

Fundamentals and Applications of Information System Dynamics

Authors: Xu Jianfeng, Liu Zhenyu, Wang Shuliang, Zheng Tao, Wang Yashi, Wang Yingfei, Dang Yingxu, Xu Jianfeng

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Abstract

Purpose: To discuss the necessity and foundation for establishing Information System Dynamics, and to introduce its basic structure and application prospects.

Methods: Based on the mathematical foundational theories of information models, properties, and metrics, as well as the framework structure of information systems, we establish the measurement efficacy and dynamic configurations of information systems, and demonstrate the application prospects of Information System Dynamics through examples.

Results: It is proven that the definitions of information models, properties, and metrics comply with a series of classical information technology principles. The foundational theoretical system of Information System Dynamics, which is of universal significance, is constructed based on eleven types of measurement efficacies and eight typical dynamic configurations of information systems.

Limitations: The related theoretical methods need to be validated through application in complex information system architectures across other industry domains.

Conclusion: Information System Dynamics based on objective information theory can support the analysis and evaluation of complex information system architectures.

Full Text

Preamble

Foundations and Applications of Information System Dynamics

Authors: Xu Jianfeng¹, Liu Zhenyu², Wang Shuliang³, Zheng Tao³, Wang Yashi², Wang Yingfei¹, Dang Yingxu³

¹(People's Court Information Technology Service Center, Beijing 100745, China)

²(China University of Political Science and Law, Beijing 100027, China)

³(Beijing Institute of Technology, Beijing 100081, China)

Corresponding author. E-mail: xjfcetc@163.com

Abstract:

[Objective] This paper discusses the necessity and foundation of information system dynamics, introducing its basic structure and application prospects. [Methods] Based on the mathematical foundations of information models, properties, and metrics, as well as the framework structure of information systems, we establish the metric efficacy and dynamic configurations of information systems, illustrating application prospects through practical examples. [Results] We prove that the definitions of information models, properties, and metrics conform to a series of classical information science and technology principles. Building upon eleven metric functions and eight typical dynamic configurations of information systems, we constitute a general theoretical framework for information system dynamics. [Limitations] Relevant theories and methods require validation through application in complex information systems across other industry domains. [Conclusions] Information system dynamics based on objective information theory can support the analysis and evaluation of complex information systems.

Keywords: Information Space; Framework Structure; Metaverse; Information Model; Information Measure; Information Systems Dynamics; Smart Court SoSs (System of Systems) Engineering Project of China

1. Introduction

James Gleick's *The Information* opens with a profound assertion: information is the blood, food, and life force upon which our world operates. As information systems proliferate in type and quantity, expand in scope, increase in connectivity, and intensify in collaborative demands, our ability to comprehend and manage them—particularly systems of systems comprising numerous information systems—has become increasingly challenging. These exceptionally complex information system architectures, influenced by various internal and external uncertainties during operation, may evolve in ways that deviate from their original purposes, even exhibiting instability. Moreover, in the construction and application of such systems, emphasizing order while neglecting vitality inevitably leads to rigidity, whereas emphasizing vitality while ignoring order inevitably results in chaos. There is a pressing desire for a comprehensive methodology, analogous to traditional dynamics guiding large-scale mechanical systems engineering, to lead and standardize the design, development, application, and evaluation of large-scale information system architectures.

However, despite rapid advancements in information technology development and application, a comprehensive, rigorous, and complete foundational theoretical system for information system dynamics has yet to emerge. The primary reasons can be summarized as follows:

First, there is a lack of universally recognized mathematical foundation for the concept of information. Shannon's 1948 publication *A Mathematical Theory of Communication* is regarded as the foundational work of information theory, revealing that communication essentially reduces uncertainty and that the uncertainty of random events with certain probability distributions can be expressed as entropy, leading some to consider information as "negative entropy." Yet information applications far exceed communication scope, and information system forms far surpass communication systems. Explaining information solely through "negative entropy" proves inadequate for contemporary information technology development, particularly for information systems engineering practice. In fact, consensus on information cognition remains elusive, with fundamental disagreements persisting on whether information belongs to objective or subjective categories. Most importantly, insufficient attention has been paid to expressing and deconstructing information using mature mathematical theories, leaving research without a unified, clear, and practical mathematical foundation, naturally hindering the establishment of a rigorous and sophisticated information system dynamics theoretical system using advanced mathematical tools.

Second, there is a lack of a clear and rich measurement system for information value. Shannon's "entropy" is indeed an important metric reflecting information value, forming the fundamental pillar of information science theory and driving the vigorous development of Shannon's information theory. Subsequent research has produced concepts such as cumulative residual entropy, cross-entropy, relative entropy, conditional entropy, joint entropy, and fuzzy entropy. However, entropy metrics alone cannot meet modern information systems engineering needs, as "uncertainty" is a relative concept while information systems must satisfy thousands of diverse users, each with different "uncertainties." Consequently, direct application of entropy metrics in modern information system design and analysis is rare. Additionally, Shannon's proposal to express information quantity in binary bits—bits—has become the most 普及 and comprehensible information measure, further demonstrating Shannon's significant contribution to information technology development. Yet bits cannot reflect all information meaning, as information with the same bit count may have vastly different values. Beyond bits, almost no other strictly defined and universally recognized information measures exist. For instance, the 5V characteristics of big data—Volume, Velocity, Variety, Value, Veracity—clearly possess measurement attributes but mostly lack rigorous consensus on connotation and mathematical definition. Without a clearly defined and richly varied information measurement system, establishing an essential reference framework for studying information mechanisms becomes impossible.

Third, there is a lack of scientifically reasonable framework structure for informa-

tion space. Information space is the objective reality where information moves and acts, with information systems serving as fundamental carriers employing information services for humanity. Today's era encompasses global internet systems at one extreme and personal smartphones at the other, each being both an independent information system and a component of larger systems. Computers, the internet, big data, cloud computing, blockchain, IoT, robotics, and virtual reality represent both landmark achievements in information technology development and diverse forms of information systems. However, what is the relationship between these information systems and our real world? What roles do emerging information technologies play in various information systems? Can we reasonably classify the collection of all information systems? Can we construct a scientifically reasonable framework for information space? These questions profoundly affect information system analysis, planning, and expectations. While input-behavior-output describes any system process, this pattern is overly simplistic for complex information spaces and systems, insufficiently supporting universal research and analysis. Becoming lost in information space's myriad changes risks entanglement in trivial details. Therefore, an urgent need exists for a comprehensive perspective that simplifies complexity, reasonably classifies information system components, and depicts the entire information space framework structure to support the formation of information system dynamics theoretical systems.

Fourth, there is a lack of clear efficacy analysis for information functions. Mechanisms describe how and to what extent one thing influences another. After Newtonian mechanics emerged, using mathematical tools like calculus and differential equations through efficacy indicators such as velocity, force, energy consumption, and power, a complete and mature dynamics theoretical system was formed. Such methods have been applied beyond dynamic systems to chemical kinetics, economic dynamics, and other fields, becoming effective tools for analyzing specific domain operational mechanisms. Although people cannot live without information, widely accepted and universally meaningful efficacy definitions and analyses for information remain lacking. Shannon's information theory confirms information's efficacy in reducing uncertainty, but this single efficacy is far insufficient to describe and analyze complex interactions between information systems. Many specific information systems like radar, sonar, computers, data centers, and control centers have numerous domain-specific information efficacy definitions and indicators supporting mechanism analysis and research. However, these domain-specific information efficacies lack universal significance like velocity and force, making them inadequate for analyzing and researching the integration of numerous information systems from different domains and functions into large-scale architectures. Only by establishing an information efficacy system with broad connotation and universal meaning can we accurately analyze the influence patterns and degrees among components of large-scale complex information systems.

These reasons have resulted in the absence of computable mathematical models capable of 刻画 information system dynamics. While the concept of information

dynamics has long existed, its expressions remain primarily qualitative, lacking quantitative regularities. Yan Bin elaborated on concepts of information, information quantity, and information limits, explaining relationships between information dynamics and factors like information flow, transmission processes, statistical states, physical concepts, theoretical expressions, and practical measurements. However, considering only entropy or information quantity as information metrics or efficacy makes it difficult to apply such information dynamics to analyzing various information systems. The concept of information system dynamics also emerged early, with A. Flory and J. Kouloundjian studying a database model design under the name of information system dynamics, which diverged significantly from traditional dynamics concepts. Ahmed Bounfour and Surinder Batra introduced an international research project on information systems and information technology effects on business models, human resources, and social organizations, without addressing the use of fundamental mathematics to establish information metrics and efficacy systems as a foundation for information system dynamics research. Precisely because a universally meaningful mathematical foundation supporting the analysis of numerous information movement mechanisms has not been formed, a reasonable paradigm for information science research remains elusive. This paper addresses these critical issues by reviewing the major course of computer and network communication development driving rapid information technology advancement, discussing the important roles of various technical achievements in information movement and application, studying the relationships between the real world, information space, and information systems, and proposing an integrated framework structure for the real world and information systems. Based on recent research and practical results, we comprehensively revise and supplement the authors' previous mathematical foundation theories on information models, properties, and metrics from [25][26]. On this basis, guided by eleven information metrics, we propose eleven metric efficacies of information systems and their distribution views across various system components, then analyze the dynamic configurations of information systems, thereby constituting a universally significant foundational theoretical system for information system dynamics. Finally, we introduce its application in China's Smart Court information system architecture engineering, aiming to provide references for analyzing, designing, developing, and evaluating complex information system architectures.

2. Problem Statement

Like matter and energy, information is the blood, food, and life force upon which our world operates. However, unlike matter and energy, our understanding of how information drives the development and change of worldly affairs remains incomplete and lacks quantitative precision. While we have exact mathematical formulas for matter and energy—such as how many calories are in food of a certain weight, or what force produces what acceleration in an object of a given mass—our consensus on measuring information remains limited to the single unit of bits. Consequently, we struggle to comprehend complex information

mechanisms and have failed to establish a complete, quantitatively rigorous, and universally applicable Information System Dynamics (ISD) theoretical system for information flow, analogous to those for material and energy flows.

2.1 Why Do We Need ISD?

According to L.V. Bertalanffy, founder of general systems theory, a system is an organic whole composed of elements connected in certain structural forms to perform specific functions. For centuries since the Industrial Age, mechanical, architectural, and electrical systems such as automobiles, ships, airplanes, buildings, telephones, and electric trains have become indispensable to normal life. Traditional system dynamics theory, formed by the close integration of foundational mathematics (calculus, differential equations) with classical physics (Newtonian mechanics, thermodynamics, Maxwell's electromagnetic theory), uses metrics like volume, weight, temperature, velocity, force, heat, power consumption, voltage, field strength, and kinetic energy to qualitatively and quantitatively describe system mechanisms dominated by material and energy flows and their transformations. This has played a crucial supporting and guiding role in analyzing, designing, constructing, integrating, and evaluating mechanical, architectural, and electrical systems of the industrial era. Such methods have also been applied beyond dynamic systems to chemical kinetics, economic dynamics, and other fields, becoming effective tools for analyzing specific domain operational mechanisms.

Since the mid-20th century, rapid computer and communication technology development, particularly the emergence of the internet, has ushered humanity into the information age. Widespread application of cloud computing, big data, mobile internet, supercomputing, blockchain, and artificial intelligence has fundamentally transformed human production and lifestyles more profoundly than industrial civilization. Various information systems far surpass traditional electromechanical systems in geographical coverage, population reach, and business domain penetration. However, our understanding of information and information system mechanisms remains far less clear and rigorous than for traditional electromechanical systems. Unlike Newton's three laws and the three laws of thermodynamics, which derive strict mathematical expressions from fundamental principles, today's network "three laws"—Moore's Law, Metcalfe's Law, and Gilder's Law—are empirical formulas based on observation. Information systems have spontaneously grown to today's massive scale rather than developing consciously under the guidance of classical dynamics laws as traditional electromechanical systems did. The fact that information has only one recognized measure—information quantity or capacity—sufficiently illustrates the challenge. Objects without adequate effective measures are difficult to evaluate accurately, making quantitative mechanism or dynamics theoretical systems hard to form.

Without ISD theoretical guidance, large-scale information system development frequently lacks quantitative analysis and constraints for each component, resulting either in integration failures or low overall system efficiency due to bot-

tlenecks in certain links. Large-scale complex information systems like smart cities and smart societies, lacking universal structural specifications and evaluation indicator systems, suffer from extensive low-level technology duplication across different cities and domains, making mutual learning difficult. This 普遍 creates system silos with inconsistent interfaces, disconnected protocols, and isolated information, wasting substantial human and financial resources while significantly reducing system usability. More importantly, without quantitative analysis and thorough research on the efficacy of advanced technologies in information systems, 盲目 deployment has frequently triggered ethical, moral, and legal issues. Concerns about future AI technologies potentially causing unpredictable disasters are also related to the absence of ISD theoretical systems.

Therefore, in today' s era where information systems are ubiquitous and large-scale information system architectures play decisive roles in society' s future development, we must urgently construct an ISD theoretical system based on information technology achievements and comprehensive foundational mathematics, employing mathematical, quantitative, and systematic methods to guide the 良性, orderly, and scientific development of large-scale information systems or architectures, leading advanced information technology R&D to maximize benefits for humanity rather than the opposite.

2.2 What Kind of ISD Do We Need?

Qian Xuesen proposed that modern science and technology structure should have three levels: engineering technology that directly transforms the objective world, technical science that directly provides theoretical foundations for engineering technology, and basic science that further abstracts and generalizes from technical science to reveal objective laws. Today' s urgent need is ISD at the basic science level, which should satisfy the following conditions and content requirements:

First, it should build the simplest and most universal bridge between information concepts and mathematical theory. Marx emphasized that a science only truly develops when it successfully employs mathematics. The purpose of constructing ISD is to use rich and powerful mathematical tools to support quantitative, computable, and derivable information system analysis and research. Information is the primary resource carried and flowing through information systems, so the prerequisite for constructing ISD is defining information concepts and models mathematically. Such definitions must be simple enough for mathematical understanding at a glance, yet comprehensive enough to encompass all information content and forms to meet analysis needs across industries.

Second, it should form an information measurement system derived from mathematical concepts and models. Information quantity or entropy alone is insufficient for analyzing modern complex information system mechanisms. Any mechanism must manifest through impacts and changes in relevant metrics. Therefore, based on mathematical information concepts and models, we must

develop a measurement system covering information value-related, universally applicable metrics for information acquisition, transmission, processing, storage, application, and their combinations. This system should be practical, operable, and capable of guiding information system analysis and research.

Third, it should reasonably deconstruct and generalize components of general information systems. ISD supports information system construction by analyzing how information flows move and function among system components. Only by forming a clear, complete, and hierarchically decomposable conceptual system of information systems, elements, structures, and functions—supporting descriptions of element-element, element-system, and system-environment relationships while fully embodying characteristics like integrity, relevance, temporal ordering, hierarchical structure, and dynamic balance—can we comprehensively and accurately understand information system working mechanisms and effectiveness.

Fourth, it should deconstruct specific information system efficacies based on the measurement system and component structure. Information system mechanisms manifest through metric impacts and changes among components. Some system links may primarily alter certain metrics while minimally affecting others. Therefore, we must examine each link's impact on every metric. Since these impacts target specific metrics, they can be understood as efficacies measurable by metrics, or simply metric efficacies. Information system overall functions and performance result from the 叠加 mixing of all these metric efficacies, making metric efficacy decomposition analysis the fundamental content of ISD.

Fifth, it should focus on typical dynamic configurations of information system architectures based on common or important application scenarios. If ISD is likened to a massive building, each link's metric efficacy represents bricks and tiles, while dynamic configurations represent overall or partial architectural structures. Dynamic configurations combine various system links and information flows, with each combination potentially possessing unique configurations. Therefore, constructing ISD requires highlighting key points, selecting typical combinations of system links and information processes, and using quantitative, computable, and derivable methods to study information metric efficacies from beginning to end, forming methods for analyzing and evaluating entire architecture effectiveness.

Sixth, it should extensively incorporate existing classical information technology principles and common methods. Information technology's transformative power does not stem from a lack of theoretical guidance. On the contrary, information theory, cybernetics, and systems theory have enriched during rapid IT development, with technologies like internet, big data, cloud computing, supercomputing, IoT, blockchain, AI, and virtual reality emerging continuously. The only missing element is a unified, rigorous, and universal ISD theoretical system. Based on broad information metric efficacies and typical dynamic configurations, existing information technology theories and methods can be conveniently accommodated, rapidly enriching the ISD theoretical system to provide

solid, unified, and universal basic science support for engineering and technical science.

Finally, it should continuously explore new theories and methods, developing and improving ISD' s open architecture with the times. Rapid IT development and significant achievements have shown that engineering technology, technical science, and basic science do not have strict sequential development order; practice and theory have always promoted and integrated with each other. Therefore, ISD should never be a closed, rigid theoretical constraint but should adopt a completely open architecture, firmly grounded in mathematics, physics, and numerous other domain theories and methods while rapidly absorbing the latest scientific and technological innovations and exploration results from all industries, becoming a theoretical and methodological system that conforms to information technology development trends and matures continuously.

2.3 What Is the Foundation for Constructing ISD?

The tremendous achievements in information technology development and application, Shannon' s classical research methodology, and objective information theory' s mathematical definitions, models, and metrics for information have provided a solid foundation for constructing ISD theoretical systems.

Thanks to the close integration of computer and digital communication technologies, information technology has flourished since the internet' s birth, with continuous emergence of applications in big data, cloud computing, mobile internet, supercomputing, blockchain, AI, IoT, virtual and extended reality, permeating every corner of human society. Internet technology supports the smooth flow and wide application of objective knowledge information. Big data technology supports distributed storage, massive capacity management, high-timeliness retrieval, strong correlation expression, and fine-grained mapping of information. Cloud computing technology supports efficient processing, storage, remote invocation, and remote services of information. Mobile internet technology supports extensive collection and 随遇 utilization of information. Supercomputing technology supports massive, parallel, and high-speed information processing. Blockchain technology supports high-trust utilization of information. AI technology supports automated utilization and high-adaptation services of information. IoT technology supports extensive collection and circulation of physical information. Virtual and extended reality technology supports high-fidelity presentation and diversified information functions. As the Chinese proverb says, "practice produces true knowledge," such fruitful information technology application practices and achievements will certainly generate profound ISD theoretical results.

