SCIENCE CHINA
Information Sciences

• **REVIEW** •

March 2015, Vol. 58 031102:1–031102:19
doi: 10.1007/s11432-014-5209-2

Cyber-physical-social-thinking space based science and technology framework for the Internet of Things

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Received May 7, 2014; accepted September 17, 2014; published online January 8, 2015

Abstract The Internet of Things (IoT) as an emerging network paradigm is bringing the next scientific and technological revolution for ubiquitous things' interactions in cyber-physical-social spaces. The IoT influences the current science and technology system by enabling its relatively stable interrelations for an inevitable architecture reconfiguration. In this paper, we aim to explore an updated science and technology framework for the IoT. Particularly, a novel cyber-physical-social-thinking (CPST) space is established by involving an attractive concept of the Internet of Thinking (IoTk), and a science and technology framework is accordingly proposed referring to both scientific aspect (i.e., cyber-physical, social, and noetic sciences) and technological aspect (i.e., fundamental, physical, cyber, and social technologies). According to the perspective of the traditional Chinese culture, we explain the established science and technology framework, in which the "Five Elements" (i.e., wood, fire, earth, metal, and water) have common properties with the restructured cyber-physical science in the IoT. Moreover, we introduce a scenario of smart city to identify the technological aspect in the IoT, and discuss the key enabling technologies, including resource management, energy management, data management, session management, security and privacy, loop control, space-time consistency, nanotechnology, and quantum technology. It turns out that the established science and technology framework will launch an innovation for academia and industry communities.

Keywords Internet of Things (IoT), cyber-physical-social-thinking, science, technology, discipline

Citation Ning H S, Liu H. Cyber-physical-social-thinking space based science and technology framework for the Internet of Things. Sci China Inf Sci, 2015, 58: 031102(19), doi: 10.1007/s11432-014-5209-2

1 Introduction

The Internet of Things (IoT) is an emerging paradigm, and aims to achieve the interactions among ubiquitous things through heterogeneous networks. It is mainly characterized by comprehensive perception, reliable transmission, and intelligent processing to achieve a perfect convergence of the cyber-physical-social spaces [1,2]. The IoT is influencing the current science and technology system by enabling its relatively stable interrelations for an inevitable architecture reconfiguration. It is significant to rebuilt a science and technology framework for the IoT considering the new system architecture.

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We first trace back the historical evolution of the science and technology classification. In ancient times, Plato declared the quadrivium (i.e., arithmetic, geometry, astronomy, and music) as the embryonic education form. Aristotle followed the human activities to define the science including theoretical philosophy (e.g., physics, mathematics, and metaphysics), practice philosophy, and creative philosophy (e.g., art, and speech). Epicurus focused on the philosophy to classify it into the natural science (i.e., physics), science of reasoning (i.e., logic), and social science (i.e., ethics). Confucian classics Rites of Zhou (i.e., Book of Rites, Zhouli in Chinese), defined the six arts including ritual, music, archery, riding, literature, and mathematics. The philosopher Hsün Tzu (Xunzi in Chinese) regarded the knowledge as general knowledge (i.e., Dao in Taoism) and specific knowledge.

During the 17th and 18th centuries, Western Europe leaded the science into different categories separated from philosophy. Baconn thought that the development of sciences indicates the rational human abilities (i.e., memory, imagination, and judgment), in which history is the memonic science, art is the imaginative science, and philosophy is the judgment science. Saint Simon divided the natural phenomena into astronomy, physics, chemistry, and physiology, and further followed the metaphysical mechanistic philosophy to obtain mathematics, inorganic physics, and organic physics. Comte additionally specified Saint Simon's system to supplement mathematics, astronomy, physics, chemistry, physiology, and sociology. Hegel's objective idealist philosophy was also a typical science classification system, and the disciplines (e.g., dialectic, mathematics, physics, geology, humanics, psychology, and art) were successively generated during an absolute spirit's development.

Towards the modern science and technology system, Engles established the science theory towards the natural science, which is classified into six categories, including mathematics, mechanics, astronomy physics, chemistry, biology, and physiography[1)]. Based on the movement rules of the physical objects, there are five main scientific fields: nature, society, thought, mathematics, and philosophy referring to the theoretical, technical, and application sciences. Such fields are inter-correlated via the boundary sciences (e.g., psychology, environmental science, and scienology). Qian [3] proposed a "three-layer and one-bridge" science and technology system, which covers eleven categories, including the natural science, sociology, mathematics, systematology, noetic science, somatology, geography, military science, behavioristics, architecture, and literature/art. The related philosophical methods are applied to achieve interconnections among the basic theories, technical sciences, and application technologies.

The IoT is emerging to promote the science and technology system reformation by its transformative effects on the cyber-physical-social spaces. It is marked with "6c" labels, including convergence, content, collection, computing, communication, and connectivity[2)]. Besides, beyond the intelligentization requirement, the IoT should be evolved towards a more wise, soulful, and humanistic system paradigm. It is necessary to reconsider the building of a new IoT system architecture to achieve the integration of abstract mental and cyber-physical-social spaces, and to revise the traditional science and technology system to adapt for the future IoT. It is necessary to propel the science and technology evolution with the cyber-physical-social-thinking space considerations for the IoT.

In this paper, we focus on our proposed U2IoT architecture (i.e., unit and ubiquitous IoT) [4], to establish a new science and technology framework, and the main contributions are as follows:

(1) A novel cyber-physical-social-thinking (CPST) space is established by involving a new concept of the Internet of Thinking (IoTk).

(2) A science and technology framework is proposed based on the CPST space, referring to the scientific aspect (i.e., cyber-physical, social, and noetic sciences) and the technological aspect (i.e., fundamental, physical, cyber, and social technologies). Here, the Chinese Taoist thought is introduced to explain the restructured cyber-physical science.

(3) The main science subjects and disciplines are discussed for the IoT, and a scenario of smart city is introduced to identify the key enabling technologies in the IoT.

The remainder of the paper is organized as follows. Section 2 reviews the related work towards the

1) Engels F. Dialectics of Nature, Lightning Source UK Ltd, 2012.

2) Internet of Things—Strategic Research Roadmap. The Cluster of European Research Project on the Internet of Things (CERP-IoT). Strategic Research Agenda (SRA), 2009.

IoT discipline construction and education exploration. Section 3 establishes a new cyber-physical-social-thinking (CPST) space. Section 4 introduces the proposed science and technology framework, and the scientific and technological aspects are respectively presented in Sections 5 and 6. Finally, Section 7 draws a conclusion.

2 Related work

In the literature, there are few works on the science and technology system in the IoT, and the existing works mainly refer to the IoT discipline construction and education exploration.

Kortuem et al. [5] focused on the IoT education issues in the Open University, UK, and introduced the My Digital Life course, which offers a collaborative learning infrastructure for a beginner to learn the IoT technologies programming. Towards the IoT teaching infrastructure, it is established for the experiment courses, in which the custom-designed hardware board and cloud computing platform are improved. Moreover, it creates increasing demands for the computer education, and the positive results have been presented to reshape the undergraduate computer education according to the IoT principles to achieve far-reaching implications.

Gluhak et al. [6] presented a survey on facilities for experimental IoT research, analyzed the requirements and challenges for IoT experimentation, with reference to scale, heterogeneity, repeatability, federation, concurrency, mobility, and user involvement. The existing testbeds are discussed from the perspectives of scope (e.g., application domain, and technology domain), and architecture (e.g., structure, composition, and deployment). Testbed services enable efficient execution of experiments throughout the complete life cycle, including the specification, preparation, and execution.

Hamblen et al. [7] proposed a practical course and laboratory approach, which is designed to allow students to develop lightweight robotic prototypes and other embedded devices in the IoT applications. The approach is featured with Internet connectivity, I/O, networking, real-time operation, and object-oriented programming. Thereinto, a 32-bit SoC (i.e., system on-a-chip) RISC (i.e., reduced instruction set computer) microcontroller module with flash memory, I/O interfaces, and on-chip networking hardware is used in the prototype, and a cloud-based C/C++ compiler is applied for software support. In the approach, student files are stored in an online server, and software development can be performed via Web services. Web-based resources are developed for the course, including eBooks, laboratory assignments, and cookbook Wiki pages with schematics and sample microcontroller application code for breadboards.

