten evolution of the environment. Researchers and users will be able to fully interact with one another to form a positive feedback cycle of requirements and technologies.
- *Imagine-Builder*—a platform that will include tools, source code, and virtual components to enhance development of distributed domain applications for large-scale networks.
- *EcoLab*—a virtual scientific research laboratory that geographically dispersed ecologists will use to efficiently publish, share, manage, and exploit distributed resources including computing power, data, information, and knowledge on a large P2P network. It will feed users' requirements back, thereby helping to improve both platforms and domain applications.

After developing and deploying Imagine-Run and Imagine-Research, we will use these as platforms to test and improve various technologies and software, and to extend the Imagine-Framework to different types of large-scale dynamic networks. Platform researchers, domain application developers, and end users will use Imagine-Framework, Imagine-Research, and Imagine-Run, respectively, in a cooperative way to improve the overall environment.

The China Knowledge Grid Research Group continues to look at ways to realize the ideal of the future interconnection environment. Ongoing work includes exploration of interconnection semantics, investigation of advanced high-level mechanisms such as dynamic soft-device inheritance, and application of research results in the development of systems for e-science and e-culture as well as supporting interscientific and intercultural research. ■

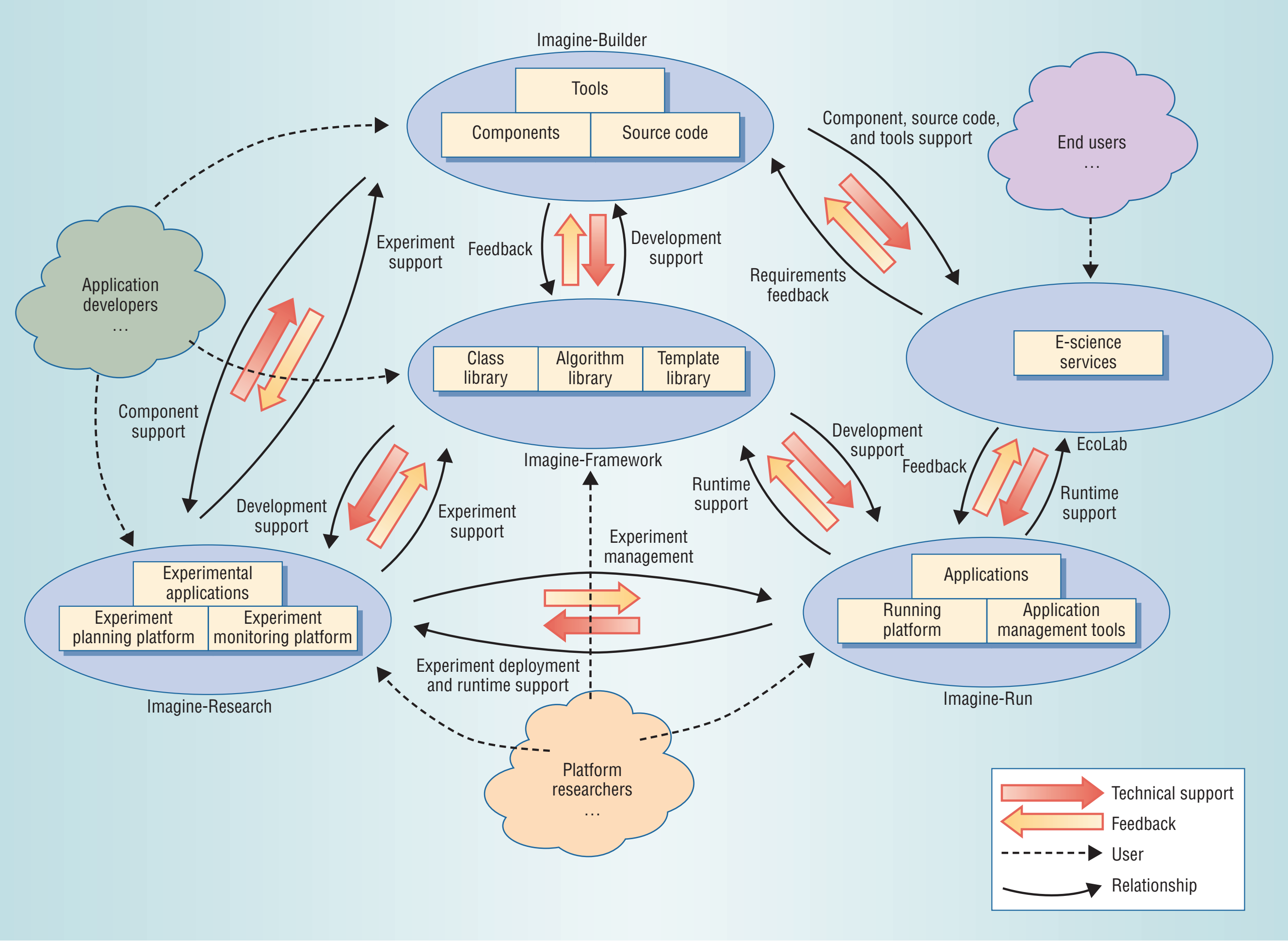

Figure 6. China's e-Science Knowledge Grid Environment. ***This evolving, self-organizing, self-managing, and scalable system is designed to support development of distributed ecological applications on a P2P network.***

Acknowledgments

This article is based on research work supported by the National Basic Research and Development 973 Program (2003CB317001) and the National Science Foundation of China under grants 60273020 and 70271007.

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