Shannon' s 1948 publication *A Mathematical Theory of Communication* is recognized as the foundational work of information theory. Studying communication systems, Shannon first decomposed and generalized communication systems into five components: source, transmitter, channel, receiver, and destination, ana-

lyzing message types flowing through them. For the simplest noiseless discrete system, Shannon provided a mathematical definition of channel capacity, obtaining explicit channel capacity formulas based on symbol duration under specific states. Subsequently assuming discrete sources as Markov processes selecting successive symbols according to specific probabilities, Shannon proposed three important conditions that information quantity measures should satisfy, thereby obtaining the entropy formula for quantitatively calculating information quantity and many important entropy properties. Further discussions extended to more complex scenarios like noisy discrete channel capacity, continuous channel capacity, and continuous source generation rates, proving the famous Shannon's three theorems. Building upon Shannon, research using information entropy to study information science has been continuous and magnificent, with later generations unable to break through Shannon's basic information constraints. Undoubtedly, Shannon's information theory itself has epoch-making significance, with extraordinary theoretical level and practical utility. However, as a scientific giant, his research methodology—decomposing and generalizing practical problems, using mature mathematical definitions and tools, obtaining mathematically formulaic and scientific laws through a series of assumptions, thereby establishing the scientific foundation of classical information theory—deserves even more respect and learning from successors. Shannon's era had no internet or large-scale complex information systems; we cannot 苛求 predecessors to create scientific theoretical tools solving today's various problems. However, as long as we fully understand and inherit the thinking paradigms and scientific methods of our predecessors, we can certainly construct an ISD basic science system to solve complex problems in information system architecture engineering.

Addressing key issues affecting information science research paradigms—lack of universally recognized mathematical foundation for information concepts, lack of clear and rich measurement systems for information value, lack of scientifically reasonable framework structures for information space, and lack of clear efficacy analysis for information functions—Xu Jianfeng et al. employed set theory, mapping theory, measure theory, and topology to propose information definitions, a six-element model, and measurement systems [25][26]. Although simple, the six-element model performs three important deconstructions of information concepts: first, a binary deconstruction of information subjects, using subject-carrier binary structure to describe information subjects based on information's reflective characteristics; second, a time-dimensional deconstruction, introducing occurrence time and reflection time parameters to support time-dimensional analysis of information movement; third, a morphological deconstruction of information content, introducing state sets and reflection sets to accommodate all information content and forms. This six-element model has already built a simple and universal bridge between information concepts and mathematical theory. Subsequently, mathematical corollaries were proven regarding information's five basic properties: objectivity, reducibility, transitivity, composability, and associativity, particularly the important corollary that reducible information's

s binary states can maintain mathematical isomorphism, opening convenient doors for using rich mathematical theories to support extensive information science research. Based on eleven categories of information metrics, it was further demonstrated that information models and measurement systems not only fully conform to numerous classical information technology principles but also possess broader inclusive and universal significance, providing solid mathematical theoretical foundations for comprehensive and systematic analysis of information science, technology, and systems. This paper also proposes an integrated framework structure for the real world and information systems based on their interrelationships, and guided by eleven information metrics, proposes eleven metric efficacies of information systems and their distribution views across various system components, then analyzes information system dynamic configurations, forming a universally significant theoretical framework that provides specific and clear directions for enriching ISD theoretical systems.

3. Review of Information Technology Development

Information technology continues evolving, with networking, big data, cloud computing, AI, and other technologies converging and integrating deeply. Today, information technology and its applications are ubiquitous, ushering in an intelligent stage characterized by deep data mining and fusion applications. In the new world vision of “digital everything,” the fusion of information space and physical world creates new human-cyber-physical computing environments, spawning human-cyber-physical fusion applications like smart justice, smart cities, and intelligent manufacturing. Studying information system dynamics particularly requires reviewing the developmental history of major technological achievements along a timeline, including network communication, big data, blockchain, cloud computing, AI, and visual/extended reality technologies.

3.1 Network Communication Technology

Network technology originated from Shannon’s information theory and continuous efforts to connect computers into networks. Shannon’s information theory, building upon Harry Nyquist and Ralph Hartley’s 1920s work, established the trade-off relationships among signal-to-noise ratio, bandwidth, and error-free transmission in noisy communication environments. Additionally, breakthroughs in transistor technology (particularly MOS transistors) and laser technology enabled rapid bandwidth network computing growth over nearly half a century. The Domain Name System and TCP/IP protocol stack, widely adopted internationally, continuously integrated computer networks worldwide, ultimately forming the global internet.

(1) Early Network Technology

The earliest network prototypes emerged from large computer architectures in the early 1940s, featuring central mainframes and user terminals connected directly for point-to-point communication. This period’s network technology

primarily solved time-sharing problems among computer users. However, point-to-point communication models had limited capacity, preventing direct communication between arbitrary systems and proving strategically and militarily vulnerable, as single link failures could paralyze entire networks.

Connecting different physical networks into logical networks to improve information pervasiveness has been a primary pursuit. Early networks used message switching models requiring rigid routing structures, making them prone to single-point failures. As electronics and communication technologies advanced in the 1950s, longer-distance (for terminals) or higher-speed (for local device interconnection) communications necessary for mainframe architectures gradually became feasible. In the early 1960s, Paul Baran proposed distributed network concepts based on message block data while studying US military network survivability during nuclear war. Simultaneously, Donald Davies at the UK's National Physical Laboratory proposed packet switching technology—a fast store-and-forward network design dividing messages into arbitrary packets with routing decisions for each. Compared to traditional circuit switching for telephones, packet switching improved bandwidth utilization on resource-limited interconnected links, increased network information capacity, shortened response times, and improved latency.

During this period, the US and UK conducted network research and experimental networking projects that continuously evolved and merged, expanding network distribution scale and effectively improving information pervasiveness in transmission systems. In 1969, the US Defense Advanced Research Projects Agency (ARPA) launched ARPANET, adopting Davies and Baran's packet switching technology. In 1978, Donald Davies' s team used packet switching and proposed the “network protocol” concept, building the operational NPL local network (Mark I), enabling interconnection of computers across different regional laboratories. When NPL evolved to Mark II in 1973, it developed into a hierarchical network protocol architecture. ARPANET and NPL were the earliest operational packet-switched networks, validating feasibility under real working conditions. Additionally, extensive research collaboration from projects like Michigan's Merit network, France's CYCLADES network, the UK's SERCnet (later JANET), and Duke University's UUCPnet gradually drove key networking technologies including Ethernet, ITU-T X.25 standards, virtual telephone circuits, international packet switching services, and TCP/IP protocol stacks, enriching information transmission types and providing ample technical preparation for the eventual global internet.

(2) Internet Technology

The term “internet” originated from the first TCP protocol draft (RFC 675: Internet Transmission Control Program) published in 1974. Generally, the internet is a collection of networks connected by a common protocol. By the late 1980s, the US National Science Foundation (NSF) funded networking among national supercomputing centers, building NSFNET. ARPANET connected with NSFNET in 1981. From 1984-1988, CERN began building the TCP/IP-based

CERNET network, which after 1988 started connecting to US NSFNET. In 1991, UK' s JANET, Europe' s EARN, RARE, and EBONE networks successively adopted TCP/IP architecture and connected with US NSFNET. Entering the 1990s, Asia, Africa, and South America began building TCP/IP networks connecting to US and European networks, forming global network distribution and vastly expanding system transmission information pervasiveness. As more countries and institutions connected to US NSFNET, "internet" became the specific term for the global communication network based on TCP/IP protocol stacks.

A key internet technology is optical fiber communication. Global-scale network connections created challenges for ultra-large capacity data transmission that traditional radio, satellite, and analog copper cables could not meet. In 1995, Bell Labs developed wavelength division multiplexing (WDM) technology driven by lasers and optical amplifiers, effectively solving traditional information transmission system channel bandwidth insufficiency, improving delay performance, and ensuring digital signal sampling rates remained uncompromised. Since then, optical fiber networks have become crucial long-distance communication infrastructure.

The World Wide Web (abbreviated "www" or "Web") is an information space based on the internet where documents and resources are identified by URIs, linked via hypertext, and accessed through web browsers and applications. Today, the Web is the primary tool for billions to interact on the internet, profoundly changing work and lifestyles. Between 2005-2010, Web 2.0 transformed the internet into a social system change force, emphasizing user-generated content, usability, and interoperability through applications like social networks, blogs, wikis, folksonomies, video sharing, hosting services, and web applications, greatly enriching information services.

(3) Mobile Network Technology

While Web 2.0 evolved, mobile communication technology underwent revolutionary changes, making smartphones important portable computing platforms. First-generation (1G) mobile networks were automatic analog cellular systems, first deployed in Japan in 1979 for vehicle phones (NTT system), later in Nordic NMT systems and North American AMPS systems. 1G used frequency division multiple access (FDMA), requiring substantial wireless spectrum, demanding high channel capacity, and providing poor security.

In the 1990s, mobile communication technology digitized, entering the second-generation (2G) era. European GSM and American CDMA standards competed globally. Unlike its predecessor, 2G used digital instead of analog transmission, providing fast out-of-band networking signals and ensuring digital signal sampling rates. The 2G era witnessed the emergence of SMS, MMS, mobile payments, and other information types. In 1999, Japan' s NTT DoCoMo launched the world' s first full mobile internet service.

Driven by increasingly rich mobile internet applications, rapid data demand

growth made 2G technology unable to meet higher speed requirements. Mobile networks began using packet switching instead of circuit switching for data transmission, entering the third-generation (3G) era. 3G featured many competing standards including CDMA2000, SCDMA, GPRS, EDGE, HSDPA, HSPA, and UMTS. Different competitors promoted their technologies to improve channel capacity, but no unified global standard emerged during 3G. 3G's high-speed wireless connections significantly improved system latency, enabling streaming broadcast (even television) content to 3G phones and prompting profound transformations in news, entertainment, and related industries.

As high-bandwidth streaming services grew rapidly in mobile networks, by 2009 3G network information capacity could no longer meet intensive application demands. The industry sought fourth-generation (4G) data-optimized technology, aiming to increase information capacity tenfold over 3G within the same time period. 4G's main technologies were WiMAX and LTE standards. A major technical difference from 3G was 4G's abandonment of circuit switching for an all-IP network scheme, enabling streaming data transmission via VoIP like on Internet, LAN, or WAN networks.

Fifth-generation (5G) mobile network technology, now commercially deployed, includes millimeter-wave radio spectrum, allowing bandwidth capacity up to 1 gigabit per second and reducing latency between phones and networks to milliseconds. 5G's powerful channel capacity (up to 10Gb/s) and low latency open doors for data real-time transmission-dependent applications like AR/VR, cloud gaming, and connected vehicles. Through 5G, high-frequency information flow interaction between vehicles' powerful computing capabilities and advanced sensors may make autonomous driving a common commuting scenario.

(4) Internet of Things Technology

As RFID, sensor, embedded system, and wireless network technologies matured and converged, Kevin Ashton first proposed the "Internet of Things" (IoT) concept in 1999. The concept has since continuously enriched and improved. Commonly recognized IoT refers to embedding short-range mobile transceivers in various production and life necessities to enable new communications between human-object and object-object, further improving information pervasiveness in networks compared to the internet. Currently, IoT has become a global network infrastructure like the internet, with main technical characteristics including standardized interoperable communication protocols, device self-configuration capabilities, unique identification mechanisms, and integrated interfaces to reduce network latency and support interconnection of various IoT information types.

IoT technology is widely applied in consumer, commercial, industrial, and infrastructure domains. Consumer IoT devices include smart homes and wearable technologies. Main commercial applications include connected vehicles (vehicle-vehicle, human-vehicle, vehicle-road interconnection), smart transportation, smart healthcare, and intelligent buildings. Industrial applications include equipment asset registration, smart factories, smart agriculture, and smart ma-

rine industries. Infrastructure applications include smart cities, energy management, and environmental monitoring. Additionally, sensor technology will greatly impact future urban warfare involving sensors, ammunition, vehicles, robots, human wearable biometric technologies, and other battlefield-related intelligent technologies. IoT integration with extended reality combines real environments with immersive augmented reality content, creating stunning multi-modal interactive user experiences that enhance information space's ability to reflect the objective world, presenting information with unprecedented breadth.

(5) Data Internet Technology

While internet and IoT technologies solved human-machine information transmission problems, providing basic technical means for entering the digital age, they cannot avoid or solve problems like information silos, data loss of control, and data rights confirmation brought by continuous IT development. The pervasiveness of information's effective reflection of all things in the objective world has always faced bottlenecks. To achieve data interconnection beyond internet data transmission, application systems must coordinate to agree on data syntax, semantics, and pragmatics, facing challenges of high coordination costs, difficult rights-responsibilities-benefits assurance, and inefficiency, error-proneness, and difficulty in 复盘. Addressing platform-based data interconnection and difficulty in improving information breadth, Chinese researchers borrowed internet design concepts, adopting software-defined approaches to connect heterogeneous data platforms and systems through data-centric open software architectures and standardized interoperable protocols, forming a "virtual/data" network—the "Data Internet"—above the "physical/machine" internet, thereby achieving network-wide integrated data interconnection and significantly improving information breadth reflecting the objective world.

The core of the Data Internet is Digital Object Architecture (DOA), formally proposed by Robert Kahn in the early 21st century. DOA's conceptual architecture includes one basic model, two foundational protocols, and three core systems. The basic model is the digital object, abstracting internet data to enable heterogeneous data resources to be modeled and described uniformly, effectively improving information breadth, granularity, and diversity. Technically, a digital object is a bit sequence or collection of bit sequences containing valuable information for someone or some organization. Each digital object must be assigned a globally unique identifier that remains unchanged regardless of ownership, storage location, or access method changes. The two foundational protocols are the Digital Object Interface Protocol (DOIP) for interacting with digital objects or their management systems, and the Digital Object Identifier Resolution Protocol (DO-IRP) for creating, updating, deleting, and resolving globally managed digital object identifiers. The three core systems are the repository system (responsible for encapsulation, storage, access, and destruction), the registry system (responsible for metadata registration, publication, modification, and deletion), and the identifier/resolution system (responsible for identifier creation, resolution, modification, and destruction). DOA unifies internet data resources through digital objects, standardizes data interaction be-

haviors through DOIP and DO-IRP, and achieves heterogeneous, remote, and multi-owner data interconnection through the open software architecture formed by three core systems, greatly improving information systems' capabilities in breadth, granularity, pervasiveness, and diversity.

DOA has achieved global-scale application in digital libraries—the DOI system. As of May 2021, the DOI system had registered approximately 257 million digital objects globally, covering major international academic databases like IEEE, ACM, and Springer. China began building the world's largest DOA application system—the National Industrial Internet Identifier Resolution System—in 2018. As of August 2021, it had built 5 national top-level nodes (Beijing, Shanghai, Guangzhou, Chongqing, Wuhan) and over 200 secondary nodes, connecting more than 20,000 enterprises across 25 provinces and autonomous regions, marking China's Data Internet application information breadth as world-leading.

3.2 Supercomputing Technology

(1) Supercomputers

Big data's characteristics of large volume, heterogeneity, and timeliness have also driven high-throughput computing technology. Faced with rapidly growing data volumes, traditional centralized computing architectures encountered insurmountable bottlenecks, leading to distributed computing architectures for Massively Parallel Processing (MPP). The “supercomputer” concept emerged in the 1960s, achieving faster speeds than general-purpose computers through highly tuned traditional designs to reduce information flow latency. In the 1970s, vector processors operating on large data arrays began dominating, with the highly successful Cray-1 appearing in 1976. Vector computers remained mainstream supercomputer designs through the 1990s. Since then, massively parallel supercomputer clusters with tens of thousands of off-the-shelf processors have become the norm. Since 2017, information processing frequency has soared, with supercomputers performing over 10^1 floating-point operations (100 petaflops), compared to desktop computers performing hundreds of gigaflops to tens of teraflops.

(2) High-Throughput Computing Technology

For massive unstructured text data, the Apache Hadoop and Spark ecosystems emerged based on distributed batch processing frameworks, aiming to avoid low performance and complexity problems in traditional big data processing and analysis. Hadoop's ability to quickly process large datasets stems from its parallel clusters and distributed file systems. Unlike traditional technologies, Hadoop only loads locally stored data into memory for computation, avoiding loading entire remote datasets into memory, effectively reducing information capacity requirements and 减轻 network and server communication loads. Hadoop's power relies on two main components: the distributed file system (HDFS) and MapReduce framework. Additionally, Hadoop can be enhanced with modules for capacity, breadth, and security, forming a rich ecosystem. Addressing MapReduce cluster computing limitations, the Apache Foundation developed

the Spark system based on Resilient Distributed Datasets (RDD) in 2012. Spark facilitates iterative algorithms (accessing datasets multiple times in loops) and interactive/exploratory data analysis (repeated database-style queries). Compared to Apache Hadoop MapReduce implementations, Spark programs can reduce information processing latency by several orders of magnitude.

For real-time computing feedback needs of time-sensitive data, ecosystems based on distributed stream processing frameworks like Apache Storm, Flink, and Spark Streaming emerged. Apache Storm is a distributed real-time data processing framework that constructs directed acyclic graph (DAG) topologies from various information reception and processing primitives, enabling pipeline-style information processing where data flows directionally from one processing node to another. Compared to MapReduce, Storm's main difference is real-time, high-frequency data processing rather than batch processing. Apache Flink provides a high-capacity, low-latency streaming engine executing arbitrary dataflow programs through data parallelism and pipelining, supporting fine-grained information processing for both batch and stream programs. Additionally, Flink's runtime supports local execution of iterative algorithms and event-time processing with state management. Spark Streaming uses Spark Core's fast scheduling for stream analysis, receiving data in micro-batches and performing RDD transformations on them. This design enables the same application code written for batch analysis to be used for stream analysis, simplifying lambda architecture implementation. Storm and Flink process streaming data event-by-event rather than in micro-batches, enabling finer information processing granularity, while Spark Streaming's micro-batch approach, though convenient, introduces larger latency issues.

3.3 Big Data Technology

Big data and IoT can work synergistically. Data collected from IoT devices provides mapping of physical device connections, which can be used for more accurate audience targeting and media efficiency improvement. As IoT is increasingly used for sensor data transmission, massive aggregated sensor data can be applied in medical, manufacturing, and transportation environments.