Ning et al. [8] focused on the technology classification, industry, and education for the future IoT. Particularly, a four-dimension technology model including body, processing, intelligence, and sociality, is established to classify the complicated IoT technologies. The future IoT development phases are predicted referring to the early stage, unit IoT stage, and ubiquitous IoT stage. Furthermore, whether to consider the IoT as an emerging industry or not is discussed, and it turns out that the IoT is inappropriate as an industry since IoT is only a phase of intelligentization and informatization development. Meanwhile, the necessity of training qualified personnel in universities is identified, and the interrelation of the science and technology system and IoT related subjects is analyzed.

He [9] studied the evolution and future trends of technology and information sciences without limiting to the IoT, and classified the technology and information sciences into three main domains: physical technology and information science (i.e., non-organic/nonliving material based science), biological technology and information science (e.g., organic/living material based science), and societal technology and information science (e.g., language/mind based science). A physical-biological-societal (PBS) technology triangle model is established to introduce the interactions among the three domains, and physical technology allows humans to change the corresponding biological and societal technologies. It indicates that the technology is a natural reflection, configuration, and innovation of physical objects, biological materials, and human mind.

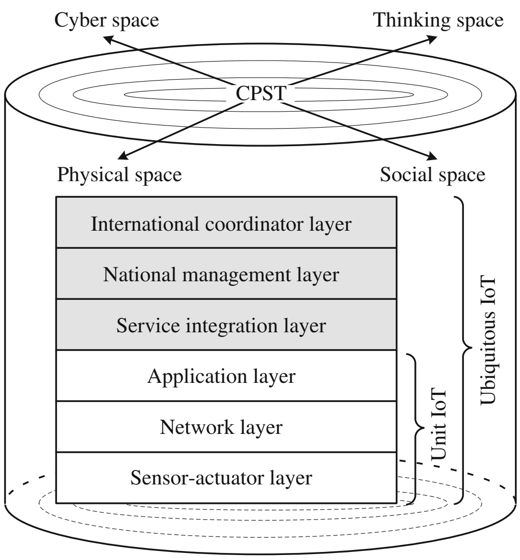

Figure 1 The cyber-physical-social-thinking (CPST) space based on the U2IoT architecture.

3 The cyber-physical-social-thinking space

Figure 1 illustrates the proposed cyber-physical-social-thinking (CPST) space, which is based on the U2IoT architecture (i.e., unit and ubiquitous IoT) [4]. The CPST space involves four space dimensions for the IoT.

• Cyber space: Cyber space refers to the virtual, digital, and ubiquitous abstraction (e.g., information, service, computing, controlling, and networking) to achieve interconnections among cyber entities. A cyber entity may have multi-identity status, including a core identity and other temporary or assistant identities, and is greatly independent on space-time constraints of physical space. The context-aware computing, including a broad range of techniques, methods, models, functionalities, applications, and middleware systems, can be applied in the cyber space.

• Physical space: Physical space refers to the real world conceived in linear dimensions, in which physical objects are respectively perceived and controlled by sensors and actuators in heterogeneous networks, and accordingly interact via network communications, remote collaboration, and autonomy functions. A physical object may be mapped into the cyber space as single or multiple cyber entities for interconnections.

• Social space: Social space mainly considers the thing's social attributes, which describe the intra- /inter- relationships with other associated things. In the IoT, the social space can be formally described in the semantic representations to address the ownership control management, affiliation relationship modeling, and human behavior formalization. The society organizational structure, and human learning principles (e.g., cognitive psychology, and decision neuroscience), can be introduced in the user-centered social space.

• Thinking space: Thinking space is established based on a new concept that "Internet of Thinking (IoTk)", which was first proposed by us on an open forum "Top 10 Questions in Intelligent Informatics/Computing" in the World Intelligence Congress for the Turing Year[3]. It is known that the computer networks have evolved into the Internet (i.e., network of computers), and then towards the IoT. Here, human wisdom can be introduced into the current cyber-physical-social spaces to launch a new era, which has an initial stage of "Internet of Thoughts/Ideas", and finally achieves the Internet of Thinking (IoTk). The IoTk is a collaborative human wisdom that thinks beyond the space-time constraints, and can ensure the human brain ability to break the cyber-physical-social space limitations. Note that the IoTk does not

3) Top 10 Questions Voting Result. The Open Forum on Top 10 Questions in Intelligent Informatics/Computing. http://wi-consortium.org/blog/top10qi/#top10.

exaggerate the effects of abstract mind, soul, mind, spirit, and subconsciousness to lead to the subjective idealism. The IoTk is based on the physical objects, cyber entities, and social attributes to achieve a wise state of spiritual interconnections, and is assigned with the four main characteristics including collection, connection, coordination, and creation. The IoTk is a higher level of IoT with more human wisdom and social organization that achieves a perfect CPST space fusion.

The four spaces should be organized in harmony to achieve organic interactions among ubiquitous things. Accordingly, a six-layer system model is established including the sensor-actuator layer, network layer, application layer, service integration layer, national management layer, and international coordinator layer. Thereinto, the bottom three layers are similar to the traditional IoT layers for a particular IoT application (i.e., unit IoT), and the upper supplemental three layers are designed with full social considerations for multiple IoT applications (i.e., ubiquitous IoT) [4].

• Sensor-actuator layer realizes to convert physical objects into cyber entities, and contains the generalized sensors to perform identification and cyberlization. The main sensing techniques include ZigBee, RFID, Wi-Fi, Bluetooth, infrared induction, global positioning system (GPS), and radar. Note that the mechanical/electronic actuators may be connected with the sensors to execute the appointed physical instructions in centralized and distributed actuation modes. The sensor-actuator layer aims to collect and extract physical information for ubiquitous sensing and intelligent control.

• Network layer includes the network components (e.g., interfaces, routers, and gateways) and communication channels. Heterogeneous network configurations may be established via the Internet, mobile communication, and other networks, in which the hybrid network topologies are involved for monitoring the real-time network configurations. Reliable data transmission is ensured by applying secure communication mechanisms.

• Application layer provides functional services to support the unit IoT, and supports the embedded interfaces to realize information extraction, aggregation and distribution. This layer takes full considerations of the specific application requirements to provide a user-friendly interface for interactions. Note that the standard protocols (e.g., TCP/IP, constrained application protocol (CoAP), and wireless application protocol (WAP)) and service composition technologies (e.g., service oriented architecture (SOA)), can be applied in the unit IoT.

• Service integration layer addresses the coordination of multiple unit IoTs in the local IoT or industrial IoT. Here, a local IoT includes multiple loosely coupled and geographically dispersed unit IoTs in the grid mode, and grid infrastructures can be adopted for service management. An industrial IoT manages multiple industries or industry chains oriented unit IoTs in the hierarchical mode. The local IoTs and industrial IoTs are correlated with particular relationships, and multi-agents based collaborative management can be applied considering the local or industrial regulations for service supports. Note that the Web services and mobile interactions, can be integrated to enhance interoperability with the associated physical objects.

• National management layer provides regulations for the local IoT and industrial IoTs, performs region/industry coordination and supervision, and fulfills arbitration. For a certain nation, its region/industry situations vary, therefore relevant management strategies should be developed considering the practical requirements during national IoT construction.

• International coordinator layer addresses international issues of transnational IoTs, establishes international policies/protocols/laws, and coordinates the interactions among the IoTs in different nations. This layer resembles the united nations organization (UNO), involving multiple nations, executing global coordination, and is like the international organization for standardization (ISO). There may be one or more global coordinators for international management with diverse religion, custom, and culture considerations.

The IoT should evolve towards a higher level with more human wisdom, soul, emotion, and even thinking to achieve the perfect integration of the cyber, physical, social, and thinking spaces.

4 The science and technology framework for the IoT

4.1 Preliminaries of the five elements

The five elements (i.e., five phases, Wu Xing in Chinese) are wood, fire, earth, metal, and water, which are extracted from "I Ching" (i.e., Book of Changes, and Zhouyi in Chinese)[4] and the Chinese Taoist thought. The five elements have profound influences on the Chinese philosophy, medicine, and geomancy. The five elements' main attributes are described in Book of Documents (i.e., Classic of History, Shujing in Chinese): "wood that is bending and straightening; fire that is blazing, rising and flaring up; earth that is sowing and reaping; metal that is moulding, changing and solidifying; and water that is soaking, moistening and descending" [10][5].

• Wood has the attributes to be strength and flexibility. The wood is associated with generosity, co-operation and idealism, and has structured texture with the regular feature.

• Fire indicates the things' flourishing and prosperity with the attributes of dynamism, strength, and persistence, but is also correlative with restlessness. The fire provides heat, warmth, and enthusiasm, however its excess may bring the aggression, impatience and impulsive behaviors.

• Earth keeps a balance of other four elements, and has the inward/centering motion, and stabilizing/conserving energy. The earth is associated with the patience, thoughtfulness, practicality, and stability, and also means nurture and supporting to bring harmony, rootedness and stability.

• Metal refers to the metallic deposit or mineral reserves, and is regarded as firmness, rigidity, persistence, strength, and determination. The metal is extended to be the natural materials existing in the primitive environments.

• Water is the source of life, and representative of wisdom, flexibility, softness, and pliancy. The water may be fluid, submissive, and weak, but an over-abundance of water may cause inundant power to overwhelm the land.

4.2 The proposed science and technology framework

Figure 2 illustrates a new science and technology framework based on the CPST space, including the scientific aspect and technological aspect. Here, science and technology are treated as the inseparably related concepts in almost the same category. In a certain degree, the science is in the knowledge form for creating knowledge, and the technology owns materialized form for knowledge utilization.

4.2.1 *The science framework*

The science framework mainly includes the cyber-physical science, social science, and noetic science, and share common properties with the five elements.

The cyber-physical science is consistent with the five elements' attributes, including the mathematical, physical and chemical science, engineering science, information science, environmental science, and life science. The subtle relationships between the cyber-physical science and the five elements include:

• Mathematical, physical and chemical science refers to the most fundamental science, which highlights the wood element's implied feature. The wood's texture is structured, and grows along with the extending branches and roots, which is similar to the feature of mathematical, physical and chemical science.

• Engineering science is a multidisciplinary science emphasizing the integrated application of engineering, scientific, and mathematical principles. Similarly, the fire as the most common thermal energy, can be transformed into kinetic energy, or further converted into electrical energy. Such energy conversion launches the first industrial revolution, which is marked with the invention of the steam engine. It turns out that the engineering science has the same original impetus as the fire's attribute.

• Information science is an interdisciplinary science referring to the information collection, manipulation, storage, retrieval, interpretation, transmission, and utilization. Around cyber properties, the

4) Wilhelm R. I Ching. The Book of Changes. http://www.iging.com/.
5) Lao-tzu. Tao Te Ching (Translated by Legge J). http://www.sacred-texts.com/tao/taote.htm.

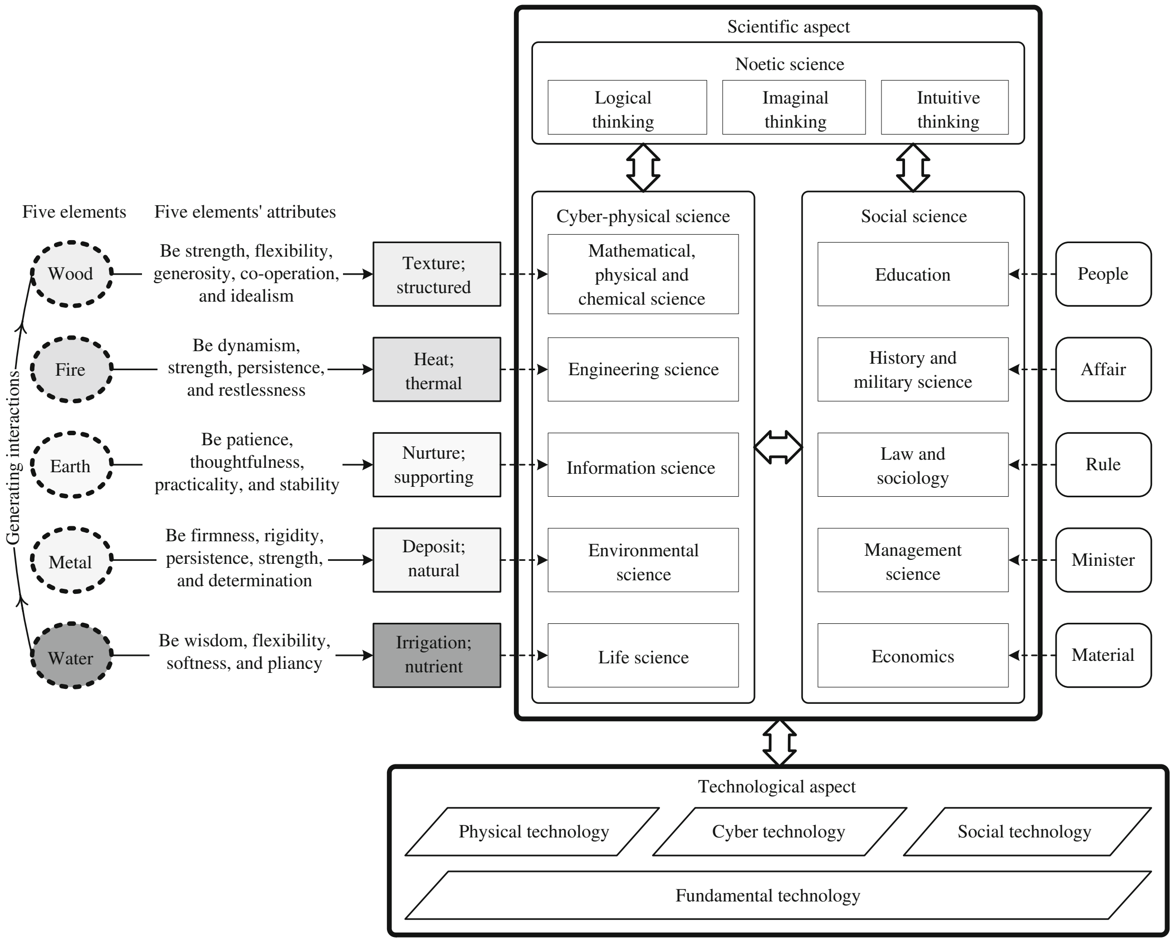

Figure 2 The five elements and the proposed science and technology framework.

information science aims to create, replace, improve, or understand information representation by natural and artificial systems. It provides a universal supporting platform for thing's interactions, and its function is similar to the earth elements' nurturing the plants for feeding and supporting. Meanwhile, Silicon (Si) mainly exists in the earth, and is a pivotal material in the chip based information area.

• Environmental science integrates multiple research areas including but not limited to ecology, astronomy, atmology, geology, and geography to address the natural issues. In the universe, the environmental science is related with natural resources, and epitomizes the metal element's presentation. The environmental science and the metal element are closely associated since metals such as Ferrum (Fe) are important products during celestial bodies' evolution, and there are 82 metallic elements and 9 semimetallic elements of 118 chemical elements in the natural environment.

• Life science involves the research areas involving the living organisms (e.g., plants, animals, and human beings), life phenomena, life interactions, and the intrinsic qualities and features. It is known that the water element as the source of life, which nourishes all things, and has obvious correlations between the life science.

The social science mainly includes education, history and military science, law and sociology, management science, and economics.