(1) Large-Scale Data Storage and Management Technology

In the mid-1960s, database technology emerged with direct-access storage devices (disks and drums). Compared to earlier tape-based batch processing systems, databases allowed data sharing and interactive use. As computer speed and capability improved, general-purpose database management systems began appearing around 1966. Early database technologies primarily used two data models: hierarchical and network (CODASYL) models, characterized by using pointers (usually physical disk addresses) to track relationships between records.

To address early database models' inefficient retrieval support issues, Edgar F. Codd first proposed the relational model in 1970. Based on the relational model, databases could use Structured Query Language (SQL) with clear semantics,

significantly improving data model integrity and refinement, refining information management granularity, and enabling efficient data access. However, not until the mid-1980s was computing hardware storage capacity and processing power sufficiently powerful for widespread relational database system deployment. Until 2018, relational systems dominated all large-scale data processing applications. In commercial markets, IBM DB2, Oracle, MySQL, and Microsoft SQL Server are the most widely used database management systems.

In the 1990s, with the rise of object-oriented programming, programmers and designers began viewing database data as objects, allowing relationships to be between objects and their attributes rather than individual fields. To solve conversion difficulties between programming objects and relational database tables, database-side solutions used object-oriented languages (as SQL extensions) to replace traditional SQL statements, while programming-side solutions used Object-Relational Mapping (ORM) calling libraries.

In the big data era, characteristics of large volume, heterogeneous sources, and high timeliness made traditional relational database technology face deployment bottlenecks for distributed systems. After 2000, non-relational NoSQL databases emerged. Compared to traditional relational databases, NoSQL databases can be deployed on distributed file systems (like HDFS), improving system information management pervasiveness while enabling faster big data processing and ensuring high digital information sampling rates. NoSQL databases include key-value stores and document-oriented types, further increasing manageable information variety. Since NoSQL databases don't require fixed table schemas, they enable horizontal database design scaling, improving information processing breadth performance. The next-generation database technology competing with NoSQL is NewSQL, which retains the relational model (thus reusing SQL technology) while providing NoSQL system scalability for online transaction processing (OLTP) workloads, achieving high processing performance matching NoSQL while providing traditional database system guarantees for atomicity, consistency, isolation, and durability.

(2) Data Security and Privacy Protection Technology

Big data sharing and circulation are important ways to realize value release. Whether directly providing data query services or performing fusion analysis with external data, both are important methods for realizing data value. In the current environment of frequent data security incidents, effective technical guarantees for secure and controllable data circulation between organizations remain lacking. Meanwhile, as relevant laws gradually improve, data circulation faces stricter regulatory constraints, with compliance issues restricting multi-organization data circulation.

Data encryption is a key technology for data security. Data encryption is the process of encoding information, converting original representation (plaintext) into another form (ciphertext), increasing information sampling rate while maintaining constant distortion. In 1790, Thomas Jefferson proposed the Jefferson Disk cipher theory for encoding/decoding information to provide more secure

military communications. In 1917, US Army Major Joseph Mauborne developed the M-94 encryption device, used until 1942. During WWII, Axis powers used the more complex Enigma machine, supporting daily letter scrambling into new combinations. Modern encryption widely uses public-key and symmetric-key schemes. Due to extremely high required information processing frequency, encryption cracking efficiency is very low, thus providing higher data security.

Privacy computing, aiming to protect data from leakage while enabling data fusion and modeling, makes secure and compliant data circulation possible. Currently, under strong demand for compliant data circulation, privacy computing-based data circulation technology has become the main approach for joint data computing, 主要分为 multi-party secure computing and trusted hardware streams. Multi-party secure computing, based on cryptographic theory, enables secure multi-party collaborative computation without trusted third parties. Trusted hardware computing builds hardware security zones based on trust in secure hardware, performing data computation only within these secure zones. Under trust mechanisms recognizing cryptography or hardware suppliers, privacy computing can achieve multi-organization joint computing without data leakage. Additionally, federated learning and shared learning balance security and computational performance, providing new solutions for cross-enterprise machine learning and data mining.

(3) Data Analysis and Application Technology

Data analysis is the process of examining, cleaning, transforming, and modeling data to discover useful information, inform conclusions, and support decision-making. Data mining aims to extract patterns and knowledge from large data to reduce information mismatch. Data analysis involves database and data management, data preprocessing, model and inference considerations, interest measures, complexity considerations, post-processing of discovered structures, visualization, and online updates.

Human attempts to extract patterns from data have existed for centuries. As early as the 18th century, methods like Bayes' theorem identified data patterns, with regression analysis modeling data after the 19th century. Computer proliferation, 普及, and increasing power have greatly improved information capacity and operation frequency, enabling semi-automatic or automatic analysis of massive data to extract broader and finer-grained knowledge. As computer data mining technology advances, traditional analysis techniques for independent datasets have matured, including cluster analysis for improving information aggregation, anomaly detection, and dependency analysis (association rule mining and sequential pattern mining), the latter being one of the most important current applications. Association analysis originated in the 1990s from "market basket analysis" discovering shopping behavior patterns from customer transaction lists. In classical machine learning, Apriori and FP-growth algorithms mine association rules, making information services more adaptable to user needs. Sequential pattern mining discovers statistically correlated patterns in order among data examples, typically assuming discrete sequence values, thus

being closely related to time series mining.

Data like deep networks, user behaviors, and web link relationships often exhibit “graph” structures. Such graph-dependent data mining analysis is difficult to achieve through traditional methods like classification, clustering, regression, and frequent pattern mining. Therefore, graph analysis technology for graph-structured data has become a new data analysis direction, exploring and discovering unknown relationships in graph structures to fully obtain inherent graph structural correlations, further improving information aggregation.

3.4 Blockchain Technology

Blockchain is essentially a distributed data storage and management technology where data is stored in distributed “blocks” linked chronologically. Through consensus mechanisms and synchronization on peer-to-peer networks, blockchain possesses openness, immutability, transparency, and traceability. In the digital age, digital twins of the physical world will generate unimaginable massive data that can hardly be stored and managed centrally. In the future, blockchain’s distributed trusted collaboration network is expected to connect everything in digital space, becoming digital society’s trust infrastructure.

(1) Distributed Ledger

The earliest blockchain technology was first proposed by cryptographer David Chaum in 1982. In 1991, signed information chains were used as electronic ledgers for digital document signatures, easily displaying all signed documents in collections while preventing alteration. However, encrypted information increases information processing delay in the time dimension. In 1992, Haber, Stornetta, and Dave Bayer introduced Merkle trees into blockchain design to improve system efficiency. In 2008, the pseudonym Satoshi Nakamoto fully described “blockchain” technology in *Bitcoin: A Peer-to-Peer Electronic Cash System*. In 2009, the modern cryptocurrency scheme described in Nakamoto’s paper was implemented, marking Bitcoin’s birth and later spawning numerous cryptocurrency blockchain applications.

Unlike traditional relational databases, blockchain is a distributed digital ledger composed of “blocks” recording transactions among multiple parties. Transaction data is hashed and encoded into Merkle trees. Different blocks are arranged chronologically, with each subsequent block including the previous block’s cryptographic hash, forming a chain—blockchain. Theoretically, blockchain can grow infinitely, thus infinitely improving capacity, breadth, granularity, and duration performance for stored and managed information. In blockchain, each subsequent block confirms the previous block’s integrity through hashing, with this iterative process 追溯 to the initial block, ensuring all block information is difficult to alter retroactively. Blockchain uses peer-to-peer networks and distributed timestamp servers for autonomous management, verified through large-scale consensus. Effective distributed consensus mechanisms eliminate security uncertainties among peer-to-peer network users, solving the “Byzantine

Generals” problem unavoidable in distributed databases and improving on-chain information authenticity.

Currently, four main blockchain types exist: public, private, consortium, and hybrid chains. Public chains have no access restrictions and provide consensus verification through proof-of-stake or proof-of-work algorithms, with Bitcoin and Ethereum being the most well-known. Private chains require administrator invitation for joining, restricting participant and validator access. Consortium chains fall between public and private chains, targeting specific group members and limited third parties, designating multiple pre-selected nodes as bookkeepers internally. Hybrid chains combine centralized management and decentralized features, producing different blockchain management and operation methods.

Blockchain provides a secure data interoperability platform enabling different transaction parties to share data securely. Cryptocurrencies based on interoperable blockchains are also called “fungible tokens” (FT). Correspondingly, non-interoperable non-fungible tokens (NFT) can also be built on blockchain foundations.

(2) Consensus Technology

A fundamental problem in distributed computing and multi-agent systems is achieving overall system reliability in the presence of numerous faulty processes, typically requiring coordination to reach consensus on certain data values needed in computation—known as consensus mechanisms. Electronic currency concepts existed before Bitcoin (e.g., ecash, NetCash) but couldn’t be widely used without solving distributed consensus problems. Blockchain’s core distributed consensus technology concepts emerged in the late 1980s and early 1990s. In 1989, Leslie Lamport proposed the Paxos protocol, publishing a consensus model in 1990 for reaching agreement in computer networks where the network itself might be unreliable.

Blockchain consensus mechanisms are decentralized self-regulating mechanisms ensuring only valid transactions and blocks are added to blockchain. Blockchain primarily uses timestamp-based consensus mechanisms like proof-of-work and proof-of-stake to serialize information changes. However, these methods suffer from excessive computational overhead and inefficiency, causing large system delays that hinder practical application. In 2021, the Institute of Software, Chinese Academy of Sciences and New Jersey Institute of Technology proposed the world’s first fully practical “DumboBFT” Byzantine fault-tolerant algorithm, significantly reducing blockchain delay performance in production environments.

In the digital age, blockchain has entered a new development stage oriented around “trust chains” and “collaboration chains” for credible data element circulation. Currently, Byzantine fault-tolerant (BFT) algorithm-based consensus mechanisms are mainstream choices for various blockchains. For higher performance, some consortium chains use Raft’s Crash Fault Tolerance (CFT) consensus to ensure global data consistency, significantly improving system information processing capacity, with current systems reaching over 100,000

transactions. However, CFT consensus further weakens consortium chain decentralization and consensus fault tolerance, making chain systems tend toward distributed databases. To address differentiated needs between capacity, delay performance, and security, most blockchain platforms can support multiple consensus algorithms and switch between them as needed.

(3) Smart Contract Technology

Smart contracts are computer programs or transaction protocols designed to automatically execute, control, or record legally relevant events and actions according to contract terms. Smart contracts aim to minimize malicious fraud and execution costs while reducing needs for trusted intermediaries and arbitration. The “smart contract” concept originated in the early 1990s. In 1998, Szabo proposed that smart contract infrastructure could be implemented through replicable asset registration and contract execution using cryptographic hashes and Byzantine fault-tolerant replication. In 2002, Askemos implemented this approach using Scheme as the contract scripting language. In 2014, the Ethereum cryptocurrency whitepaper described the Bitcoin protocol as a simplified smart contract version. Since Bitcoin, various cryptocurrencies have supported scripting languages allowing smart contracts between untrusted parties.

Similar to value transfer on blockchain, deploying smart contracts on blockchain is achieved by sending transactions from the blockchain, including the smart contract’s compiled code and recipient address. The transaction must be included in a block added to the blockchain, after which the smart contract code executes to establish its initial state. Distributed Byzantine fault-tolerant algorithms prevent attempts to tamper with smart contracts. Once deployed, smart contracts cannot be updated. Smart contracts on blockchain can store arbitrary states and perform arbitrary computations, with end clients interacting through transactions.

Smart contracts enable multi-party transactions, provide provable data and transparency, promote trust, enable better business decisions, reduce reconciliation costs in traditional enterprise applications, and shorten transaction completion times. Currently, smart contracts are widely used in bonds, birth certificates, wills, real estate transactions, labor contracts, and other fields.

(4) Cross-Chain Extension Technology

As blockchain technology integrates innovatively with 5G, AI, big data, cloud computing, and other new technologies, “blockchain+” 融合 other new information technologies is increasingly becoming industry consensus. Large-scale, deep blockchain applications continuously strengthen its position as a cross-business and cross-technology integration hub.

Blockchain-IoT integration enables trusted physical-digital world links, improving information space’s breadth, granularity, and pervasiveness in reflecting the real world. IoT terminal devices’ trusted execution environments can solve IoT terminal identity confirmation and data rights confirmation problems, while blockchain’s accuracy and immutability can promote standardized data market

transactions and accelerate industry integration innovation. Blockchain itself has certain complexities, with deployment, usage, and operation difficulties hindering development. Cloud computing-based integration of development tools, smart contract management, automated operation, digital identity, and cross-chain services enables one-stop development and deployment of blockchain 底层 and applications, reducing blockchain response delay and application development costs. Blockchain-privacy computing integration enables blockchain to add trust to multi-party collaboration processes while privacy computing achieves data availability without visibility. This combination ensures full-process verifiable, traceable, and auditable data sharing while effectively protecting against data leakage, applicable to data generation and collection legitimacy verification, data processing certification and consensus, data usage authorization, data circulation, data collaboration, data auditing, etc., providing effective solutions for trusted information circulation.

As blockchain application breadth and depth expand, problems like cross-chain difficulties between different blockchain platforms, difficult switching between upper-layer application systems and 底层 chains, and difficult trusted interaction between on-chain and off-chain have become prominent. Currently, blockchain's main challenges are inter-platform interoperability technologies affecting information pervasiveness, including notary mechanisms, side chains/relay chains, hash time locking, and distributed private key control.

3.5 Cloud Computing Technology

Digital transformation has become society's future development "must-have option." Cloud computing, as a service model based on virtualization technology and networks, provides users with distributed computing resources like computing, storage, data, and applications. With cloud computing as the technical platform foundation, integrating new-generation digital technologies like big data, AI, blockchain, and digital twins has become a necessary and sufficient condition for economic and social digital transformation.

(1) Cloud-Native Technology

The earliest documented "cloud computing" concept appeared in Compaq's internal documents in 1996. In 2002, Amazon began providing commercial cloud services (AWS), allowing developers to build innovative and entrepreneurial applications independently. In 2008, Google released Google App Engine, enabling users to quickly deploy and scale various applications on demand. Cloud-native technologies include virtualization, multi-tenancy support, automated deployment and operation, microservices, containers, and DevOps. Virtualization decouples 底层 hardware from operating systems, enabling information systems' physical hardware to self-map in information space, increasing system self-information breadth and granularity. Containerization uses virtualized hardware resources for elastic expansion of system memory, network, and other information capacities. Microservices decouple applications, avoiding system crashes from single-point failures and extending processed information duration.

After containers and microservices achieve fine-grained resource and application distinction, Serverless technology refines services to the function level, significantly improving application development iteration speed, product deployment, and update capabilities through function encapsulation and orchestration.

Simultaneously, cloud-native technology reconstructs traditional software development and operation models, organically combining testing infrastructure with continuous delivery to cover the entire software development and delivery process. Based on containers providing consistent application environments, microservice architectures providing loosely coupled application development frameworks, independent iteration and deployment capabilities, and DevOps providing one-stop application development and operation platforms, information processing breadth extends across the full lifecycle including software coding, hosting, building, integration, testing, release, deployment, and operation. Integrating testing with development and operations significantly shortens software development cycles and improves iteration efficiency.

Accompanying rapid IT development, information capacity expansion, information type diversification, and algorithm model complexity pose higher requirements for computing resources. Cloud computing, with its powerful elastic scaling and high availability capabilities, can quickly meet computing resource demands from AI, big data, and other applications. Cloud-native-based AI product systems have proven effective in simplifying development processes, data management, and strengthening processing performance, accelerating the 落地 innovation of AI, big data, blockchain, and various applications.

(2) Edge Computing Technology

Mobile internet promoted widespread mobile device usage, but mobile devices' limited graphics and chipset processing capabilities often increased system latency. To reduce mobile devices' computing and memory burdens, load balancing is typically used for compensation at the cost of further increasing network latency. Therefore, effective and transparent load balancing is crucial for high-quality user experiences. However, due to cloud computing's highly variable and unpredictable latency characteristics, cloud-native loads cannot always achieve optimal balance, even causing long-tail latency phenomena. In 2009, research found that deploying powerful cloud-like infrastructure just one wireless hop from mobile devices could greatly improve overall system latency performance, with subsequent work proving this physically-deployed improved solution more realistic than pure cloud computing resource orchestration. This led to the "edge computing" concept—placing computing, storage, and data transmission physically closer to end users and their devices to reduce user experience latency compared to traditional cloud computing.

As real-time interactive applications like ultra-high-definition video and virtual reality with fine visual information granularity and high sampling rates rapidly 普及, low system latency becomes increasingly important. Currently, leveraging edge computing's low-latency advantages has effectively improved latency performance for 16K, 24K, and even higher-resolution streaming media. Consequently,

the European Telecommunications Standards Institute (ETSI) proposed MEC standards, deploying edge servers co-located with base stations or one routing hop away, operated and maintained by regional carriers. MEC technology can effectively reduce round-trip time (RTT) for packet delivery while supporting near-real-time orchestration of multi-user interactions, effectively improving system latency performance and laying important foundations for future 6G development.

Simultaneously, because edge computing architecture increases information replica scale, the number of information 作用 objects also increases, thereby improving overall information system pervasiveness.

(3) Cloud-Network-Edge Integration Technology

Network virtualization technology integrates cloud computing, edge computing, and various information resources within wide area networks into one entity, shifting computing power deployment from traditional single data centers to a center-region-edge three-level integrated “cloud-network-edge” distributed architecture. In this architecture, supercomputing center processing capabilities can allocate different computing power according to information flow capacity size and delay level through coordination with computing infrastructure, thereby optimizing computing services. For example, compute-intensive applications execute high-frequency computing tasks through supercomputing center platforms, while data-intensive applications reduce system latency and efficiently complete data access and processing through edge computing.

Driven by IoT, 5G, and other technologies, cloud-edge collaboration has expanded from initial central cloud-edge cloud coordination to a comprehensive “cloud-edge-device” technical architecture covering central cloud, edge cloud, edge devices, and IoT devices, with computing power 下沉 to the user side, further improving overall system latency performance. Meanwhile, cloud-native technologies like containers and microservices 下沉 to the edge, achieving resource elastic scheduling by subdividing information types, providing new deployment methods for applications in resource-constrained, device-heterogeneous, and demand-complex edge environments, enabling cloud-edge-device to leverage respective advantages and continuously enhance cloud-network-edge collaboration capabilities.

Under the cloud-network-edge integration trend, edge-side computing power deeply couples with cloud computing power, with cloud-network-edge distributed computing processing modes gradually replacing centralized computing processing modes, providing more powerful computing infrastructure for various intelligent application scenarios. Traditional AI development processes are complex, involving multiple links like data processing, model development, training acceleration hardware resources, and model deployment service management, with difficulties in both model training and application 落地. As heterogeneous computing power like CPU, DSP, GPU, and FPGA expands from cloud to edge, AI technology has shifted to a cloud-edge collaborative processing mode of cloud training-edge inference, increasing domain

information pervasiveness, effectively improving intelligent application system latency, and forming a complete model training and deployment closed loop.

(4) Zero-Trust Security Mechanism

In traditional information system architectures centered on organizational internal data centers, network location and trust have potential default relationships, adopting completely trusted strategies for internal network boundaries. As digital processes deepen, traditional information system architectures are transforming into digital infrastructures carrying cloud-network-edge integration and fusing new-generation technologies like big data, AI, and blockchain. Multi-cloud and hybrid clouds have become main information infrastructure forms, with frequent cross-cloud information flow interactions breaking traditional secure information boundaries.

To address this major information security challenge, cloud computing security concepts based on trust mechanisms have emerged, represented by technologies like Zero-Trust Network Access (ZTNA) and Software-Defined Perimeter (SDP) models. These new security concepts break the default relationship between network location and trust in boundary security concepts, where network boundaries are no longer security boundaries and everything is untrusted by default. Any object in information space must undergo identity verification and minimum privilege granting to block rapid propagation of potential risks, enabling cloud computing to adapt to security needs under blurred network boundaries.

Additionally, traditional cloud platforms need to collect user data to data centers for processing, posing user privacy leakage risks. Emerging federated learning technology trains and stores user data locally without uploading user private data beyond local gradient updates, implementing global model updates. This machine learning mode of local training and distributed server aggregation in cloud-network-edge integrated environments can improve data security and privacy by limiting information pervasiveness while ensuring information adaptation mechanisms.

3.6 Artificial Intelligence Technology

Artificial Intelligence (AI) refers to theories and technologies enabling machines to learn from experience and perform various tasks like intelligent organisms. AI is a broad concept including knowledge representation, reasoning, machine learning, swarm intelligence, and other subfields.

(1) Symbolic AI

Since the late 19th century, mathematical logic developed rapidly, beginning to describe intelligent behavior in the 1930s. In 1950, Alan Turing, regarded as the “father of computer science,” published the famous paper “Can Machines Think?” proposing machine thinking concepts and the renowned “Turing Test.” After electronic computers emerged, formal logic deduction appeared as computer programs. In 1952, Arthur Samuel developed a self-learning checkers program

that could defeat human professional players after training. In 1956, Herbert Simon and Allen Newell developed the heuristic AI program Logic Theorist, which proved 38 mathematical theorems, demonstrating computer simulation of human thinking processes. Representatives of this period included Newell, Simon, and Nilsson. At the 1956 Dartmouth Conference, John McCarthy and Marvin Minsky proposed the “artificial intelligence” concept to distinguish it from connectionism in cybernetics.

“Symbolic” AI aimed to place artificially defined knowledge or rules into computer systems, endowing machines with abstraction and logical abilities to manipulate systems at higher levels. Symbolic AI’s main characteristic was providing computers with a symbol system-based autonomous reasoning space. Symbolic reasoning space theory is closely related to cognitive science, which believes that the world’s internal representation in thought and thought activities can be described and manipulated by symbols embedded in programs. Therefore, symbolic AI believes physical information processing can be described through symbols, including comparison, hierarchy, and inference. However, early symbolic AI greatly simplified the complex external world into “toy” space forms, making practical application difficult.

In the early 1980s, symbolic AI experienced its second revival—expert systems. Based on more powerful computer processing and storage capabilities, expert systems transformed early overly simplified “toy” worlds into “knowledge bases” built by domain experts. When building AI systems, domain experts abstract and decompose domain knowledge from the top down, forming a conceptual system that refines information granularity. Simultaneously, representing knowledge as declarative propositions enables interaction with the external world through natural language. Taking Edward Feigenbaum’s Dendral, the first expert system for identifying material chemical components, as an example, expert systems innovated in knowledge bases, heuristic production systems derived from knowledge bases, and system architectures separating knowledge representation from inference engines. Subsequently, knowledge representation evolved through semantic networks, frames, scripts, etc., continuously optimizing information space breadth and granularity, gradually developing into complete knowledge engineering theory and technology. By 1985, the second AI wave represented by expert systems peaked. However, developing expert system knowledge bases faced the difficult challenge of ensuring information distortion didn’t increase while efficiently extracting, organizing, and reusing human expert knowledge, making large-scale application difficult.

Expert systems’ success was particularly important for AI’s transition from theory to engineering application. To this day, knowledge representation and reasoning remain important AI research directions. Recently, deep learning has been widely criticized for low data efficiency (high sample distortion), poor generalization ability (high mismatch), and lack of interpretability—precisely symbolic AI’s advantages. Therefore, combining symbolic (knowledge base) and connectionist (deep learning) methods has become a current AI research

hotspot.

(2) Machine Learning and Deep Learning

In recent years, benefiting from rapid machine learning, especially deep learning technology development, AI has achieved excellent performance in natural language processing, computer vision, and recommendation systems. Machine learning is a widely used AI technology enabling machines to learn and improve performance using knowledge extracted from empirical data. Machine learning includes three categories: supervised learning, unsupervised learning, and reinforcement learning. Supervised learning requires labeled training samples to reduce information space mismatch, while unsupervised and reinforcement learning typically apply to unlabeled data, utilizing information's inherent aggregation to discover information movement patterns and rules. Typical supervised learning algorithms include linear regression, random forests, and decision trees; unsupervised learning includes K-means, PCA, and SVD; reinforcement learning includes Q-learning, Sarsa, and policy gradients. Classical supervised learning typically requires manual feature selection.

Neural networks originated from early cybernetics connectionism, a mathematically modeling method inspired by human brain nerves, proposed by neuroscientist Warren McCulloch and logician Walter Pitts in 1943. In 1949, neuroscientist Donald O. Hebb discovered that neuron activation through synaptic information could be viewed as a learning process, linking neural networks with machine learning. By the late 20th century, with multi-layer neural network technology development, neural networks became known as "deep learning." Compared to classical machine learning, deep learning can automatically extract features from massive data, thus also called "representation learning." In deep learning neural networks, each layer receives input from the previous layer and outputs processed data to subsequent layers. Compared to traditional machine learning algorithms, deep learning can fully exploit deep correlations in big data, providing satisfactory prediction accuracy and effectively improving information breadth, granularity, and delay capabilities, but requiring massive training data and large information capacity. Currently, Convolutional Neural Networks (CNN) and Recurrent Neural Networks (RNN) are two typical and widely applied deep learning algorithms capable of processing text, images, video, audio, and other information types, playing enormous roles in computer vision (face recognition, image classification, target tracking, semantic segmentation) and natural language processing (semantic analysis, information extraction, text mining, information retrieval, machine translation, question-answering systems, dialogue systems).

(3) Intelligent Agents and Robots

In AI, an Intelligent Agent is anything that can perceive its environment, autonomously act to achieve goals, and improve performance through learning or knowledge use. Intelligent agents have pre-designed "objective functions" that guide them to create or execute tasks maximizing expected objective function values, enhancing information adaptation. For example, reinforcement learning

shapes intelligent agents' expected behaviors through "reward function" mechanisms, while evolutionary computing adjusts intelligent behaviors through "fitness functions."

Intelligent agents are closely related to AI's "robot" concept. The ideal of creating autonomously operating robots dates to classical times, but substantive research on robot functions and potential uses only made real progress in the 20th century. In 1948, Norbert Wiener's cybernetics principles laid the theoretical foundation for practical robotics. Fully autonomous robots only emerged in the second half of the 20th century. In 1961, the first digital-operated programmable robot Unimate could lift hot metal sheets from die-casting machines and stack them. Recently, robots have been widely applied in manufacturing, assembly, packaging, mining, transportation, earth and space exploration, surgery, weapons, laboratory research, security, and mass production of consumer and industrial products.

In digital games or social scenarios, intelligent agents are also called "non-player characters" (NPCs)—characters not controlled by human players. NPCs remotely reflect human presence, facial, and motion characteristics. Early NPC technology 普遍 used finite state machine (FSM) models, which were easy to implement but had poor scalability, making it difficult to support optimization of information breadth and granularity. In the early 21st century, support vector machine technology, as a classifier with maximum margin between categories, was applied to control game NPCs, effectively improving information adaptation but lacking flexibility in simulating human behavior and decision-making. Recently, reinforcement learning has enabled agents to automatically learn from environmental interaction experiences, increasing information breadth, granularity, and pervasiveness, providing NPCs with superior adaptation compared to other models, thus gaining wide application. The most famous application is DeepMind's 2015 AlphaGo based on deep reinforcement learning, which makes winning probability-maximizing decisions through neural network processes.

(4) Digital Twins

The "Digital Twins" concept model first appeared in 2003, proposed by University of Michigan professor Grieves, initially called "mirror space model," later evolving into "information mirror model" and "digital twins." In 2010, NASA first introduced the digital twin concept in its space technology roadmap, using digital twins for comprehensive flight system diagnosis and prediction. Later, NASA and the US Air Force jointly proposed a digital twin paradigm for future aircraft, defining it as an integrated multi-physics, multi-scale, probabilistic simulation process. Its essence is enhancing information breadth, granularity, and pervasiveness through information systems. General Electric uses digital twins for asset lifecycle management. As complex equipment operating environments in industrial domains become more dynamic, monitoring data volumes multiply, exhibiting typical industrial big data characteristics of high speed, multi-source, heterogeneity, and variability. Traditional PHM technology has limited information capacity, breadth, granularity, delay, and sampling rate,

making it difficult to meet complex equipment' s real-time state assessment and prediction accuracy and adaptability needs under dynamic and variable operating environments. Digital twin technology provides new solutions. Siemens uses digital twins to help manufacturing enterprises achieve full-process digitization from product design to manufacturing execution in information space, comprehensively improving industrial production physical environments' breadth, granularity, delay, duration, and variety in information space.

With sensor technology bringing multi-domain multi-scale fusion models, big data and AI bringing data-driven and physical model fusion and full-lifecycle data management, internet and IoT bringing data collection and transmission, and cloud computing bringing high-performance computing, various IT developments and fusions have further generalized the digital twin concept to simulate physical entities, processes, or systems in the real world through information technology. With digital twins, humans can understand physical entity states in information space and control predefined interface components within physical entities, achieving globally improved state mapping of the physical world in information space. Digital twins can automatically change based on physical entity changes through AI technology, substantially improving system delay efficacy. Ideally, digital twins can self-learn based on multiple feedback data sources, almost real-time presenting physical entities' true conditions in the digital world, improving information fidelity. Digital twins' self-learning (i.e., machine learning extension in information space) can quickly perform deep mining and accurate simulation based on massive information feedback, improving information adaptation. Data twins use existing cognition and knowledge structures with high-performance computing to infer real-world problems. In the future, as information space continuously enriches and improves, information space' s capacity, delay, breadth, granularity, duration, variety, fidelity, and adaptation performance will comprehensively improve, potentially shifting human cognitive activities from "physical world-centered" to "digital information space-centered," entering the so-called "digital native" era.

3.7 Visual and Extended Reality Technology

Extended reality technology originated from Milgram and Kishino' s "reality-virtual continuum" concept, with latest extended reality technologies increasingly 倾向于 deep integration with physical reality—i.e., mixed reality and future holography. This section discusses visual computing, then virtual reality (VR), augmented reality (AR), mixed reality, and how extended reality connects virtual entities with physical environments.

(1) Visual Computing

Computer vision is an interdisciplinary computer science field studying how computers obtain high-level understanding from digital images or videos. Computer vision tasks include acquisition, processing, analysis, and understanding of digital images, and methods for extracting high-dimensional data from the real world to produce digital or symbolic information.

In the early 1960s, image processing aimed to improve image quality for better visual effects. In 1972, Nasir Ahmed first proposed discrete cosine transform (DCT)-based lossy image compression technology. The International Image Experts Group proposed the JPEG digital image standard in 1992. DCT's efficient compression capability promoted widespread digital image and photo dissemination, improving image information capacity. By 2015, billions of JPEG images were generated daily, making JPEG today's most widely used image file format. In 1977, researchers combined spatial DCT encoding with temporal predictive motion compensation to develop motion-compensated DCT (MC-DCT) encoding technology, enabling video compression and improving visual information sampling rate and capacity. Today, MC-DCT-based video compression technology MPEG has become the most widely used international information technology standard. 1970s research laid important foundations for many current computer vision algorithms, including edge extraction, line labeling, non-polyhedral and polyhedral modeling, optical flow, and motion estimation. In the 1980s, visual computing developed toward more rigorous mathematical analysis and quantification, including scale-space concepts and object shape inference from shadows, textures, and focus. Many mathematical optimization problems were processed within regularization and Markov random field frameworks. By the 1990s, important progress was made in 3D scene reconstruction from sparse images and multi-view stereo techniques with camera calibration optimization methods, significantly enhancing visual information breadth and granularity. In the late 1990s, deep integration between computer graphics and computer vision produced complex visual computing technologies like image rendering, image morphing, view interpolation, panoramic image stitching, and early light field rendering, supporting processing of various visual information types.

Entering the 21st century, machine learning and complex optimization frameworks, especially deep learning advances, have brought huge leaps to visual computing. To achieve digital twin interoperability between physical and digital spaces, visual computing technology must deeply understand human activities and behaviors. Recently, Simultaneous Localization and Mapping (SLAM) technology has become important for reconstructing unknown environments' 3D structures through mobile device motion estimation, enhancing information space's granularity in reflecting physical space. Meanwhile, interaction between physical and virtual world objects requires overall scene understanding technology support, including semantic segmentation (classifying images into different categories at pixel level) and object detection (locating and identifying object categories in images/scenes), improving information granularity and adaptation. In immersive environments, virtual object positions determined by stereo depth estimation technology are key for physical-virtual object exchange. Recently, combining deep learning with stereo camera technology has achieved very accurate depth estimation performance, reducing distortion by improving information capacity. In many extended reality applications, observing and recognizing user actions to generate action-specific feedback in 3D immersive environments is required. In machine vision, understanding human actions is called action

recognition, including locating and predicting human behaviors. Recently, deep learning based on pure RGB image data or sensor-fused multimodal data can process different information types, applied to action recognition in augmented reality and showing potential for emotion recognition in virtual reality.

In computer vision, these problems are studied from image restoration and image enhancement perspectives. Image restoration aims to reconstruct clean images from degraded images (e.g., noisy, blurred) to improve image information fidelity. Image enhancement focuses on improving image quality—i.e., increasing visual information capacity and pervasiveness. Image restoration technology has been used to restore texture details and remove artifacts in virtual reality virtual images. In fully immersive environments, super-resolution displays affect 3D virtual world perception, requiring not only optical imaging super-resolution but also imaging process super-resolution. Currently, thanks to high-sampling-rate optical and display technology development, image super-resolution technology has been directly applied to ultra-high-definition displays.

(2) Virtual Reality

Virtual reality's prominent technical feature is fully synthetic views. Commercial VR headsets provide user interaction through head tracking or tangible controllers, placing users in completely virtual environments interacting with virtual objects. VR technology represents the farthest end of the virtual continuum from reality, requiring users to focus completely on virtual environments and separate from physical reality. Current commercial VR technology enables users to create content in virtual environments (e.g., VR painting). Heuristic exploration can be achieved through user interaction with virtual entities, such as modifying virtual object shapes and creating new artistic objects. In such virtual environments, multiple users can collaborate in real time, with main characteristics including shared spatial sense, shared presence sense, shared time sense (real-time interaction), communication methods (gestures, text, voice, etc.), and shared information and object manipulation methods, demanding high efficacy in information breadth, granularity, latency, duration, and variety. Key technical challenges in such highly virtualized spaces include how users control virtual objects and how multi-user collaboration works in virtual shared spaces.

(3) Augmented Reality

Augmented reality technology further provides users with alternating experiences in physical environments beyond virtual environments, focusing on enhancing our physical world through information space to optimize information space breadth and granularity. Theoretically, any computer-generated virtual content can be presented through various sensory channels like audio, visual, olfactory, and tactile—the variety of information and related pervasiveness are key AR metrics. First-generation AR technology only considered visual enhancement, organizing and displaying digital overlays on physical environments. For example, early 1990s work used bulky see-through displays without considering user mobility, requiring stationary postures and tangible controllers for interacting with text and 2D images, resulting in high information latency.

Therefore, ensuring seamless and real-time user interaction with digital objects in AR is a key technical challenge. Since AR's inception, extensive research has 致力于 improving user interaction experiences with digital objects in AR. For example, hand-drawn interaction technology provides AR users with intuitive and easy-to-use interfaces, allowing users to select and manipulate objects in virtual space through "pinch" gestures, improving information breadth, granularity, and pervasiveness. In other words, AR technology users can interact with virtual objects in digital space simultaneously in physical work environments, reducing information latency.

To achieve seamless connection between physical world objects and virtual digital objects, breakthroughs in machine vision detection and tracking technologies are needed to map visualized virtual content to corresponding positions in real environments, enhancing information breadth, granularity, and adaptation. In recent years, AR headset technology has significantly improved. Embedding headset technology into glasses effectively improves lightweight AR mobility, allowing users to recognize different types of objects in AR through receiving headset visual and audio feedback. Although AR can also be implemented through handheld touchscreens, ceiling projectors, Pico (wearable) projectors, and other devices, headset technology is generally considered the main means for future metaverse user interaction with virtual worlds due to advantages like free attention switching and hands-free operation, with low information latency.

(4) Mixed Reality

AR and VR describe the two ends of the "reality-virtual continuum," while mixed reality is the alternate reality between them. AR typically simply displays information overlaid on physical environments without considering physical-virtual world interoperability issues. In contrast, mixed reality focuses more on how physical environments and virtual entities interact. Therefore, many researchers consider mixed reality an enhanced AR scenario with tighter connections and collaborative relationships between physical space and virtual objects, comprehensively enhancing physical world's breadth, granularity, pervasiveness, adaptation, and variety in information space.