• Education—People: focuses on pedagogical phenomena to summarize the scientific theories and practical experiences, and to solve practical problems during human education activities based on the principle of "people oriented values".

• History and military science—Affair: are parts of politics to research on the historical and military events, which are taken as a mirror for objectively determining strategies. History and military science refer to affairs, towards which a set of chronological historic events jointly compose the human history, and the military events also belong to the field of affairs.

• Law and sociology—Rule: are the coupled sciences, thereinto law is the foundation in governing a society, and sociology provides universal guidance for drafting a law. Law provides rules as criterion to measure the social issues.

• Management science—Minister is to explore the basic principles and scientific methods for management activities (e.g., business administration). Management has the similar functions of ministers, which are the managerial talents for project organization and configuration.

• Economics—Material: aims to address material scarcity and resource utilization, for which the microeconomics and macroeconomics are respectively to research the economic issues according to an individual and a region/nation. Materials are the necessities during the economic development.

The noetic science includes three main aspects: logical thinking, imaginal thinking, and intuitive thinking, respective with abstract, intuition, and insight considerations.

• Logical thinking (i.e., abstract thinking) is the academically disciplined method of conceptualizing, analyzing and evaluating data generated by observation, experience, reasoning as a guide to self belief and action. It is the part of human thinking that can be imitated by computers and other machines. Reasoning is the main aspect of the logical thinking, which refers to applying the deductive reasoning, inductive reasoning, and abductive reasoning to obtain a conclusion.

• Imaginal thinking refers to that the human brain uses images as representation of experience and knowledge. The images covers the low-level information apperceived by the perception of human body, and the high-level information obtained by imitating and learning. Literature and art are typical imaginal thinking, which reflect the social ideology from the perspective by the methods of language (e.g., poetry, essays, and fiction), acting (e.g., music, dance, and drama), and modeling (e.g., painting, architecture, and sculpture).

• Intuitive thinking (i.e., intuition) is an expansion of the imaginal thinking, which is expanded from the consciousness towards the subconsciousness. It is an overachieving specific psychological state during literary/artistic creation and scientific research, and is the ability to acquire knowledge without inference or reasoning. The intuition provides views, understandings, judgements, or beliefs, which cannot be empirically verified or rationally justified.

4.2.2 *The technology framework*

The technology framework mainly refers to the fundamental technology, physical technology, cyber technology, and social technology, which are classified based on the CPST space.

• Fundamental technology is mainly related with the mathematical, physical and chemical science, and noetic science, that provides the fundamental technical supports for other three technologies. The main supports include the applied mathematics/physics/chemistry knowledge, systematic analysis methodology, and logical thinking skills.

• Physical technology mainly considers the engineering science, environmental science, and life science that provides physical mechanisms for IoT applications. The physical technology aims to provide solutions for physical object oriented applications, such as engineering optimization, environment detection, and organism gene recombination.

• Cyber technology mainly correlates with the information science to provide cyber entity oriented services for the communication, computer, control, electrical, and electronic application areas.

• Social technology mainly is based on the social science to provide supervision, organization, coordination, restraint, and other effects on human activities and social events.

5 The science framework

The science framework includes three main aspects: cyber-physical science, social science, and noetic science, in which the cyber-physical science is restructured according to the traditional Chinese culture.

According to the "Classification of Instructional Programs (CIP 2000)" of American higher education[6), the subject category of Thomson Reuters[7), and the catalogue of disciplines and specialties for postgraduate education in China[8), the science descriptions are presented considering the main subjects and related disciplines.

5.1 The cyber-physical science

5.1.1 *Mathematical, physical and chemical science* (*MPCS*)

Mathematical, physical and chemical science refers to the most fundamental cyber-physical science, to provide the basic theoretical support for other sciences. Concretely, mathematical science covers broad and general mathematics approaches, including topology, algebra, functional analysis, combinatorial theory, differential geometry, and number theory. Physical science covers the research fields such as optics, electronics, cryogenics, magnetics, acoustics, and mechanics. Chemical science addresses the matter's composition, properties and reactions at the molecular or atomic level, and analyzes molecules, atoms, and chemical bonds. Note that systematics is also included in this science, and aims to realize system harmony considering the relationships between the whole and the parts of a thing.

5.1.2 *Engineering science* (*EngS*)

Engineering science covers the most widely researched areas, involving the industrial applications of aerospace industry, construction industry, military industry, bio-industry, chemical industry, mining industry, light industry, metallurgical industry, and transport industry. There are 32 main subjects in the engineering science, and the scope of the engineering science is dissimilar to that of the traditional engineering science. Here, the information related subjects are eliminated from the engineering science, and the reconstructed engineering science mainly focuses on the non-information oriented engineering fields.

5.1.3 *Information science* (*InfS*)

Information science as an independence science separated from the traditional engineering science, and aims to provide information services for ubiquitous things. It mainly includes the subjects of communication, computer, control, electricity, and electronics, to address both physical information issues (e.g., raw data acquisition, object feature extraction, and event information feedback), and cyber information issues (e.g., entity representation, online resource addressing, and semantic analysis).

5.1.4 *Environmental science* (*EnvS*)

Environmental science revolves around the issues of the earth and universe, including astronomy, atmology, geography, geology, geophysics, and marine. Thereinto, the natural issues such as celestial body, meteorological phenomena, epigeosphere, continental crust, auroral electrojets, and submarine lithosphere, are covered in the environmental science. This science addresses the primal physical environments to solve the mysteries of the universe, and to achieve harmony of human beings and nature.

5.1.5 *Life science* (*LifeS*)

Life science is not limited to the bioscience focusing on more widespread living organisms to address the issues of agriculture, biology, and medicine. Thereinto, agriculture mainly includes agricultural resources, crop, fisheries, horticulture, plant protection, and veterinary medicine. Biology mainly refers to the fields including unicellular organism, multicellular organism, micro-biology (e.g., molecular biology, and structural biology), macro-biology (e.g., evolutionary biology, and ecology). Medicine mainly covers the basic medicine, clinical medicine, pharmaco, stomatology, and public health and preventive medicine.

6) Classification of Instructional Programs. 2000 Edition. http://nces.ed.gov/pubs2002/cip2000/index.asp.

7) Journal Citation Reports. ISI Web of Knowledge. http://admin-apps.webofknowledge.com/JCR/JCR.

8) The Catalogue of Disciplines and Specialties for Awarding the Degrees of Ph.D. and Master, and Postgraduate Education. 2008 Edition. http://www.chinadegrees.cn/xwyyjsjyxx/sy/glmd/264462.shtml.

The cyber-physical science can be regarded as the restructured natural science, and Table 1 present the main subjects and related disciplines.

5.2 The social science

5.2.1 *Education*

Education aims to research the pedagogical phenomena and educational problems to reveal the educational properties (e.g., objectivity, inevitability, repeatability, and certainty), and includes three main subjects: general education science, psychology, and physical culture and sports. Thereinto, psychology can be specified according to basic psychology, applied psychology, and developmental and educational psychology. The education addresses the relationships among education, society, and human.

5.2.2 *History and military science* (*HMS*)

History is based on historical facts to research the process and regularity of the human society. According to the different periods and regions, the research objects have different historical conceptions, historical materials, and historical methods. Military science serves the national defense and evaluates military strategy, tactics, commands, operations, and logistics, to explore war's essential attributes through extremely complex military phenomena.

5.2.3 *Law and sociology* (*LS*)

Law is the rules and guidelines based system, which is enforced through the social institutions for behavior constraint, and mainly researches the science of law (e.g., statute law, and common law), legal phenomena (e.g., legislation, justice, and legal supervision), and other related issues. Sociology focuses on the human society, and its related origins, development, organizations, and institutions. It applies the scientific methods (e.g., empirical investigation, and critical analysis) to establish a knowledge system on social activities, structures, and functions.