Many researchers believe that digital twins connecting physical worlds to virtual worlds are the starting point of the future metaverse, while mixed reality provides users with windows for seamless interaction between physical and virtual worlds in the metaverse. In the metaverse, physical objects, physical objects' digital avatars, and interactions between objects integrate to form a massive-scale virtual shared space. All virtual environment activities should synchronize and reflect virtual space motion state changes. Through mixed reality technology, human users can create in digital twins. Content created in digital space can simultaneously reflect in physical environments, achieving cross-temporal fusion with physical environments. Even if we cannot accurately predict how the future metaverse will ultimately affect our physical world, we can glimpse it through current mixed reality technology prototypes, such as high-fidelity scenes, realistic presence, and empathetic physical spaces, which are basic features people

envision for the future metaverse where physical space and multiple virtual worlds complement each other.

In the metaverse, extended reality technology's significant visualization content characteristics provide solutions for open communication between robots and virtual environments. Moreover, integrating virtual environments in tasks like scene analysis and security analysis enables human users to understand robot operations, establishing trust and confidence in robots, leading to paradigm shifts in human-robot collaboration. Simultaneously, robots will serve as physical containers for human digital avatars in the real world, and metaverse virtual environments can change human perception of collaborative robots. In the future, digital twin technology and the metaverse will be virtual test fields for new robot designs.

In future metaverses where virtual and physical worlds connect seamlessly in real time, 3D vision technology with less noise, blur, and high resolution becomes crucial. Both traditional handcrafted features and deep learning-based semantic segmentation or object detection technologies have excessive computational overhead, still struggling to support real-time overall scene understanding required by metaverses. Therefore, visual research will integrate image restoration and image enhancement methods to achieve the seamless virtual-physical vision of the metaverse. Meanwhile, the metaverse will cause exponential growth in real-time multimedia applications, requiring massive bandwidth for ultra-high-resolution content real-time transmission and extremely low network latency, with many interactive applications treating motion as photon delay—the latency between user actions and screen responses. Therefore, current 5G can hardly meet latency requirements for metaverse perspective AR or VR multimedia applications. To enable truly ubiquitous metaverse user experiences, seamless outdoor wireless mobile network access becomes crucial. Currently, last-mile access remains the bottleneck for LTE/5G networks. To overcome this, Multi-access Edge Computing (MEC) provides standard, universal edge load balancing services one wireless hop from user devices, promising to reduce 5G latency to 1 millisecond. However, considering infinite concurrent users in metaverses 共同作用 on virtual objects and interacting with each other, especially how possible delays negatively impact user experience, managing and synchronizing information motion states at such ultra-large scales is an enormous challenge.

4. Framework Structure of Information Space

The close integration of computer and communication technologies has driven vigorous IT development, promoting widespread application of the internet, mobile internet, cloud computing, big data, supercomputing, AI, blockchain, IoT, virtual reality, and other important achievements, increasingly and comprehensively changing human production and lifestyles. Recently, the term “metaverse” has attracted high attention in information technology and broader society. Semantically alone, metaverse implies a more vast and even boundless meaning than previous IT achievements. Therefore, an urgent need exists to compre-

hensively examine information space' s framework structure based on major IT achievements and objective laws of information movement and utilization, from the holistic perspective of real world, human society, and information systems, striving to reach foundational cognitive consensus.

4.1 Metaverse Concept and Essence

The metaverse concept emerges during continuous IT achievements and ongoing new scientific and technological revolutions. Some contemplate its potential 巨大 transformations, others use it to package their businesses and products, and some view it as hype or joke in technological development history. Regardless, after decades of vigorous IT development, more expansive concepts are indeed needed to fully 包容, integrate, and consolidate various rich achievements to promote faster, more orderly, and more predictable IT development.

The metaverse can be viewed as the phased integration of various IT achievements in today' s era, capable of absorbing digital technology results to date and potentially significantly changing scientific research paradigms, promoting more comprehensive interaction between information science and life sciences, social sciences, quantum science, and other broad fields. In fact, all IT achievements to date promote various forms of information movement and utilization through different efficacies, with information flow—closely integrated and interacting with material and energy flows—running through them all. Therefore, based on existing representative views, the metaverse can be considered the sum total of ubiquitous, diverse, and continuously flowing information streams in the real world and information space.

(1) Metaverse Basic Elements

From its concept, the metaverse includes basic elements like information, information movement, information systems, and information utilization.

The metaverse is the sum of all information streams in the world, with information as the main body of information flow. Therefore, the most fundamental metaverse element is information. If the universe' s origin is matter, then the metaverse' s origin is information.

On the other hand, information that doesn' t move cannot become information flow and thus isn' t part of the metaverse. Therefore, another basic metaverse element is information movement—information flow formed by information traveling from source through various links to destination. Information movement can be a single optoelectronic conversion within a device or a globe-spanning journey through countless twists and turns, with these forms and efficacies being important factors the metaverse must 关注.

In today' s information age, almost no information flow can be formed solely through natural objects; it must rely on global information infrastructure, human-computer interaction, media centers, spatiotemporal computing, creative economy, innovative discovery, deep experience, and other information

systems. Therefore, information systems are the main carriers carrying information and driving information flow, also being important factors that have given rise to the metaverse concept through IT development. Studying the metaverse cannot be separated from fully understanding existing information systems and requires insight and foresight into future information system development.

Similarly, in today's information age, the fundamental significance of information flow lies in utilizing information to serve humanity. Therefore, the metaverse must 关注 higher-level information utilization. A related example is deep experience technology that naturally and accurately simulates human behavior in the real world through identity, friends, immersion, diversity, any-time/anywhere access, economy, and civilization interconnection, fusion sharing, and learning improvement, enabling people to switch identities at will, 穿梭 between real world and information space, arbitrarily entering metaverses constituted by any space-time node, to learn, work, make friends, shop, and travel with "immersive presence." In this scenario, the concrete metaverse is based on abstract information space, supporting more 随心所欲 information utilization. Countless similar scenarios provide infinite possibilities for metaverse technology development and system R&D, thereby promoting higher-level information utilization.

(2) Metaverse Technical Features

Information is the metaverse's blood, and information flow gives the metaverse vitality. The metaverse uses information systems as carriers to achieve intersection, integration, and organic combination of real world and information space. Therefore, the metaverse is not static but dynamic; not local but global; not single-form but diverse; not belonging solely to real world or information systems but being a tight bridge connecting both.

Movement is the metaverse's main technical feature. Continuous information flow drives the metaverse to serve humanity day and night. Information movement's sources and destinations, methods, speeds, even accelerations, and experienced links and processes all relate to specific metaverse implementations, requiring establishment of corresponding dynamic mechanisms to truly understand and master metaverse basic laws.

Globality is an important metaverse technical feature. Since we hope the metaverse concept can 容纳 all IT achievements, we cannot limit metaverse development to certain links or scenarios but must consider information sensing, transmission, knowledge, and utilization links, users worldwide, and various domains like science, economy, society, humanities, and nature. We must plan metaverse development based on metrics like information utilization breadth, pervasiveness, and authenticity. Information flow forms will also be an important metaverse technical feature. After decades of rapid IT development, technology can already provide information flows in various forms like digital signals, data, text, audio, video, and multimedia to meet diversified production and life needs. With mature 5G mobile communication and high-performance AI technology applications, using VR, AR, and mixed reality technologies to

enhance users' presence, immersion, and 代入感, significantly improving user experience of information flow and information space, is the proper meaning of metaverse development. Consequently, metrics like information flow fineness, timeliness, richness, and adaptability will become important metaverse technology evaluation indicators.

More closely achieving seamless connection between real world and information systems is another important metaverse technical feature. Humans have achieved great success in using information technology and resources to improve work efficiency and optimize lifestyles. However, just as we have not yet opened a reasonable paradigm for information science research, the full utilization of information resources in the real world remains at a low level. Many domains don't lack more sophisticated practical application needs but face technical bottlenecks and even cognitive gaps in information collection, transmission, processing, aggregation, and function links. In short, information systems and the real world still suffer from serious disconnections and divisions. Therefore, information flow-filled metaverses should drive comprehensive integration of real world and information systems to achieve higher-level information utilization.

(3) Metaverse Social Form

The metaverse will use multiple new technologies to integrate and spawn a society form blending virtual and real, enriching digital economy models and driving breakthroughs in traditional philosophy, sociology, and even humanities systems. As humans 关注 and participate in metaverse formation and development, traditional concepts of life, time-space, energy, ethnicity, economy, and value may all be changed and subverted, forcing reconsideration of basic philosophical concepts: a priori knowledge, existence and existentialism, empiricism, dualism, language nature, hyper-real society, etc. From the metaverse information flow perspective, real humans and their created virtual humans—including biological, electronic, digital, virtual, and information humans—and their descendants with different personalities, skills, knowledge, and experience will form new social relationships and emotional connections, eventually evolving into organic and inorganic entities becoming pioneers exploring metaverse boundaries and building a "post-human society" on the digital new continent. If we view the "post-human society" formation process as a transition of life forms from "carbon-based life" to "silicon-based life," there will be biological, information-theoretic, and technological evolution, as well as ethical, cultural, and social evolution, full of expectations and risks. During this process, new forms of humans between real and virtual will depend on information flow empowerment, future walking between biological entities and machines.

4.2 Real World and Information Space

Discussing the metaverse, researching information flow, and exploring information system dynamics requires considering the relationships between real world, information space, and their interconnections. We can consider the real world as the essence and information space as the form.

(1) Information Space in the Real World

Cybernetics founder Wiener pointed out that “information is information, not matter or energy.” Based on this, German philosopher Steucke proposed that “information is the third thing alongside matter and energy.” The most famous information theory is Shannon’s information theory, followed by almost all representative achievements including Zhong Yixin’s complete information theory, Burgin’s general information theory, Vigo’s representational information theory, Fleissner and Hofkirchner’s unified information theory, and information geometry theoretical systems, all following information entropy’s basic laws. Shannon’s information theory believes information only generates meaning when received by the destination, implicitly indicating information must be objectively real. In fact, people can recognize, describe, and utilize information but cannot change it through personal subjective will. Even though interpretations of information vary based on disciplinary fields and knowledge backgrounds, this cannot negate information’s objective existence. Just as matter and energy are independent of human will, information’s objectivity should also be independent of human subjective consciousness, especially for information systems. Therefore, we define information within the objective category, viewing matter, energy, and information as the three major elements constituting the objective world, where information uses matter and energy in the real world as media to objectively reflect things and their motion states.

British scientist Popper proposed real world divisions: first, the world of physical objects or physical states; second, the world of consciousness or mental states, or behavioral intention worlds; third, the world of objective thought content, especially scientific, poetic, and artistic works, particularly emphasizing the third world’s objectivity. The first and third worlds further divide the objective world, while the second world is the subjective world. Accordingly, the real world contains subjective and objective worlds, with the objective world further divided into objective knowledge and objective physical worlds. The subjective world refers to the conceptual world, the sum of spiritual activities and psychological activities for understanding and grasping the entire world—not information, but cognition and perception. The objective world refers to the material, perceivable world, the sum of all matter and its motion outside consciousness activities, existing on physical carriers like books, tapes, and optical discs.

Thus, information space has existed in the real world since ancient times. Nature’s sound, light, and electricity all provide information to observers; language, text, and images express information to people—these are all contents of information space in the real world, belonging to Popper’s first and third worlds, which themselves are information carriers and can be seen as collections of information space in the real world. However, until large-scale information systems emerged, these information’s scope and efficacy were very limited, making today’s information age people 反而容易 overlook their existence.

(2) Information Space in the Information Age

Entering the information age, various information systems have emerged, digitizing real world information into information systems that objectively reflect the real world. Information increasingly accumulates in information systems, with information flow functions becoming increasingly prominent, making information systems the main carriers and focus of information space. For example, information systems use digital configurations of real people's physical, cultural, psychological, and spiritual existence to constitute virtual humans in information space. Another example is digital twins in information systems—building data-expressed object entities completely in information space, using information space's core to reflect the real world's shell. At this stage, people don't 关注 processing and storage but only the precision of real world expression.

Thus, the real world contains information space, while information space is mostly carried by information systems. The real world is information space's essence and connotation, providing the information source. Information space reflects the real world, also simulating and 推演 things difficult to achieve in the real world, feeding back to the real world.

Furthermore, information space containing information systems interacting with the real world helps achieve complementarity and balance from concept, technology to culture. We can imagine real humans and virtual human individuals inhabiting both real world and information space simultaneously, not with single but multiple identities. At this time, humans and their virtual lives conduct social activities and lifestyles in information space through self-learning, self-adaptation, self-interaction, and self-evolution, gaining more happiness and bringing such feelings and experiences back to the real world, conducive to 向善 changing the real world and forming a new "human community" civilization ecology, where life may extend from physiological finiteness to digital infiniteness in information space.

(3) Elements of Information Space

Thus, information space spans the real world and information systems, including the first world (objective physical world) and third world (objective knowledge world) in the real world, as well as all information in information systems—including various digital information during collection, transmission, processing, and function processes, and various information completely expressed in data form through aggregation and 沉淀. The metaverse is precisely the complete collection of various information flows in information space.

Further analysis reveals information space contains three basic elements: natural information, behavioral information, and media information.

1) Natural Information

Natural information is the direct manifestation of matter and energy motion states in the objective world—the first basic information form. Sun, moon, stars, mountains, rivers, cities, streets, countryside, and fields all constantly display natural information. Spring buds on branches, autumn leaves on hills, gray hair on elderly people approaching, and fit figures of

young people reflected in mirrors all express natural information. Natural information lets us most directly feel nature's infinite variety. Main characteristics: first, natural information's 本体 are things in the objective world (geography, buildings, animals, plants, etc.), reflecting only people's external images even though humans have complex subjective worlds; second, natural information manifestation is time-varying, with many landscapes macroscopically unchanged for long periods but likely 瞬息万变 microscopically; third, natural information can be displayed through the 本体 itself or other carriers—majestic mountains can be personally experienced by climbers and also displayed through water reflections or mirages via water, air, and other carriers.

2) Behavioral Information

Behavioral information is the indirect reflection of consciousness and thought states in the subjective world acting upon matter and energy in the objective world. Human joy, anger, sorrow, and happiness reflect subjective mood states through expressions or language; birds' wing flapping and chirping express escape or mating desires through posture or sound; elephants linger around deceased companions' bodies for long periods to express inner sorrow. Behavioral information indirectly reflects consciousness and thought states of humans and other living beings through actions, expressions, language, and sound. Main characteristics: first, behavioral information's 本体 are consciousness and thought states in the subjective world (instincts, desires, emotions, judgments, decisions of humans, animals, even some plants and microorganisms); second, behavioral information manifestation is also time-varying, with complex and changeable subjective consciousness causing behavior to present 千姿百态 over time; third, behavioral information can only be indirectly reflected through other carriers like bodies, sounds, or tools, never directly presented as the subjective state itself. Although lie detectors attempting to 窥视 human subjective worlds have existed for over a century, no matter how technology advances, living beings' subjective worlds will never directly appear in broad daylight, because subjective and objective worlds are fundamentally different categories—making the world's existence and development more 精妙.

3) Media Information

Media information is the stored 映像 of natural and behavioral information after collection, transmission, or processing, expressed in matter and energy forms. Newspapers, journals, and books recording large amounts of social news, character commentary, and encyclopedic knowledge are media information that can be repeatedly read; broadcast, film, and television audio/video are media information that can be repeatedly listened to or watched; globally distributed internet servers storing massive, variously formed data codes are media information that can be displayed to users or support various information system operations. Media information records or copies various natural or behavioral information, indirectly

enabling continuous or long-term manifestation of motion states of things in objective and subjective worlds. Main characteristics: first, media information's 本体 can be things in the objective world or consciousness and thought states in the subjective world; second, media information has temporal stability, facilitating repeated user 感受 or processing; third, media information only reflects 本体 motion and change states through other carriers like paper, bamboo slips, stone, disks, circuits, and screens.

Table 1 reflects the brief characteristics of information space's three basic elements.

Table 1: Characteristics of Information Space Elements

Element	Definition	Example	Carrier	Time Variation	Other Characteristics
Natural Information	Direct manifestation of objective world matter/energy motion states	Landscape, cityscapes, body shapes	The thing itself or other carriers	Varies with time	Reflects external forms
Behavioral Information	Indirect reflection of subjective consciousness/ideas acting on objective world	Facial expressions, language, songs, animal movements/sounds	Body, voice, tools	Varies with time	Cannot be directly presented
Media Information	Stored 映像 of natural/behavioral information after processing	Books, artworks, audio/video media, databases	Other carriers	Stable over time	Enables repeated access

4.3 Information Space Framework Structure Based on Information Flow

Based on the relationship between real world and information space, reasonably classifying information system components, and based on information flow'

s driving role, depicting the entire information space framework structure is an important foundation for forming information system dynamics theoretical systems.

(1) Construction Principles

Information space relies on information for resources, information flow for vitality, and information systems for efficacy value. Information space framework structure should fully integrate real world and information systems, accommodate IT achievements, cover all information processes, demonstrate information movement functions, and support information system research, analysis, and evaluation. Therefore, constructing information space framework structure requires following four principles:

- 1) **Virtual-Real Fusion**—the framework should be a comprehensive integration of real world and information systems;
- 2) **Information Flow**—the framework relies on sufficient information flow and driving role to show vitality;
- 3) **Process Coverage**—the framework must include all important process links of information movement;
- 4) **Achievement Inclusion**—the framework must accommodate a series of important IT achievements.

(2) Framework Structure

Based on these principles, we propose the information space framework structure shown in Figure 1.

Figure 1: Information Space Framework Structure

In Figure 1, the red area represents the subjective world in the real world. The complete blue area represents all carriers of information space, covering both the objective physical world and objective knowledge world in the real world, as well as all information systems from the outer second ring inward including information collection/function, information transmission, information processing, and data space. Arrows 穿梭 various links represent various information flows moving in the real world and information systems, from the real world inward through information collection, transmission, and processing rings, finally converging and depositing into the core area—data space—then moving outward through information processing, transmission, and function rings to act upon the real world. Since information collection and function directly face the real world, we represent them in the same ring, distinguished only by color depth and different information flow directions. Theoretically, information systems are components of the real world, but due to their special roles for information, information flow, and information space, and being the main research objects of information system dynamics, we separate them from the real world in the information space framework structure, placing them centrally as our focus. The sum of all information flows in the figure constitutes the metaverse, driving various interactions between real world and information systems.

(3) Real World

According to Popper's division, the real world consists of three parts: subjective world, objective physical world, and objective knowledge world. The subjective world sends information to and receives information from information systems but doesn't store information, containing only consciousness, cognition, perception, knowledge, and other subjective content, consistent with the basic positioning that information belongs only to objective categories. The objective physical world includes natural and artificial objects. The objective knowledge world includes symbols, data, pictures, books, voice, and video knowledge products. Both objective physical and knowledge worlds can generate or receive information and store information, making them important carriers of information space.