5.2.4 *Management science* (*MS*)

Management science addresses the business and organizational activities, and emphasizes application of efficient methods (e.g., opsearch, and statistics) for quantitative and qualitative analysis of the management related issues. Management science includes four main subjects: agricultural/forestry management, business administration, library, information and archives, and public management. Thereinto, resources, including human, financial, technological and natural resources, are organized to achieve sound deployment and manipulation.

5.2.5 *Economics*

Economics aims to analyze the production, distribution, and consumption of goods and services, and focuses on the how an economic entity operates, behaves, or interacts in an economic system. Economics mainly includes the applied economics and theoretical economics, besides positive and normative economics, rational and behavioral economics, and mainstream and heterodox economics. It covers diverse social issues, such as business, crime, education, family, politics, and religion.

Table 2 presents the main subjects and related disciplines in the social science.

5.3 The noetic science

The noetic science becomes more noteworthy along with the progressing of the US's brain activity map project (i.e., BRAIN Initiative), which is to map the human brain's cells and neural connections in entirety. Meanwhile, EU's human brain project (HBP) launches the following complementary areas: future neuroscience, future medicine and future computing. Thereinto, brain informatics (BI) is a systematic methodology of brain sciences that addresses human thinking and brain issues in the human information processing system (HIPS), and focuses on the functions of the human brain, like human perception,

Table 1 The cyber-physical science descriptions

	Subjects	Related disciplines
MPCS	Chemistry	Analytical chemistry, high polymer chemistry, inorganic chemistry, organic chemistry, physical chemistry.
	Mathematics	Applied mathematics, computational mathematics, operational research and cybernetics, probability and mathematical statistics.
	Physics	Acoustics, atomic/molecular physics, optics, particle/nuclear physics, plasma physics, radio physics, quantum physics.
	Systematics	Systems analysis and integration, systems theory.
EngS	Aeronaut./Astronaut.	Aerospace vehicle manufacturing, flight vehicle design.
	Agric./For. Eng.	Agricultural mechanization engineering, agricultural water-soil engineering, forest products chemical processing.
	Archit. Civ. Eng.	Building (interior/urban) technology, bridge/tunnel, geotechnical engineering, municipal/structural engineering.
	Armament Nucl. Eng.	Weapon, military chemistry and pyrotechnics, nuclear energy science and engineering, radiation and environmental protection.
	Biol./Biomed. Eng.	Biological engineering biomedical engineering.
	Chem. Eng.	Applied chemistry, biochemical engineering, industrial catalysis.
	Environ. Health Eng.	Environmental engineering, health engineering.
	Food Eng.	Aquatic products processing, cereals/oils/vegetable protein.
	Geol. Eng.	Geodetection engineering, mineral resource exploration.
	Hydraul. Eng.	Harbor/coastal/offshore engineering, hydraulic/hydro-power engineering, hydrology/water resources, hydraulic structure.
	Instrum. Eng.	Measuring and testing, precision instrument and machinery.
	Light Ind. Eng.	Fermentation, leather chemistry, pulp/paper, sugar engineering.
	Mater. Eng.	Materialogy, materials physics/chemistry, materials processing.
	Mech. Eng.	Engineering mechanics, fluid/solid mechanics, vehicle engineering.
	Metall. Eng.	Ferrous/non-ferrous metallurgy, physical chemistry of metallurgy.
	Miner. Eng.	Mining engineering mineral processing engineering.
	New Energy Eng.	Biomass/fusion/geothermal/ocean/solar/wind energy.
	Ocean. Eng.	Marine engine, ocean structure, underwater acoustics.
	Opt. Eng.	Optical engineering.
	Pet. Gas Eng.	Petroleum/gas storage and transportation.
	Power Eng.	Fluid/power machinery, refrigeration/cryogenic, thermophysics.
	Surv. Mapp. Eng.	Cartography and geographic information, geodesy and survey, photogrammetry and remote sensing.
	Text. Eng.	Clothing, textile chemistry, textile material/design.
	Transp. Eng.	Highway/railway, traffic, transportation, vehicle operation.
InfS	Communication Sci.	Communication and information, signal/information processing.
	Computer Sci.	Computer and information, computer network and telecommunications, computer programming, computer software/media.
	Control Sci.	Detection and automatic equipment, navigation/guidance, pattern recognition and intelligent systems, systems engineering.
	Electric Sci.	Electric machines and electric apparatus, high voltage and insulation, power electronics /drives/automation.
	Electronics Sci.	Circuits and systems, electromagnetic field and microwave, microelectronics and solid state electronics, physical electronics.
EnvS	Astronomy	Astrophysics, astrometry/celestial mechanics, star science.
	Atmology	Atmospheric physics and environment, meteorology.
	Geography	Cartography/geography information, human/physical geography.
	Geology	Geochemistry, mineralogy, petrology, paleontology, stratigraphy.
	Geophysics	Space physics, solid earth physics.
	Marine	Marine biology/chemistry/geology, physical oceanography.
LifeS	Agriculture	Agricultural resources, animal, crop, fisheries, forestry, horticulture, veterinary medicine.
	Biology	Botany, ecology, genetics, hydrobiology, microbiology, neurobiology, physiology, population biology, zoology.
	Medicine	Immunology, neurology, oncology, pathology, stomatology.

Table 2 The social science descriptions

	Subjects	Related disciplines
Edu.	Gen. Edu. Sci.	Adult education, multicultural education, pre-school education, special education, vocational and technical education.
	Psychology	Clinical/comparative/cognitive/educational/legal/personality/physiological/biological /social psychology.
	Phys. Cult. Sport	Ethnic traditional sports, sports pedagogy and training theory.
HMS	History	Ancient history, archaeology and museology, historical geography/literature/theories, modern/contemporary/world history.
	Military Sci.	Military logistics/equipment, operations/strategy/tactics science.
LS	Ethnology	Ethnology, ethnic art/economics/history/policy.
	Legal Sci.	Civil/commercial/constitutional/administrative law, criminal jurisprudence, economic/international/military law, jurisprudence.
	Political Sci.	Diplomacy, international politics, ideology/politics education.
	Sociology	Anthropology, criminology, regional/ethnic/gender, sociology.
Manag.	Agric. For. Manag.	Agricultural/forestry economics and management.
	Bus. Adm.	Accounting, corporate/tourist/real property management.
	Libr. Inf. Arch.	Archival science, information science, library science.
	Public Manag.	Administration management, educational economy management, land resource management, social security.
Econ.	Applied Econ.	Finance, insurance, international trade, labor/national/regional economics, public finance, statistics.
	Theoretical Econ.	Economic history/thought, political economy.

thinking, attention, emotion, memory, reasoning, decision making, and problem solving. The BI applies experimental, computational, and cognitive neuroscience measures to develop the brain's features and principles. Additionally, the noetic science also research human consciousness formalization, cognitive experimental design, brain data management, analysis and simulation, in which the brain data, information, and knowledge should be integrated to support human intelligence.

Meanwhile, human body communication (HBC) further propels the development of the noetic science, and applies the human body as a transmission medium for body-proximal wireless communications, in which a sensing body data from one biomedical sensor is transmitted to another sensors through human body. It is mostly applied in body sensor networks (BSNs) and body area networks (BANs), with several merits, including low power consumption, high security, and high efficiency. Note that the HBC is not limited to the human intra-body data transmission, and also considers the human thinking related data intra-body and inter-body communications. The body signals (e.g., autocrine signals, paracrine signals, and endocrine signals) should be correlated with the human thinking.

5.4 Interdiscipline

Interdiscipline (i.e., boundary science) involves the combining of two or more disciplines into one research area, and has the similar meaning with the cross-discipline. In the IoT, the sciences and technologies may be organized crossing the traditional boundaries between two independent fields to satisfy the emerging application requirements. Accordingly, three typical examples are presented to introduce the interdisciplinarity in the CPST space.

• Bioinformatics as an interdiscipline in the cyber-physical spaces: Bioinformatics mainly focuses on the engineering, information and life sciences, to store, retrieve, organize, imitate, and analyze the biological data. Theoretical foundations including discrete mathematics, informatics, statistics, control theory, and computer technologies (e.g., data mining) are applied to abstract biological knowledge from the massive noisy data. Thereinto, data management and knowledge discovery are two main issues for biological data processing [11]. Specifically, accurate instruments are adopted to precisely measure the biological data for information acquisition, cloud database is used to store biological data for information organization, and data analysis algorithms (e.g., artificial intelligence, and image processing) are applied for information representation and extraction.

• Behavioral science as an interdiscipline in the physical-social-thinking spaces: Behavioral science mainly refers to the life, social and noetic sciences, to explore the interactions among the organisms (e.g., animals, and human beings) [12]. It involves the research areas including biology, ethology, psychology, sociology, neurology, anthropology, economics, and physiology, to systematically analyze the organisms' behaviors by rigorous formulations and scientific experimentations. Here, social computing, realizing to transfer social informatics to social intelligence, becomes noteworthy for the behavioral science. Information processing is performed by the cognitive entities to realize decision making, social judgment, and social perception.

• Cognitive science as an interdiscipline in the cyber-physical-social-thinking spaces: Cognitive science mainly covers the engineering, information, environmental, life, social and noetic sciences. It includes the research areas such as psychology, artificial intelligence, philosophy, neuroscience, linguistics, and anthropology. According to "thinking can best be understood in terms of representational structures in the mind and computational procedures that operate on those structures"[9], cognitive science aims to achieve an advanced intelligence (referring to language, memory, and emotion), especially focusing on information representation, reasoning, and transformation.

6 The technology framework

6.1 Technology category

Based on the CPST space, the technology category includes the bottom-up four main categories: fundamental technology, physical technology, cyber technology, and social technology. These technologies are interrelated with no obvious boundaries, and the fundamental technology supports other technologies according to different scenario requirements. The physical technology, cyber technology, and social technology respectively serve for the physical, cyber, and social spaces. Note that there is no an independent technology particularly assigned for the thinking space since human thinking related wisdom, soul, emotion, and subconsciousness are hard to be supported by a certain form of technology.

• The fundamental technology mainly provides basic speculative knowledge and spiritual knowledge for the physical, cyber, and social technologies through the whole space, and invokes the things' intrinsic characteristics and principles for pure technical supports.

• The physical technology mainly exploits the physical space to address the aspects such as time-space simulation, loop control, time-space simulation, instruments and meters maintenance, channel traffic analysis, environmental surveillance, and power management for the physical objects.

• The cyber technology mainly relies on the cyber space to address the issues, including signal processing, session management, data interaction, authentication, and semantic analysis for the cyber entities. Thereinto, cyber resources are accordingly invoked to achieve the pervasive information interactions.

• The social technology is mainly to address the issues, referring to educational training, behavioral conventions, legal regulations, social administration, public services, and economic supervision for social participants (e.g., an individual, enterprises, and utilities).

Figure 3 illustrates a scenario of smart city, which serves for an individual, enterprises, and utilities to provide intelligent infrastructures and services, revolving around human livelihood (e.g., healthcare, and education), business operations (e.g., transportation, and power grid), and government administration (e.g., public safety, and urban planing). The smart city involves the key enabling technologies, including resource management, energy management, data management, session management, security and privacy, loop control, space-time consistency, nanotechnology, and quantum technology.

9) Thagard P. Cognitive Science. The Stanford Encyclopedia of Philosophy. 2012 Edition. Zalta E N, ed. http://plato.stanford.edu/archives/fall2012/entries/cognitive-science/.

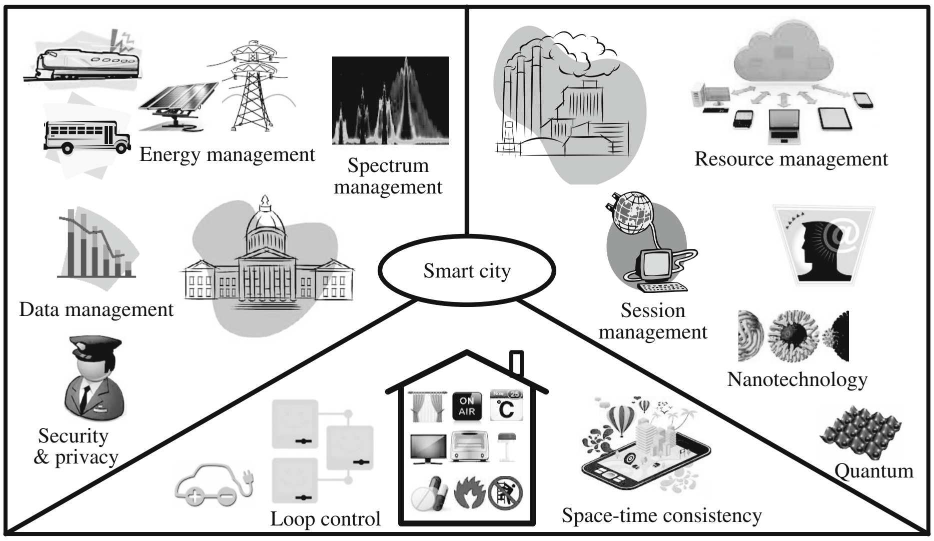

Figure 3 A scenario of smart city involving the key enabling technologies.

6.2 Key enabling technologies

Considering the IoT contexts, the main requirements and characteristics of the key enabling technologies are introduced as follows [13].

6.2.1 *Resource management*

The IoT resources have a more generalized scope along with the ubiquitous things' interconnections. Besides the traditional cyber resources (e.g., file data, computing capabilities, and memory storage) in the Internet, more physical objects (e.g., sensor, actuator, locator, and advanced metering infrastructure (AMI)), social resources (e.g., ownership, and affiliation), and thinking related features (e.g., mentality, and emotion). In the IoT, the resource management should consider the following features:

• Functionality: Resources should support particular functions by performing single or parallel tasks. For instance, an RFID tag identifier is associated with sensitive information [14], which is a resource for information inquiry; and wireless communication channels are resources for distribution of autonomous sensors that support data transmission.

• Shareability: Resources can be interoperated by multiple users or applications to achieve the enhanced resource discovery and sharing in distributed networks (e.g., grid computing). The resource organizations can be easily extended by adding new functionality at a minimal effort.

• Power demand-supply: Resources and power have subtle relationships: resources act as an energy demand to consume power for the functional operations; and resources may also provide power as an energy supply in some scenarios. For instance, distributed electric vehicles in the smart grid, can be regarded as both power demand and power supply to achieve energy balance.

• Collaboration: Heterogeneous resources establish interrelationships, and are jointly applied to support a particular application in dynamic environments.

• Duty cycling: Resources have a certain duty cycling (i.e., activity cycle, and life cycle), and can be created, updated, released, and reloaded in applications.

In the IoT, most sensing devices are expected to be resource constrained, related to memory and processing capabilities, but the low-power radio standards further constrain the network interfaces. The resource management becomes noteworthy, referring to the main aspects of resource naming (e.g., resource description framework (RDF), web ontology language (OWL), and physical markup language (PML)), resource addressing (e.g., domain name system (DNS), and object name system (ONS)), resource discovery (e.g., distributed hash table (DHT)), and resource allocation (e.g., artificial intelligence, and random graphs).

6.2.2 *Energy management*

Energy management becomes an open issue due to the limited physical infrastructures and cyber capabilities. The traditional energy management aims to realize persistent lifetime by the energy harvesting and dynamic power management. Towards the information and communications technology (ICT), energy management mainly considers reducing energy consumption by power-saving technologies (e.g., energy feedback, and virtualization). Meanwhile, micro-grids and demand side response become attractive to achieve the energy supply-demand balance. In the IoT, the energy management should satisfy the following requirements.

• Dynamic: Due to the dynamic of topology, service, and power supply in the IoT, and dynamic energy management should be designed to adapt unstable and unpredictable energy sources (e.g., solar, and wind).