(4) Information Collection/Function Ring

The information collection/function ring directly faces the real world. Information collection uses optical, audio, dynamic, temperature, electromagnetic, and other methods to collect various information from the real world and send it to other information system components. Information function works in reverse, receiving information from other components and feeding it back to the real world through language, text, images, data, dynamics, temperature, VR, AR, MR, and other methods.

(5) Information Transmission Ring

The information transmission ring mainly uses communication, dedicated networks, internet, mobile internet, data internet, IoT, and other methods to achieve end-to-end transmission or mutual information exchange of various information types within information systems.

(6) Information Processing Ring

The information processing ring mainly uses traditional computing, supercomputing, cloud computing, big data, AI, blockchain, and other methods that can be further subdivided into sub-methods and algorithms with specific efficacies, performing various necessary processing on information system information according to business needs to satisfy various user information requirements.

(7) Data Space

Data space is the core of information systems. Various information from the real world, after digital collection, transmission, processing, and other links, transforms into massive data of rich types, large scales, and close associations, converging into data space as data information, text, audio, graphics, images, video, knowledge graphs, digital twins, etc., sufficient to form a holographic mirror 表征 the real world. Such holographic mirrors obviously have many incomparable conditions and conveniences in transmission and processing compared to the real world itself, enabling almost arbitrary utilization to feed back to the real world and promote human civilization progress. Therefore, to some extent, information systems' central task is building data space capable of 表征 real world holographic mirrors.

5. Revisiting Information Models, Properties, and Metrics

To study information system dynamic mechanisms, Xu Jianfeng et al. proposed objective information theory and mathematical definitions of information space for ubiquitous information in the objective world [25], with subsequent minor improvements [26], also conducting example analysis and evaluation combined with air traffic control systems. The information space discussed in this paper mainly involves important links like information collection, transmission, processing, convergence, and function, naturally requiring the use of information definitions, models, properties, and metrics to support functional performance and mechanism research of entire architectures and components. Based on the authors' recent research results and architecture engineering practice, more thorough understanding of related content has been formed. For reader convenience, we comprehensively introduce the revised and supplemented objective information theory foundational theoretical system.

5.1 Information Model

Definition 1 Let W represent the objective world set, M the subjective world set, and T the time set. Elements in W and M can be appropriately specifically divided according to domain requirements, yielding the mathematical definition of information:

Let 本体 O , occurrence time T_O , state set S_O on W , carrier C , reflection time T_C , and reflection set R_C on W all be non-empty sets. Information I is a surjective mapping from $S_O \times T_O$ to $R_C \times T_C$, i.e.:

$$I : S_O \times T_O \rightarrow R_C \times T_C \quad (4.1.1)$$

All information sets are called information space, denoted as $\mathcal{J}$, which is one of the three major elements constituting the objective world:

$$\mathcal{J} = \{I\} \quad (4.1.2)$$

It must be emphasized that to maximally accommodate possible scenarios, [3] stated that the mapping in information definition “is not limited to single-valued mapping, but can also be multi-valued mapping.” After years of research and analysis, the authors have found no examples that must be explained by multi-valued mapping. Although complex functions also have multi-valued mapping mathematical expressions and theoretical results, multi-valued mapping is difficult to understand and prone to cause practical application confusion. Therefore, the current definition still limits information to single-valued mapping, which brings obvious convenience to subsequent research without affecting the vast majority, possibly all, application scenarios.

Definition 2 $(O, T_O, S_O, C, T_C, R_C)$ is called the six-element model of information, also denoted as $I(O, T_O, S_O, C, T_C, R_C)$.

Although simple, the six-element model performs three important deconstructions of information concepts: first, a binary deconstruction of information subjects—using subject-carrier binary structure to describe information subjects based on information's reflective characteristics; second, a time-dimensional deconstruction—introducing occurrence time and reflection time parameters to support time-dimensional analysis of information movement; third, a morphological deconstruction of information content—introducing state sets and reflection sets to accommodate all information content and forms. Through these three deconstructions, we can analyze information more profoundly and comprehensively beyond information quantity, providing sufficient mathematical foundations for establishing information system dynamics.

Figure 2 shows the full information flow of news interviews and releases that people face almost daily. This abstracted scenario helps intuitively understand the six-element model. The information collection link mainly obtains state information of interviewees through video, audio, and text collection methods; the information transmission link sends collected information to corresponding processing systems via internet and other wide-area networks; the information processing link performs video, audio, text, and fusion processing to form various news materials; these materials need to converge into more comprehensive news databases to support broader access applications; subsequently, in the information processing link, richer news information in content and form undergoes distribution and arrangement processing to meet release conditions; then through information transmission links, various media news information reaches various information terminals via internet transmission; finally, in the information function link, various terminal devices worldwide directly display corresponding news information to various audiences or readers through multiple forms.

Figure 2: Information Flow in News Interview-Release Process

According to information space framework structure analysis, the entire news interview and release process mainly includes seven important links, where each link's information has six elements: subject, occurrence time, state set, carrier, reflection time, and reflection set. Table 2 shows specific contents.

Table 2: Information Elements in Each Main Link of News Interview-Release Process

Link	Subject (O)	Occurrence Time (T_O)	State Set (S_O)	Carrier (C)	Reflection Time (T_C)	Reflection Set (R_C)
1. Info Col-lection	Interviewer	Interview start time	Interviewee's images, voice, text, and subjective content	Camera, recorder, note-book	From interview start to end	Interview site images, voice, text data and documents
2. Info Trans-mission	Camera, recorder, note-book	From interview start to end	Interviewee and site images, voice, text data	Internet	From data transmission start to end	Interviewee and site images, voice, text digital encoding
3. Info Processing	Internet	From data transmission start to end	Interviewee and site images, voice, text digital content	Video/audio processors, codecs, editing systems	From decoding start to processing completion	News video, audio, text, and fusion materials
4. Data Spaces	Video/audio processors, editing systems	From decoding start to processing completion	News video, audio, text, fusion materials	News database	From information entry to deletion/disable	News video, audio, text, fusion information
5. Info Processing	News database	From information entry to deletion/disable	News video, audio, text, fusion information	Media production systems	From accepting to completion	News video, audio, text ready for playback/release
6. Info Trans-mission	Media production systems	From accepting to completion	News video, audio, text ready for release	Internet transmission	From release transmission start to end	Released news digital encoding

Link	Subject (O)	Occurrence Time (T_O)	State Set (S_O)	Carrier (C)	Reflection Time (T_C)	Reflection Set (R_C)
7.	Internet Info trans- Func- mis- tion sion	From release transmis- sion start to end	Released news digital encoding	TV, broad- cast, news- papers, mobile, web	From playback start to end	News video, audio, text received by audience

In Table 2, each link' s information subjects and carriers differ, with the next link' s subject, occurrence time, and state set being the previous link' s carrier, reflection time, and reflection set, reflecting important characteristics of information transfer. On the other hand, since news information reflects interviewees' subjective/objective states, all links' subjects and states can be understood as the interviewee' s images, voice, text, and other subjective/objective content during the interview period, which is also basic information transfer property.

5.2 Basic Properties of Information

Based on the six-element model, we can further discuss several particularly important basic properties of information.

(1) Objectivity

According to Definition 1, information I is a surjective mapping from $S_O \times T_O$ to $R_C \times T_C$, thus information can only be embodied through $R_C \times T_C$. Since R_C is the state set of carrier C in the objective world at time T_C , information can only be embodied through the objective world. Therefore, we say information necessarily belongs to the objective world—this is information' s **objectivity**.

Corollary 1 Information can be perceived and measured through things in the objective world.

Proof: For information I , reflection set R_C is the state set of carrier C in the objective world at time T_C . According to British philosopher Popper' s division of the real world, the objective world contains two major parts: the world of physical objects or physical states, and the world of objective thought content, especially scientific, poetic, and artistic works. The former exists in natural or behavioral forms, the latter in books, paintings, audio/video, data, and other forms. Thus, regardless of carrier C s form, its state set can obviously be perceived and measured. Since R_C is the mapping of subject O s state set S_O at occurrence time T_O , as long as certain conditions are met, we can always perceive or measure content indicating that information' s main content can be perceived and measured through things in the objective world.

Because information possesses objectivity, we call the series of theoretical sys-

tems derived from Definitions 1 and 2 **objective information theory**. Since information is objective, people can use numerous deterministic methods to collect, transmit, process, converge, and apply information. In fact, large-scale information systems driving human society into the information age are all objectively existing systems. Although AI, brain-like systems, brain-computer interfaces, and other new technologies develop rapidly, their main functions use advanced equipment to fully simulate human thinking modes or accept human subjective consciousness, transforming them into objectively existing information that information systems can process. Therefore, objective information theory plays a fundamental supporting role in analyzing and researching information systems and technologies.

(2) Reducibility

Information I is a surjective mapping from $S_O \times T_O$ to $R_C \times T_C$. If this mapping is also injective—that is, for any $(s_1, t_1), (s_2, t_2) \in S_O \times T_O$, if

$$I(s_1, t_1) = I(s_2, t_2) \quad (4.2.1)$$

then

$$(s_1, t_1) = (s_2, t_2) \quad (4.2.2)$$

At this time I is an invertible mapping, i.e., there exists inverse mapping $I^{-1} : R_C \times T_C \rightarrow S_O \times T_O$, such that for any $(r, t) \in R_C \times T_C$, there exists a unique $(s, t') \in S_O \times T_O$ making

$$I(s, t') = (r, t) \quad (4.2.3)$$

and

$$I^{-1}(r, t) = (s, t') \quad (4.2.4)$$

Thus, based on R_C and T_C , we can restore to O 's states on S_O and T_O . We call such information **reducible**, also calling $(O, T_O, S_O, C, T_C, R_C)$ the **reduction state** of information I . This is information's **reducibility**. In the real world, 绝大多数 information is reducible—people can find its reduction state through information—this is information's most important property or significance.

Corollary 2 For reducible information I , if state set S_O is a mathematical object, then we can define a mathematical structure on reflection set R_C that is isomorphic to S_O .

Proof: Since I is reducible, I is a bijective mapping from $S_O \times T_O$ to $R_C \times T_C$. Therefore, for any $(s, t) \in S_O \times T_O$, there exists a unique $(r, t') \in R_C \times T_C$ such that $I(s, t) = (r, t')$. Thus, for any subset of S_O , when all its elements constitute a mathematical structure, we can define that R_C also constitutes the same mathematical structure. Obviously, this enables isomorphism between S_O and R_C .

The isomorphism between reducible information's subject state set S_O and carrier reflection set R_C is of great significance. This allows applying the same mathematical methods to two different sets of information subject and carrier state, with objects on both sets having the same attributes and operations, and

propositions holding for one set also holding for the other, opening convenient doors for using rich mathematical theories to support extensive information science research. The detailed proofs about internal set relationships later in this paper will demonstrate this special role.

(3) Transitivity

Information I is a surjective mapping from $S_O \times T_O$ to $R_C \times T_C$. There may also exist a set C' in the objective world, time set $T_{C'}$, and all state set $R_{C'}$ on W , forming a surjective mapping $I' : S_C \times T_C \rightarrow R_{C'} \times T_{C'}$. According to the definition, this mapping I' is also information, and

$$I' \circ I : S_O \times T_O \rightarrow R_{C'} \times T_{C'} \quad (4.2.5)$$

is actually the composite mapping of I through I' . Thus, composite mapping achieves information transfer from O to C to C' , from S_O to R_C to $R_{C'}$, and from T_O to T_C to $T_{C'}$ —this is information's **transitivity**. It is precisely because information has transitivity that movement can be realized in various links like collection, transmission, processing, convergence, and function.

Corollary 3 (Serial Information Transfer Chain) Let $\{I_i\}_{i=1}^n$ be a set of reducible information. If for any $i = 1, 2, \dots, n-1$, we have

$$R_{C_i} = S_{O_{i+1}}, \quad T_{C_i} = T_{O_{i+1}}$$

then $\{I_i\}$ is called a **serial information transfer chain** between information I_1 and I_n , and there exists reducible information $I = I_n \circ I_{n-1} \circ \dots \circ I_1$ with the same reduction state.

Proof: For $i = 1$, obviously I_1 is reducible with reduction state (O_1, T_{O_1}, S_{O_1}) . Assume for $i = k$, $I_1 \circ \dots \circ I_k$ is reducible. Then for $i = k+1$, since I_{k+1} is reducible and $R_{C_k} = S_{O_{k+1}}$, $T_{C_k} = T_{O_{k+1}}$, the composition $I_{k+1} \circ (I_1 \circ \dots \circ I_k)$ is also reducible. By induction, $I = I_n \circ \dots \circ I_1$ is reducible with reduction state (O_1, T_{O_1}, S_{O_1}) .

Serial information transfer is a very common information movement form in information systems, and analyzing many mechanisms of serial information transfer chains is important for building information system dynamics theoretical systems.

(4) Composability

Information I involves various sets with different functions and can naturally be decomposed or combined into several new sets, so information has **composability**.

Definition 3 (Sub-information) For information I and I' , if

$$O' \subseteq O, \quad T_{O'} \subseteq T_O, \quad S_{O'} \subseteq S_O, \quad C' \subseteq C, \quad T_{C'} \subseteq T_C, \quad R_{C'} \subseteq R_C$$

and for any $(s, t) \in S_{O'} \times T_{O'}$, we always have

$$I'(s, t) = I(s, t) \quad (4.2.7)$$

then I' is called a **sub-information** of I , denoted $I' \subseteq I$, meaning I contains I' . When at least one of the above inclusions is proper, I' is called a **proper sub-information** of I , denoted $I' \subset I$, meaning I properly contains I' .

Corollary 4 Let information I' be a sub-information of I . If I is reducible, then I' is also reducible.

Proof: To prove I' reducible, we only need to prove I' is injective. In fact, if I' is not injective, there exist two different $(s_1, t_1), (s_2, t_2)$ and one (r, t) such that $I'(s_1, t_1) = I'(s_2, t_2) = (r, t)$. But by sub-information definition, this means $I(s_1, t_1) = I(s_2, t_2) = (r, t)$, contradicting I 's reducibility. Therefore I' is also reducible.

Definition 4 (Composite Information) For information I and its two proper sub-informations I_1 and I_2 , if

$$O = O_1 \cup O_2, \quad T_O = T_{O_1} \cup T_{O_2}, \quad S_O = S_{O_1} \cup S_{O_2}$$

and for any $(s, t) \in S_O \times T_O$, we have

$$I(s, t) = \begin{cases} I_1(s, t), & (s, t) \in S_{O_1} \times T_{O_1} \\ I_2(s, t), & (s, t) \in S_{O_2} \times T_{O_2} \end{cases} \quad (4.2.11)$$

then I is called the **composition** of I_1 and I_2 , denoted

$$I = I_1 \oplus I_2 \quad (4.2.13)$$

Information's composability determines that information can be flexibly split and arbitrarily combined, creating sufficient conditions for people to determine information processing objects according to actual needs.

(5) Associativity

Information's associativity manifests in at least three aspects.

First, for information I , O and C , S_O and R_C , T_O and T_C all appear in pairs. Especially I , as a surjective mapping from $S_O \times T_O$ to $R_C \times T_C$, establishes specific connections between states of such paired things. Moreover, due to transitivity, information can connect more things together—this is an important manifestation of information associativity, leading to the common saying that information is the bridge connecting all things.

Second, because information can be decomposed into several sub-informations, different information may have inclusion relationships or jointly contain another information relationship. Thus, various relationships can be established between information—this is another manifestation of information associativity, enabling analysis and utilization of various information relationships.

Furthermore, analyzing information's internal structure reveals that information associativity's most important manifestation is its ability to reflect various relationships within its reduction state. It can be proven that reducible information can completely preserve its reduction state's internal association structures,

providing important prerequisites for processing, analyzing, and utilizing information internal structures.

Corollary 5 For reducible information I , if $\sim$ is an equivalence relation on state set S_O , then there must exist an equivalence relation $\approx$ on reflection set R_C such that for any two sub-informations I_1, I_2 of I , if $S_{O_1} \sim S_{O_2}$, then 必有 $R_{C_1} \approx R_{C_2}$.

Proof: For any $(s_1, t_1), (s_2, t_2) \in S_O \times T_O$, since I is reducible, when $s_1 \sim s_2$, there must exist $(r_1, t'_1), (r_2, t'_2)$ such that $I(s_1, t_1) = (r_1, t'_1)$, $I(s_2, t_2) = (r_2, t'_2)$, and $r_1 \approx r_2$. Thus, we can define relation $\approx$ on R_C based on relation $\sim$: $(r_1, t'_1) \approx (r_2, t'_2)$ iff $s_1 \sim s_2$.

Since $\sim$ is an equivalence relation with reflexivity ($s \sim s$), and $I(s, t) = (r, t')$, by $\approx$'s definition we have $(r, t') \approx (r, t')$. Thus $\approx$ also has reflexivity. Similarly, $\sim$ has symmetry ($s_1 \sim s_2 \Rightarrow s_2 \sim s_1$). By $\approx$'s definition, when $(r_1, t'_1) \approx (r_2, t'_2)$, 必有 $(r_2, t'_2) \approx (r_1, t'_1)$. Thus $\approx$ also has symmetry. Moreover, $\sim$ has transitivity ($s_1 \sim s_2 \wedge s_2 \sim s_3 \Rightarrow s_1 \sim s_3$). When $(r_1, t'_1) \approx (r_2, t'_2)$ and $(r_2, t'_2) \approx (r_3, t'_3)$, by $\approx$'s definition we have $s_1 \sim s_2$ and $s_2 \sim s_3$, thus $s_1 \sim s_3$, and again by $\approx$'s definition $(r_1, t'_1) \approx (r_3, t'_3)$. Thus $\approx$ also has transitivity.

Since $\approx$ has reflexivity, symmetry, and transitivity, it is also an equivalence relation on R_C .

5.3 Information Metric System

[25][26] established information metric systems following these principles:

- 1) **Traceability**—forming specific definitions and mathematical expressions of various metrics from information' s definitional model;
- 2) **Completeness**—forming complete metric systems covering information value-related aspects from information' s actual connotation;
- 3) **Universality**—forming universally applicable metric definitions for information acquisition, transmission, processing, application, and their combinations, not limited to specific domains;
- 4) **Practicality**—forming practical and operable metric systems that can guide information system analysis and research.