• Ubiquitous management: Energy management covers the whole range of system components (e.g., sensors, actuators, gateways, and servers) to realize ubiquitous energy management. Energy heterogeneity of devices, networks, and services should also be considered for the heterogeneous systems.

• Self-management: The self-organization, self-adapting, self-recovery, self-configuration, and self-sufficiency, should be applied for intelligent management without human interventions.

Along with the development of energy management, the IoT turns into the Internet of Energy (IoE), which is regarded as a web-enabled smart grid. The IoE considers both space dimension (e.g., balance energy supply-demand in different areas) and time dimensions(e.g., preserve sufficient energy for future utilization). It enables the traditional power grid for improving energy usage efficiency, adding intelligent information interactions, and makes renewable energy accessible to the power grid.

6.2.3 *Data management*

Data management mainly applies computing technologies for data collection, storage, processing and other operations, and provides the on-demand resource utilization, potential information extraction, and intelligent decision support. In the IoT, the big data is applied in various applications such as the e-business, bioresearch, and public services. Ensuring data reliability (referring to confidentiality, integrity, and availability), reducing data redundancy, and enhancing data sharing, have become the main challenges in the IoT. Additionally, cloud computing characterized by anything as services (XaaS), which virtualizes the distributed resources in a common pool, makes it easier for big data management [15,16]. The emerging technologies are applied for big data.

• MapReduce is a programming model for processing large data sets with a parallel, distributed algorithm in clustered computing environments. MapReduce comprises two main functions: Map(·) for performing filtering and sorting, and Reduce(·) for performing a summary operation.

• Google file system (GFS) is a proprietary distributed file system, and provides efficient, reliable access to data using large clusters of hardware. The GFS is mainly based on master-slave structure, and it owns enhanced fault tolerance by applying data blocking and supplemental update to realize massive core data storage and usage needs. Besides, Colosuss, Hadoop distributed file system (HDFS), FastDFS, CloudStore are also typical distributed file systems.

• Hadoop developed by Apache software foundation and enlightened by the MapReduce and Google files system, is a framework to realize the reliable, scalable, distributed computing for big data. Hadoop consists of subprojects such as Hadoop common and Hadoop distributed file system (HDFS), and is used in keyword searches on the Internet. Based on users' information and questions, customized analyses can be performed for complex data processing. Meanwhile, Cloudera, MapR, and Hortonworks also developed other Hadoop versions.

6.2.4 *Spectrum management*

Spectrum management refers to planning, coordinating, and managing the spectrum resources, and aims to enable the spectrum-dependent devices to access spectrum resources in the spectrum-contested environment without bringing unacceptable interferences. Traditional solutions have been proposed for spectrum management, mainly including the spectrum trading, dynamic spectrum access, and cognitive radio. In the IoT, the spectrum management should consider additional aspects, including legal/policy regulations, spectrum planning, licensing, spectrum authorization, spectrum monitoring, electro magnetic compatibility (EMC), and electro magnetic interference (EMI). The vision of the spectrum management is described as that "understandable, agile, seamless and integrated"[10)], and the IoT should provide customized and coordinated management for the qualified spectrum users.

• Being customized means that spectrum allocation varies according to the regional and real-time spectrum conditions. Dynamic access should be achieved based on the intelligent reconfiguration and allocation mechanisms on the idle and reusable spectrum resources.

• Being coordinated means that the spectrum operations should inter-coordinate, and create a multi-layered harmony with the regional, national, and international spectrum coordination.

6.2.5 *Session management*

In the IoT, session management is to manage the interactions between the ubiquitous resources and resource users in heterogeneous networks. It is important to manage longer lasting interactions with dynamic characteristics, particularly for sessions with multiple resource users. Session management ensures the resource users with the improved interaction operability. In an all-IP environment, mobility-aware session management becomes the mainstream [17,18], and the related issues include session establishment, handoff delays, transient packet loss, end-to-end traffic delays, and seamless session handoff across heterogeneous networks. The IoT includes the single-session and multiple-session management.

• Single-session management refers to five steps (i.e., apply, create, register, act, and release), during which resource joining/quiting management and time management are two main issues. Thereinto, the active and passive session joining modes are performed to obtain resource permission, and the relative/absolute timeout modes are applied to enhance resource utilization.

• Multiple-session management mainly considers session conflict management and resource deployment. The session conflict management is an important issue, which manages the conflict when multiple users desire accessibility of the same exclusive resource. There are three typical session conflicts (i.e., mutual exclusion, deadlock, and collision), and several approaches are designed, including priority comparison, banker's algorithm, and ALOHA/Tree anti-collision protocols.

6.2.6 *Security and privacy*

Security and privacy are particularly crucial for the IoT, and the current researches mainly refer to the system, network, and application security solutions, including cryptographic mechanisms (e.g., key distribution, data aggregation, and secure routing protocols) and recommended safeguard countermeasures [19,20]. In the IoT, security and privacy should be studied considering the following aspects:

• Physical security and privacy considers external contexts and inherent infrastructures, in which human-like immune mechanisms can be applied for safeguard. Things should be adaptable to dynamic contexts with both innate and adaptive immunities against the malicious attacks (e.g., denial of service (DoS), and traffic analysis). The typical physical approaches include the intrusion detection, intrusion tolerance, Faraday cage, and active jamming.

• Information security and privacy mainly considers the security and privacy issues on the raw data and contextualized data in the cyber space. The awareness of information is interpreted and represented, and the main approaches, including authentication, access control, advanced signature, can be introduced for secure information interactions. During such information interactions, there are two main attacks: data collection (e.g., skimming, tempering, and eavesdropping), and data imitation (e.g., spoofing, cloning, and replay).

• Management security and privacy provides the recommended strategies, including the application requirements, local/industry/national regulations, and international policies/standards to guide activities

10) Department of Defense (DoD). Strategic Spectrum Plan. National Telecommunications and Information Administration (NTIA), 2008.

and events in the social space [21,22]. Due to the limitations of technological approaches, the appropriate management strategies should be coupled with the implementation of physical and information security approaches.

Among diverse security and privacy approaches, authentication is the most popular approach to validate the interactive things' identity. Authentication operators are adopted according to the hardware conditions, and authentication algorithms should fully consider the heterogeneous, mobile, and large-scale networks, therefore the tiered multicast authentication and batch authentication become significant in the IoT. Furthermore, anonymous mechanisms are emerging to address privacy-preserving issues, and mainly refers to pseudonym, k-anonymization, homomorphic encryption, and oblivious transfer protocol.

6.2.7 *Loop control*

In the IoT, loop control, referring to open actuation loops and closed actuation loops, has the following two main functions:

• Determination of the actuation loop's logic, components, and process: The actuation loop logic is designed with expected results of the users or the actuation loop itself, and the loop components together with process are determined according to the prior knowledge (e.g., function, condition, and attribute).

• Maintenance of the actuation loop's execution: It is necessary to maintain the actuation loop's normal execution, and adapt the loop to the internal limits (e.g. time delay) and the external interferences (e.g. loop interaction, and actuation loop conflicts). Concretely, time synchronization technology can mitigate the time delay to enhance performance. The relative gain array and steady-state information are applied to address the loop interaction, and actuation loop conflicts can be solved by the first-in-first-out (FIFO) and precedence algorithm.

6.2.8 *Space-time consistency*

Space and time are the most basic characteristics in the physical-cyber space, and the consistent space-time data is important for the mapping between physical objects and cyber entities. The space-time interaction patterns particularly influence the scattered, pervasive context-embedded networked physical objects [23]. In the IoT, the space-time data is required to be accurate, comprehensive, and continuous, and the following approaches can be applied for space-time consistency.

• Time synchronization refers to exchanging each node's local clock to maintain internal time consistency through the whole system. The traditional time synchronization algorithms such as network time protocol (NTP) is widely used in wired systems. For the wireless networks, the main synchronization modes include the receiver-receiver modes, sender-receiver modes, and pairwise modes.

• Object localization is based on time synchronization for earth measurement, navigation, and logistics. GPS is the most popular global navigation satellite system, but it has limitations caused by urban canyon effects. The local and indoor localization technologies (e.g., RFID, and Wi-Fi) are subsequently applied to address such problem.

• Time registration eliminates the sampling cycles' transmission delay and inconsistency, and adjusts the measurement sequence into the same time level. The least squares, interpolation and extrapolation, curve-fit, and 3-point parabola interpolation can be used for time registration.

• Space registration refers to converting the measured data to a reference frame for estimating and eliminating the registration biases (e.g., system bias, and position bias). Considering different coordinates (e.g., polar, orthogonal, and cartesian) may be adopted for space expression, the reference frame should be converted into a unified form. The registration biases can be estimated by least squares, maximum likelihood estimation, and Kalman filter.

Considering the thinking space in the IoT, the space-time issue becomes particularly crucial during an individual mapping of one or more cyber entities, and it brings a set of considerations towards how to achieve the space-time consistency between an individual's thinking and a cyber entity's thinking, how to perform the space-time registration between an individual's thinking and multiple cyber entity's thinking, and how to determine the space-time tolerance among multiple cyber entities' thinking.

6.2.9 *Nanotechnology*

Nanotechnology launches a new nano-scale field, and promises new solutions for the IoT by creating high performance devices, equipments, and platforms to achieve the Internet of Nanothings [24,25].

• Ubiquitous sensing: Nanotechnology is available to improve the sensors/actuators' performance (e.g., higher sensitivity and selectivity, shorter response time, and longer lifetime). Thereinto, nanomaterials (e.g., carbon nanotubes (CNT), graphene, gold nanoparticles, and nanowire) have been widely used in IoT applications.

• Communication networks: Nanotechnology has shown promising application in improving the performance of wired and wireless communications, and achieves high bandwidth demands and low energy efficiency in RF communications. The possible communication channels for the nano-scale sensor networks include molecule communication, nano-electromagnetic communication, and quantum communication.

• High performance computing: Nanomaterials are applied to design high performance computing systems, including molecular electronic devices, carbon based nanomaterials, and memristors. The nanotechnology can replace the silicon semiconductor based technologies with lower power consumption and higher energy efficiency.

6.2.10 *Quantum technology*

Quantum mechanics is a fundamental physical theory that describes the interactions of energy and matters [26], and the engineering quantum technology is based on the quantum mechanics and principles, which mainly include quantization (i.e., quantum size effect), uncertainty principle, quantum superposition, tunneling, entanglement, and decoherence.

• Quantum dots refer to the quantum size effect based nano-fabricated physical systems, and can be regarded as the artificial atoms technology. This technology is especially suitable for developing new chemical sensors based on energy-transfer phenomena. Due to the luminescent properties, quantum dots have been used in the biological labels, optical sensors, and opt-electrochemistry.

• Quantum communication is to transfer a quantum state from one place to another place, and quantum information is coded by the quantum states with higher performance. The quantum key distribution (QKD) and quantum teleportation are the critical issues during secure quantum communications.

• Quantum computer adopts the full complexity of a many-particle quantum wave function to solve a computational problem, and it is engineered to control the coherent quantum mechanical waves with an advantage of inherent parallelism. Applying the quantum superposition principle, quantum computers are expected to address the complicated tasks (e.g., factoring large numbers).

The quantum technology will drive the IoT for making sensor networks more powerful, communication securer, and massive data processing more efficient.

7 Conclusion

In this paper, we have identified the necessity to re-consider the science and technology issues for the IoT, and the new CPST space is established by involving the IoTk. A science and technology framework is established referring to scientific aspect (i.e., cyber-physical, social, and noetic sciences) and technological aspect (i.e., fundamental, physical, cyber, and social technologies), in which the five elements are introduced for establishing the cyber-physical science. Considering the proposed framework, we further introduce the reconstructed science and technological aspects, and present the main science subjects/disciplines and enabling technologies.

Acknowledgements

This work was supported by National Natural Science Foundation of China (Grant Nos. 61471035, 61174103), National High-tech R&D Program of China (863 Program) (Grant No. 2012AA013002). We also thank DNSLAB, China Internet Network Information Center, Beijing 100190, China.

References

1 Atzori L, Iera A, Morabito G. The Internet of Things: a survey. Comput Netw, 2010, 54: 2787–2805

2 Liu Y, Wu J, Zhang Z, et al. Research achievements on the new generation internet architecture and protocols. Sci China Inf Sci, 2013, 56: 111101

3 Qian X. The behavior science system (in Chinese). Phil Res, 1985, 8: 11–15

4 Ning H, Wang Z. Future Internet of Things architecture: like mankind neural system or social organization framework? IEEE Commun Lett, 2011, 15: 461–463

5 Kortuem G, Bandara A K, Smith N, et al. Educating the Internet-of-Things generation. Computer, 2013, 46: 53–61

6 Gluhak A, Krco S, Nati M, et al. A survey on facilities for experimental Internet of Things research. IEEE Commun Mag, 2011, 49: 58–67

7 Hamblen J O, van Bekkum G M E. An embedded systems laboratory to support rapid prototyping of robotics and the Internet of Things. IEEE Trans Edu, 2013, 56: 121–128

8 Ning H, Hu S. Technology classification, industry, and education for future Internet of Things. Int J Commun Syst, 2012, 25: 1230–1241

9 He M. The evolution and future trends of technology and information sciences. In: Proceedings of WASE International Conference on Information Engineering (ICIE 2009), Taiyuan, 2009. 11–15

10 Chen C Y. Early Chinese Work in Natural Science: A Re-Examination of the Physics of Motion, Acoustics Astronomy and Scientific Thoughts. Hong Kong University Press, 1996

11 Ng S K, Wong L. Accomplishments and challenges in bioinformatics. IT Prof, 2004, 6: 44–50

12 Chamberlain T E. Behavioral science: a progress report. IEEE Aerosp Elect Syst Mag, 2000, 15: 3–6

13 Ning H. Unit and Ubiquitous Internet of Things. CRC Press, Taylor & France Group, 2013

14 Zhang Y, Qian Z, Zheng W. Employing intelligence in object-based storage devices to provide attribute-based file access. Sci China Inf Sci, 2013, 56: 032115

15 Melo G, Weikum G. Taxonomic data integration from multilingual wikipedia editions. Knowl Inf Syst, 2014, 39: 1–39

16 Evrim V, McLeod D. Context-based information analysis for the web environment. Knowl Inf Syst, 2014, 38: 109–140

17 Munasinghe K S, Kibria M R, Jamalipour A. Designing VoIP session management over interworked WLAN-3G networks. IEEE Wirel Commun, 2008, 15: 86–94

18 Chen L, Wu J, Zheng Z, et al. Modeling and exploiting tag relevance for web service mining. Knowl Inf Syst, 2014, 39: 153–173

19 Ning H, Liu H, Yang L T. Cyberentity security in the Internet of Things. Computer, 2013, 46: 46–53

20 Roman R, Najera P, Lopez J. Securing the Internet of Things. Computer, 2011, 44: 51–58

21 Basher A R M A, Fung B C M. Analyzing topics and authors in chat logs for crime investigation. Knowl Inf Syst, 2014, 39: 351–381

22 Zhou T C, Lyu M R T, King I, et al. Learning to suggest questions in social media. Knowl Inf Syst, 2014: 1–28

23 Ning H, He W, Hu S, et al. Space-time registration for physical-cyber world mapping in Internet of Things. In: Proceedings of IEEE 12th International Conference on Computer and Information Technology (CIT2012), Chengdu, 2012. 307–310

24 Balasubramaniam S, Kangasharju J. Realizing the Internet of Nano Things: challenges, solutions, and applications. Computer, 2013, 46: 62–68

25 Akyildiz I F, Jornet J M. The Internet of Nano-Things. IEEE Wirel Commun, 2010, 17: 58–63

26 Dowling P J, Miburn G J. Quantum technology: the second quantum revolution. Phil Trans Roy Soc A-Math Phy, 2003, 361: 1655–1674