Based on theoretical research and practical experience, a fifth principle is needed:

- 5) **Openness**—due to information' s complex characteristics, it' s difficult to fully recognize information' s metric system, requiring reasonable supplementation, revision, and improvement based on theoretical research and engineering application needs.

[25][26] proposed nine categories of information metric definitions based on the six-element model and basic properties, obtaining related basic propositions according to set measure, cardinality, and distance properties. This paper emphasizes all metrics target reducible information, revising some metric names

and definitions based on latest research results. Additionally, it adds **sampling rate** and **aggregation degree** indicators—the former characterizing information state density in time domain, the latter measuring closeness among information internal components—both having important guiding significance in information system design and implementation. Overall, the order is adjusted to place capacity, delay, and other most easily understood information metrics first, helping readers understand the entire metric system from simple to complex.

Definition 5 (Information Capacity) Let W be the objective world set, $(W, \mathcal{F}, \mu)$ a measure space, and μ some measure on set W . The capacity of reducible information I about measure μ is the measure of R_C , i.e.:

$$V(I) = \mu(R_C) \quad (4.3.1)$$

For the same object set, mathematics can define multiple different measures based on different concerns. Therefore, the defined information capacity is not unique but can be changed according to different needs. The same reasoning applies to subsequent metric definitions.

In information systems, information capacity is usually measured in bits, the most easily understood information metric.

Corollary 6 (Minimum Reducible Capacity of Random Event Information) Let random event X take value x_i with probability p_i ($i = 1, \dots, n$), $0 < p_i < 1$, and $\sum_{i=1}^n p_i = 1$. Let information I represent X 's value situation, called random event information, where subject O is random event X , occurrence time T_O is X 's value time, state set S_O is values $\{x_i\}$, carrier C is the object or medium recording values, reflection time T_C is the time when carrier records values, and reflection set R_C is the specific form of recorded values. If b represents carrier C 's bit number, according to Shannon's information entropy principle, the minimum reducible capacity of reducible information I is:

$$V_{\min}(I) = - \sum_{i=1}^n p_i \log_2 p_i$$

Proof: For random event information I , since X can take values $\{x_i\}$, carrier C can be considered a binary code. For example, C 's bit number can be b , defined such that when $X = x_i$, C 's i -th bit is 1 and others are 0 ($i = 1, \dots, n$). Then based on C 's value we can derive X 's value, so I is reducible with $V(I) = b$.

Alternatively, we can define that when $X = x_i$, C takes value c_i , also making I reducible with $V(I) = \lceil \log_2 n \rceil$.

For simplicity, we assume n and $\log_2 n$ are integers in subsequent discussions.

Clearly, as long as b is greater than a certain value, I 's reducibility can be maintained. But if b is smaller than required, I becomes irreducible. According to Shannon's information entropy principle, when X takes value x_i with

probability p_i , I 's information quantity is $H(X) = -\sum p_i \log_2 p_i$, which is the minimum reducible capacity of information I .

Therefore, if $b < H(X)$, information I is irreducible. The following proof reflects the capacity size ordering of the three cases mentioned above.

First, find the maximum of strictly concave function $f(p_1, \dots, p_n) = -\sum p_i \log_2 p_i$ under constraint $\sum p_i = 1$. Since f is strictly concave, if it attains maximum in the interior, the maximum point is unique. Using Lagrange multipliers, we find the unique critical point $p_i = 1/n$ with extreme value $f_{\max} = \log_2 n$.

Using mathematical induction, we can find f 's maximum on the boundary. When $n = 2$, the boundary is $p_1 = 0$ or $p_2 = 0$, and f 's maximum is $\log_2 2 = 1$ at the interior point. Assuming for $n = k$ the maximum is $\log_2 k$ at the interior point, for $n = k + 1$ the interior critical value is $\log_2(k + 1)$. Since the boundary is homeomorphic to the disjoint union of k cases, by induction hypothesis the maximum on the boundary is $\max\{\log_2 k, 0\} = \log_2 k < \log_2(k + 1)$. Thus the maximum is attained at the interior point.

By induction, for any natural number n , f attains maximum $\log_2 n$ at $p_i = 1/n$. Therefore, $H(X) \leq \log_2 n$, with equality when X is uniformly distributed. Since variables can only take non-zero natural numbers and $n \geq 1$, we have $V_{\min}(I) = H(X) \leq \log_2 n = \lceil \log_2 n \rceil$ when n is a power of 2.

Definition 6 (Information Delay) The delay of reducible information I is the difference between the supremum of its reflection time and the supremum of its occurrence time:

$$D(I) = \sup T_C - \sup T_O \quad (4.3.3)$$

Delay is also an easily understood information metric, as it intuitively 刻画 the speed of carrier C 's reflection of subject O 's states. It's important to emphasize that delay definition allows negative values. Specifically, when

$$\sup T_C < \sup T_O \quad (4.3.4)$$

this indicates the carrier predicts future related states before the subject state's occurrence time, such as information systems predicting related object motions or events.

Here we revise the delay definition proposed in [26]. Compared to [26], the current definition represents the delay from state occurrence time end to reflection time end, rather than from atomic information state occurrence time start to reflection time end. The former better reflects information's objective characteristics by not considering factors of state occurrence time itself. Moreover, defining delay using whole information's reflection time and state occurrence time difference is more concise and clear than considering all atomic information delays, and for reducible information, has more deterministic significance.

Corollary 7 (Serial Information Transfer Delay) Let $\{I_i\}_{i=1}^n$ be a serial information transfer chain between I_1 and I_n . According to Corollary 3, $I = I_n \circ \dots \circ I_1$ is also reducible information. Its delay is the sum of all information I_i 's delays.

Proof: For serial information transfer chain $\{I_i\}$, by definition, for any i , we have $T_{C_i} = T_{O_{i+1}}$. Therefore:

$$\begin{aligned} D(I) &= \sup T_{C_n} - \sup T_{O_1} \\ &= (\sup T_{C_n} - \sup T_{O_n}) + (\sup T_{C_{n-1}} - \sup T_{O_{n-1}}) + \dots + (\sup T_{C_1} - \sup T_{O_1}) \\ &= \sum_{i=1}^n D(I_i) \end{aligned}$$

Definition 7 (Information Breadth) Let W and M be objective and subjective world sets respectively, $(W, \mathcal{F}, \mu)$ a measure space, and μ some measure on set W . The breadth of reducible information I about measure μ is the measure of subject O :

$$B(I) = \mu(O) \quad (4.3.5)$$

Corollary 8 (Breadth of Radar Detection Information) Let reducible information I be radar detection information, where subject O is the object detected by radar, occurrence time T_O is when radar beam illuminates the detected object, state set S_O is the detected object itself and its motion states, carrier C is the radar, reflection time T_C is when radar receives, processes, stores, and displays echo signals/data, and reflection set R_C is the received, processed, stored, and displayed echo signals/data. Define subject O 's measure as its radar cross-section (RCS). According to the radar equation, when radar transmit power P_t , antenna gain G , effective aperture A_e , and minimum detectable signal $S_{\min}$ are determined, radar maximum detection distance $R_{\max}$ depends on information breadth and is proportional to the fourth root of breadth.

Proof: For radar detection information I , subject O is the detected object, and $B(I) = \mu(O)$ is its RCS σ . The radar equation is:

$$R_{\max} = \left(\frac{P_t G A_e \sigma}{(4\pi)^2 S_{\min}} \right)^{1/4}$$

Here $R_{\max}$ is radar maximum detection distance, P_t transmit power, G antenna gain, A_e effective aperture, and $S_{\min}$ minimum detectable signal. When radar's key parameters $P_t, G, A_e, S_{\min}$ are determined, $R_{\max}$ is completely determined by σ and is proportional to $\sigma^{1/4}$, i.e., proportional to the fourth root of information breadth.

Definition 8 (Atomic Information) For reducible information I and its sub-information I' , if I' is a proper sub-information of I and there exists no other

proper sub-information I'' such that $I' \subset I'' \subset I$, then I' is called an **atomic information** of I .

Definition 9 (Information Granularity) Let W and M be objective and subjective world sets, $(W, \mathcal{F}, \mu)$ a measure space, and μ some measure on set W . Let $\mathcal{A}$ be the set of all atomic information of I , with index set Λ . Let ν be a measure on Λ with $\nu(\Lambda) > 0$. Then the granularity of reducible information I about measure μ is the ratio of the integral of all atomic information subjects' measures to the measure of index set:

$$G(I) = \frac{\int_{\Lambda} \mu(O_{\lambda}) d\nu(\lambda)}{\nu(\Lambda)} \quad (4.3.7)$$

where ν usually takes counting measure as most appropriate. This revises the fineness definition in [3]. Compared to [26]'s minimum-based definition, the current average-based granularity criterion is more universal and meaningful.

Corollary 9 (Resolution of Optical Imaging Information) Let reducible information I be optical imaging information, where subject O is the photographed/object, occurrence time T_O is shutter opening/recording time, state set S_O is the photographed object and its motion states, carrier C is the camera, reflection time T_C is shooting, processing, storage, and display time, and reflection set R_C is photos/images. Define subject O 's measure as the minimum resolvable angle when photographed. According to Rayleigh criterion, optical imaging information's resolution (granularity) is proportional to light wavelength and inversely proportional to photosensitive unit width.

Proof: For photographed object O , each frame in optical imaging information I contains many pixels, each being an indivisible local image of O and thus an atomic information of I , $I_{\lambda}, \lambda \in \Lambda$. By definition, information granularity is the average of all atomic information subjects' measures. By optical imaging principle, for all λ , $\mu(O_{\lambda})$ are identical, and by Rayleigh criterion:

$$\mu(O_{\lambda}) = 1.22 \frac{\lambda}{d}$$

where λ is light wavelength and d is photosensitive unit width. Thus, information granularity $G(I) = \mu(O_{\lambda})$ for any λ , proportional to λ and inversely proportional to d .

Definition 10 (Information Variety) For reducible information I , let $\sim$ be an equivalence relation on state set S_O , and let $S_O/\sim$ be the set of equivalence classes of elements in S_O about $\sim$. Then the variety of information I about $\sim$ is the cardinality of set $S_O/\sim$:

$$V_y(I) = |S_O/\sim| \quad (4.3.8)$$

We always use $|\cdot|$ to denote set cardinality. It can be proven that reducible information can transfer equivalence relations from state set to reflection set, so carrier C 's state reflection set R_C can fully reflect information's variety metric.

Corollary 10 (Variety Invariance Principle of Reducible Information)

For reducible information I , let $\sim$ be an equivalence relation on state set S_O , and $S_O/\sim$ the equivalence class set. Then there must exist an equivalence relation $\approx$ on reflection set R_C such that elements' equivalence classes in R_C about $\approx$ have a bijective surjection with $S_O/\sim$ through information I , making the cardinalities of the two equivalence class sets equal:

$$|S_O/\sim| = |R_C/\approx|$$

Proof: Corollary 5 has proven that equivalence relation $\approx$ on R_C can be established based on equivalence relation $\sim$ on S_O . For any two sub-informations I_1, I_2 of I , if $S_{O_1} \sim S_{O_2}$, then 必有 $R_{C_1} \approx R_{C_2}$. Therefore, there are also equivalence classes on R_C . Since equivalence relation $\approx$ is completely established based on information I 's mapping relation, the two equivalence class sets $S_O/\sim$ and $R_C/\approx$ can also establish a bijective surjection based on information I , making their cardinalities completely equal.

Definition 11 (Information Duration) The duration of reducible information I is the difference between the supremum and infimum of T_C :

$$L(I) = \sup T_C - \inf T_C \quad (4.3.9)$$

Corollary 11 (Average Duration of Continuous Monitoring Information) The average duration of continuous monitoring information equals the information collection device' s mean time between failures (MTBF).

Proof: Let reducible information I be continuous monitoring information, where subject O can be viewed as the monitored object, occurrence time T_O as the period when the object is in monitored state, state set S_O as states during monitored period, carrier C as information collection device, reflection time T_C as device C ' s working period, and reflection set R_C as collected and displayed information. Continuous monitoring systems generally require sustained, uninterrupted monitoring of monitored objects, so their duration often equals information collection device' s working period, i.e., $L(I) = \text{MTBF}$. However, any device may fail, so engineering requires specifying system' s mean time between failures MTBF, representing the continuous period the system can work normally without failure during its lifecycle. In continuous monitoring systems, if information collection device' s MTBF is MTBF, it means the average value throughout the lifecycle is MTBF, showing that continuous monitoring information' s average value is also MTBF.

Definition 12 (Information Sampling Rate) For reducible information I , if $T_O \subseteq \mathbb{R}$, let $\{T_i\}_{i \in \Lambda}$ be a family of pairwise disjoint connected sets satisfying: for any $i \in \Lambda$, $T_O \cap T_i \neq \emptyset$, where Λ is an index set. Then the sampling rate of information I is the ratio of Λ ' s cardinality to T_O ' s Lebesgue measure:

$$S_r(I) = \frac{|\Lambda|}{m(T_O)} \quad (4.3.10)$$

Specifically, if $|\Lambda| = \infty$ or T_O 's Lebesgue measure $m(T_O) = 0$, we define $S_r(I) = \infty$. This indicates that information's state set is completely continuous in time.

Corollary 12 (Minimum Reducible Sampling Rate of Periodic Information) For reducible information I , if $S_O \subseteq \mathbb{R}$ and there exists minimum value $f_{\min}$ such that for all $s \in S_O$, $|s| \leq f_{\min}$. Also let $\{T_i\}_{i \in \Lambda}$ be a family of pairwise disjoint connected sets with equal Lebesgue measure satisfying: for all $i \in \Lambda$, $T_O \cap T_i \neq \emptyset$, where Λ is an index set. Then I is called **periodic information**, and its minimum reducible sampling rate equals $2f_{\min}$.

Proof: For periodic information I , obviously $S_O \subseteq [-f_{\min}, f_{\min}]$. Since for all $s \in S_O$, $|s| \leq f_{\min}$, and $f_{\min}$ is the minimum value satisfying this condition, for any time t , S_O doesn't contain frequencies higher than $f_{\min}$. According to Nyquist sampling theorem, for time t , S_O is completely determined by a series of samples with intervals not larger than $1/(2f_{\min})$. In information definition, $\{T_i\}$ is a series of sampling intervals with equal measure, and $|\Lambda|$ is the number of sampling intervals. Thus, $m(T_O) = |\Lambda| \cdot m(T_i)$, and information sampling rate:

$$S_r(I) = \frac{|\Lambda|}{m(T_O)} = \frac{1}{m(T_i)}$$

When and only when $m(T_i) \leq 1/(2f_{\min})$, S_O 's values are completely determined for all t , giving I a definite reduction state.

Definition 13 (Information Aggregation Degree) For reducible information I , let $|S_O|$ be set S_O 's cardinality, and $\mathcal{R}$ be the set of all relations among elements in S_O . Then I 's aggregation degree is the ratio of $|\mathcal{R}|$ to $|S_O|$:

$$A_g(I) = \frac{|\mathcal{R}|}{|S_O|} \quad (4.3.11)$$

Aggregation degree characterizes the closeness of relationships among elements in state set S_O . Generally, the closer the relationships among elements in S_O (higher aggregation degree), the higher the information value.

Corollary 13 (Aggregation Degree Invariance Principle of Reducible Information) For reducible information I , let $|S_O|$ be state set S_O 's cardinality, and $\mathcal{R}$ the set of all relations on S_O . Then for reflection set R_C , its cardinality $|R_C| = |S_O|$, and there exists relation set $\mathcal{R}'$ on R_C with $|\mathcal{R}'| = |\mathcal{R}|$, thus:

$$A_g(I) = \frac{|\mathcal{R}'|}{|R_C|}$$

showing reducible information can maintain aggregation degree invariance.

Proof: Since I is reducible, there exists a bijection between $S_O \times T_O$ and $R_C \times T_C$, so the cardinalities of the two sets must be equal: $|R_C| = |S_O|$. Meanwhile, we can define relation set $\mathcal{R}' = \{(r_1, r_2) \mid \exists (s_1, s_2) \in \mathcal{R}, I(s_1, t_1) =$

$(r_1, t'_1), I(s_2, t_2) = (r_2, t'_2)\}$, making $\mathcal{R}'$ a relation on R_C with a bijection between $\mathcal{R}'$ and $\mathcal{R}$, so their cardinalities are equal: $|\mathcal{R}'| = |\mathcal{R}|$. Therefore, the aggregation degree remains unchanged.

Definition 14 (Information Replica) For reducible information I , if there exists I' that is also reducible information, and there exists inverse mapping I^{-1} such that:

$$I' = I^{-1} \quad (4.3.12)$$

then the two information I and I' are called **replicas** of each other.

Definition 15 (Information Pervasiveness) Let J_I be the set containing reducible information I and all its replicas, Λ the index set, ν a measure on Λ , and μ a measure on measurable set W . Then the pervasiveness of information I about measure μ is the integral of all $\mu(C_\lambda)$:

$$P_v(I) = \int_{\Lambda} \mu(C_\lambda) d\nu(\lambda) \quad (4.3.13)$$

Corollary 14 (Network System Value Equals Product of Maximum Breadth and Maximum Pervasiveness) For reducible information I , if its carrier C is a network system composed of finite nodes, then its value equals the product of the maximum possible values of I 's breadth and pervasiveness.

Proof: Since reducible information I 's carrier C is a network system with finite nodes, let the number of nodes be N . According to Metcalfe's Law, network system value equals the square of node count. On the other hand, we can view I as information from all network nodes, so subject O is the network system, its measure is node quantity N , and information breadth's maximum value is $B_{\max}(I) = N$. Meanwhile, carrier C 's measure is also node quantity N , and information pervasiveness's maximum value is $P_{v,\max}(I) = N$. Therefore, this network system's value equals the product of information breadth and pervasiveness's maximum values: $V = B_{\max}(I) \cdot P_{v,\max}(I) = N^2$.

Definition 16 (Information Reflection and Reflection State) For reducible information I , if there exists mapping J such that $J \circ I = I'$, where I' has subject O , occurrence time T_O , and some state set S'_O on W , then J is called a **reflection** of I , and I' is the **reflection state** based on J .

Clearly, when $J = I^{-1}$, I' is I 's reduction state.

Definition 17 (Information Distortion Degree) For reducible information I , let its state set S_O and reflection state S'_O based on J both be elements of distance space $(\mathcal{S}, d)$, where d is distance on $\mathcal{S}$. Then the distortion degree of I 's reflection J in distance space is the distance between S_O and S'_O :

$$D_d(I, J) = d(S_O, S'_O) \quad (4.3.14)$$

Clearly, distortion degree is the deviation between reflection state and reduction state. Distortion degree $D_d(I, J) = 0$ iff reflection state equals reduction state.

Corollary 15 (Minimum Distortion Estimation for Discrete Linear Stochastic Systems) Let I be state information of a discrete linear stochastic system with motion and measurement affected by Gaussian white noise. Then reflection based on Kalman filter can achieve minimum distortion estimation.

Proof: For discrete linear stochastic system state information I , where subject O is the system itself, occurrence time set T_O is a series of equal-interval time sequence denoted $\{t_k\}$, state set S_O can be denoted $\{x_k\}$ satisfying:

$$x_{k+1} = A_k x_k + B_k u_k + w_k \quad (4.3.15)$$

where x_k is system state at time t_k , u_k is system input at t_k , A_k, B_k are system parameters (matrices for multi-model systems), w_k is motion noise with covariance Q_k .

Carrier C is the measurement system, reflection time set T_C is same as T_O denoted $\{t_k\}$, reflection set R_C is series of measurement values $\{z_k\}$ on T_C satisfying:

$$z_k = H_k x_k + v_k \quad (4.3.16)$$

where z_k is measurement at t_k , H_k is measurement system parameter (matrix for multi-measurement systems), v_k is measurement noise at t_k with covariance R_k .

If reflection J consists of the following five formulas:

$$\hat{x}_{k|k-1} = A_{k-1} \hat{x}_{k-1|k-1} + B_{k-1} u_{k-1} \quad (4.3.17)$$

$$P_{k|k-1} = A_{k-1} P_{k-1|k-1} A_{k-1}^T + Q_{k-1} \quad (4.3.18)$$

$$K_k = P_{k|k-1} H_k^T (H_k P_{k|k-1} H_k^T + R_k)^{-1} \quad (4.3.19)$$

$$\hat{x}_{k|k} = \hat{x}_{k|k-1} + K_k (z_k - H_k \hat{x}_{k|k-1}) \quad (4.3.20)$$

$$P_{k|k} = (I - K_k H_k) P_{k|k-1} \quad (4.3.21)$$

where $\hat{x}_{k|k-1}$ is prediction using previous state, $\hat{x}_{k-1|k-1}$ is previous optimal state, P are covariance matrices, and K_k is Kalman gain.

Clearly, this can recursively achieve bijection from $\{z_k\}$ to $\{\hat{x}_{k|k}\}$, i.e., from R_C to S_O , thus J is a reflection of I . According to Kalman filter principle, $\hat{x}_{k|k}$ is the optimal estimate for x_k , i.e., the minimum distortion estimation achievable by reflection based on Kalman filter.

Definition 18 (Information Mismatch Degree) Let target information be reducible information I_{target} . For reducible information I , let O, T_O, S_O, C, T_C, R_C and $O_{\text{target}}, T_{O_{\text{target}}}, S_{O_{\text{target}}}, C_{\text{target}}, T_{C_{\text{target}}}, R_{C_{\text{target}}}$ be elements of sets W, T, S , respectively, with $S_O, S_{O_{\text{target}}}$ being elements of distance space (S, d) . Then the mismatch degree of I to target information I_{target} is the distance between them in the distance space:

$$M_d(I, I_{\text{target}}) = d(S_O, S_{O_{\text{target}}}) \quad (4.3.15)$$

Corollary 16 (Average Search Length of Minimum Mismatch Degree Information in Finite Set) Let target information I_{target} and elements of set $\mathcal{J}$ all be reducible information, with corresponding components being elements of sets $W, T, \mathcal{S}$, and $S_O, S_{O_{\text{target}}}$ being elements of distance space $(\mathcal{S}, d)$. Let $I^* \in \mathcal{J}$ such that:

$$M_d(I^*, I_{\text{target}}) = \min_{I \in \mathcal{J}} M_d(I, I_{\text{target}})$$

Then the average search length (ASL) from $\mathcal{J}$ to I^* depends on both mismatch degree and different search algorithms.

Proof: As internet information content becomes richer and people use more information query tools, in many complex information queries, users have needs for information's subject, occurrence time, and states, as well as carriers, reflection times, and methods, yet cannot clearly describe all these needs, making it difficult to find target information completely matching user needs. Advanced retrieval or intelligent push systems often analyze and estimate target information meeting user needs for specific application scenarios, then search and calculate from limited information sets, pushing the information with minimum mismatch degree to users.

According to average search length principle, ASL is defined as:

$$\text{ASL} = \sum_{i=1}^n p_i c_i$$

where p_i is search probability of information I_i , generally assuming equal probability $p_i = 1/n$, and c_i is the number of comparisons to find I_i . Two cases exist:

Case 1: Exact Match Search

If using sequential search from I_1 to I_n , calculating mismatch degree sequentially until finding I^* , then:

$$c_i = i, \quad \text{ASL} = \frac{1}{n} \sum_{i=1}^n i = \frac{n+1}{2}$$

If using binary search, always using middle element as root to divide left/right subtrees recursively, then:

$$c_i = \lfloor \log_2 i \rfloor + 1, \quad \text{ASL} = \frac{1}{n} \sum_{i=1}^n (\lfloor \log_2 i \rfloor + 1) \approx \log_2 n$$

Case 2: Minimum Mismatch Search

Since we must compare mismatch degrees of all information and select the minimum, $c_i = n$ for all i , making $\text{ASL} = n$. When n is huge, search computation becomes enormous. Therefore, we can set appropriate threshold θ , stopping search when mismatch degree $\leq \theta$, to sufficiently reduce ASL.

[25][26] pointed out that Shannon information entropy is actually the information capacity metric required for communication systems to transmit discrete messages. In fact, the series of corollaries above prove that the eleven categories of information metrics defined in this paper can all find corresponding examples in classical or commonly used information science principles (Table 3).

Table 3: Correspondence Between Information Metric System and Classical/Commonly Used Principles

Information Metric	Classical/Commonly Used Principle	Correspondence
Capacity	Shannon Information Entropy	Minimum reducible capacity of random event information is its information entropy
Delay	Serial Information Transfer Delay	Overall delay of serial information transfer equals sum of each link's delay
Breadth	Radar Equation	Radar maximum detection distance is proportional to fourth root of information breadth
Granularity	Rayleigh Criterion for Optical Imaging	Optical imaging information granularity is proportional to wavelength, inversely proportional to photosensitive unit width
Variety	Variety Invariance Principle of Reducible Information	Reducible information can preserve information variety

Information Metric	Classical/Commonly Used Principle	Correspondence
Duration	Mean Time Between Failures	Average duration of continuous monitoring information equals information collection device's MTBF
Sampling Rate	Nyquist Sampling Theorem	Minimum reducible sampling rate of periodic information equals half its highest frequency
Aggregation Degree	Aggregation Degree Invariance Principle	Reducible information can preserve information aggregation degree
Pervasiveness	Metcalf's Law	Network system value equals product of maximum breadth and maximum pervasiveness
Distortion Degree	Kalman Filter Principle	Minimum distortion estimation for discrete linear stochastic systems
Mismatch Degree	Average Search Length	Average search length for minimum mismatch degree information in finite sets

6. Metric Efficacy and Dynamic Configuration of Information Systems

Information is on par with matter and energy as one of the three major elements constituting the objective world. Dynamics theories for matter and energy have long existed and flourished, powerfully driving industrial civilization progress. Many theoretical achievements about information, such as Nyquist sampling theorem, Shannon information entropy, and Kalman filter methods, all reveal profound mathematical rules followed by information collection, transmission, and processing, and can be regarded as information dynamics principles for certain processes or links, playing extremely significant roles in IT development and application. However, their scope is limited to local processes, making it difficult to fully grasp the 全貌 of information dynamics. After the information dynamics concept was proposed, many papers and monographs discussed it. But as [20] states, these concepts remain mainly qualitative, lacking quantitative regularities. [20] also points out that “the concept of dynamic systems is a mathematical expression form for any existence with fixed ‘rules’,” and “mechanics, as an experimental science studying object motion and change in space and time, cannot do without measurement and units.” Thus, “mathematical expression form” and “measurement” are necessary conditions for studying specific object dynamic mechanisms. This paper’s research on information mathematical expression, basic properties, and metric systems has laid a solid mathematical foundation for profound and quantitative information system dynamics analysis.

6.1 Metric Efficacy of Information Systems

Any information system can be simplified into a basic process of receiving input information, applying various functions, and finally producing output information. Thus, information systems’ main significance lies in their various efficacies applied to input information, manifested through output information. Without comprehensive analysis, reasonable deconstruction, and quantitative expression of these efficacies, we cannot deeply understand information systems’ operational mechanisms and internal laws, nor can we build information system dynamics theoretical systems that guide information system construction and development. Therefore, accurately understanding various efficacies of information systems is decisive for in-depth ISD research. Section 4’s six-element model and eleven-category metric system provide the key to entering ISD’s theoretical building. Since any efficacy cannot be quantitatively expressed without metric indicators, and any metric 背后 must have actual functional efficacy, using metric systems to comprehensively and quantitatively describe and analyze information systems’ main efficacies is a natural approach. Thus, we can establish eleven categories of metric efficacies that information systems may possess through eleven information metrics: **capacity efficacy, delay efficacy, breadth efficacy, granularity efficacy, variety efficacy, duration efficacy, sampling rate efficacy, aggregation degree efficacy, pervasiveness efficacy, distortion degree efficacy, and mismatch degree efficacy.**

Figure 3: Information System and Distribution of Metric Efficacies Across Components

Where **capacity efficacy** is the function and effect of information systems acting on information, causing capacity metric changes. Since capacity metric depends on information carrier' s carrying capacity, in actual systems, information collection, transmission, processing, data space, and function links all affect information capacity indicators due to system carrying capacity (Figure 3). For example, information collection, data space, and function links may discard some information due to insufficient storage capacity, reducing information capacity. Information transmission links may discard information due to channel bandwidth insufficiency, also reducing capacity. Shannon information entropy is actually the minimum information capacity metric required for communication systems to transmit discrete messages while ensuring information reducibility. Information processing links also need sufficient storage space support, thus affecting capacity. Particularly, information processing links can reduce information capacity requirements through data compression, thereby actually improving overall system information capacity, while data decompression reduces capacity—different compression/decompression processing has different capacity efficacies.

Delay efficacy is the function and effect causing delay metric changes. Since any information flow and processing process inevitably requires time, all links affect delay metrics (Figure 3). However, each link can optimize delay efficacy through equipment or algorithm improvements to achieve minimal delay. Particularly, information processing links can reduce delay metrics through time-dimensional extrapolation algorithms predicting future states, improving system delay efficacy.

Breadth efficacy is the function and effect causing breadth metric changes. Breadth characterizes information subject' s scope of extensiveness. Information collection links affect breadth metrics due to collection devices' physical attributes like energy and distribution. The fundamental radar equation in radio detection expresses how physical parameters like antenna aperture, transmitter power, and receiver sensitivity determine detection range—actually information collection breadth. Information function links also affect output information' s breadth efficacy due to device methods, modes, and interfaces. Note that typical information processing doesn' t directly involve information subjects, seemingly not affecting breadth efficacy. However, spatial-dimensional extrapolation algorithms can extend subject scope, improving breadth efficacy. Data space, as specific reflection of real world in information systems, also affects breadth due to model completeness and database capacity. It' s important to note that while transmission link capacity affects breadth efficacy, this is an indirect effect of capacity efficacy on breadth efficacy, not transmission link' s direct impact on breadth. Thus, to focus on key issues, we can consider information transmission links not directly having breadth efficacy (Figure 3).

Granularity efficacy is the function and effect causing granularity metric

changes. Granularity characterizes information subject's fineness features. Information collection links affect granularity metrics due to collection devices' physical attributes like aperture area and sensor quantity. For example, the number of photoelectric sensors integrated in video information collection devices determines video picture resolution or pixel count—this is collection granularity efficacy. Information function links also affect granularity efficacy due to output device methods, modes, and interfaces. Similarly, spatial-dimensional interpolation algorithms can densify subject scope, optimizing granularity efficacy. Data space also affects granularity due to model completeness, fineness, and database capacity. Similar to breadth analysis, we can consider transmission links not directly having granularity efficacy (Figure 3).

Variety efficacy is the function and effect causing variety metric changes. Variety characterizes the richness of information subject state set types. Analysis shows all main information system links affect variety metrics, producing system variety efficacy (Figure 3). Specifically, information collection and function links affect input/output information types due to different means and methods—e.g., microwave vs. audio collection devices obtain different inputs, optical vs. audio output devices produce different outputs—showing collection and function links affect variety efficacy. With network technology development, transmission links have designed protocols for various information types, standardizing and simplifying system interfaces while ensuring transmission efficiency, becoming universal implementations for internet, data internet, and IoT. Thus, transmission links have obvious variety efficacy. Different information types naturally require different processing methods, so processing links obviously affect variety efficacy. Data space's internal structure, model design, and storage capacity directly affect information type richness, thus having variety efficacy.

Duration efficacy is the function and effect causing duration metric changes. Duration characterizes information's time span. Clearly, collection duration directly determines duration metrics, and function duration also affects output information duration. Although in many cases transmission duration may not affect output duration, for live broadcasting scenarios, transmission duration directly affects broadcast duration. Generally, processing links don't directly affect duration, but through information extrapolation, they can expand state sets in time dimension, thus affecting duration metrics. Data space's storage capacity and structure design directly affect duration metrics, so all links have duration efficacy (Figure 3).

Sampling rate efficacy is the function and effect causing sampling rate metric changes. Sampling rate characterizes information state set occurrence density per unit time. Collection density directly determines sampling rate metrics—Nyquist sampling theorem shows that for periodic sinusoidal curves, as long as sampling rate exceeds half the frequency, original curves can be reconstructed from sampled information. Similarly, function frequency obviously affects output information density (sampling rate). In transmission links, if communication system bandwidth exceeds input information sampling rate, output sam-

pling rate won't be affected; otherwise, output sampling rate must be reduced. Generally, processing links don't directly affect sampling rate, but through interpolation processing, they can densify state sets in time dimension, thus affecting sampling rate metrics. Data space's storage capacity and structure also directly affect sampling rate metrics, so all links have sampling rate efficacy (Figure 3).

Aggregation degree efficacy is the function and effect causing aggregation degree metric changes. Aggregation degree characterizes closeness among elements in information state set, with many features not explicitly obtainable from fragmentary or local information. Thus, collection and transmission links don't directly affect aggregation degree metrics. Through computation, correlation, and fusion processing in information processing links, internal relationships in state sets can be found, established, and expanded, improving aggregation degree metrics. Data space's internal structure and model design directly determine aggregation degree metrics. Information function links based on processing and data space need to consider aggregation degree metrics to achieve more comprehensive functional effects. Therefore, processing, data space, and function links have aggregation degree efficacy (Figure 3).

Pervasiveness efficacy is the function and effect causing pervasiveness metric changes. Pervasiveness reflects the spread degree of information and its replicas' carriers in target sets. Generally, collection links don't consider replica formation, thus being unrelated to pervasiveness metrics. Function links ultimately produce output information, with their 作用 range directly reflecting pervasiveness metrics. Transmission links' network distribution is the prerequisite determining information function scope, thus directly affecting pervasiveness metrics. Processing links, though not directly connected to end users, can determine and control information function objects through gating or distribution processing, thus affecting pervasiveness metrics. Data space's distributed structure design and replica distribution scope directly relate to pervasiveness metrics. Therefore, transmission, processing, data space, and function links have pervasiveness efficacy (Figure 3).

Distortion degree efficacy is the function and effect causing distortion degree metric changes. Collection links are mostly physical or human-in-the-loop processes, often producing errors that increase distortion degree. Similarly, function links are mostly physical or human-in-the-loop processes, also affecting distortion degree. Transmission links increase distortion due to bandwidth limits, bit errors, and packet loss. Processing links can increase distortion due to computation errors, but also reduce distortion through filtering and smoothing algorithms, improving processing precision. Data space's information expression and storage methods affect distortion degree. Thus, all links have distortion degree efficacy (Figure 3).

Mismatch degree efficacy is the function and effect causing mismatch degree metric changes. Mismatch degree reflects information's deviation from specific user needs. Obviously, distortion degree is a metric of concern to all user types.

Since all links have distortion degree efficacy, we can simply infer all links also have mismatch degree efficacy (Figure 3). Detailed analysis of each link can more clearly reach the same conclusion.

Figure 3 集中 reflects information systems and distribution of metric efficacies across components. positions indicate that the component where resides has the information metric efficacy of the sector where is located. Information collection and function are in the same outermost ring, distinguished by dark and light colors—dark for collection, light for function. Thus, we can deconstruct entire information system functions and performance indicators through metric efficacy distribution, providing sufficient quantitative basis for system design, analysis, testing, and integration.

6.2 Single-Loop Information System Dynamic Configuration

Figure 3 presents the complete information system framework structure and metric efficacy distribution. However, actual system construction doesn't always need all components. System designers often simplify mature or unnecessary technologies and products to focus on key issues. Thus, we can analyze several typical dynamic configurations of information systems based on included components, simply classified as single-loop, double-loop, triple-loop, and triple-loop with core configurations.

Figure 4 shows the dynamic configuration of single-loop information systems—the simplest and possibly earliest form, containing only information collection and function components in the same loop. Though simple and often overlooked, it's actually the most classic and universal information system application mode. Typical scenarios include handheld telescope observation of distant scenery or microscope examination of cell structures—telescopes or microscopes are simple information systems collecting real world item information and immediately functioning it on observers. If pure optical telescopes/microscopes differ somewhat from modern information system concepts, digital cameras/cameras better embody single-loop configurations. Travelers use digital cameras, camcorders, or ubiquitous mobile phones to shoot surrounding scenery—the lens direction is part of the real world, captured photos/videos are collected information, and shooters' operations and appreciation are function links. In this process, shooting devices' physical parameters and operators' actions determine/adjust collection metrics like capacity, delay, breadth, granularity, variety, duration, sampling rate, distortion, and mismatch, which directly determine function link's metric efficacies. Although advanced shooting devices may have strong processing, storage, and transmission functions, these are subordinate during shooting, significantly different from general information systems' transmission, processing, and data space concepts. Thus, we include advanced digital device shooting processes in single-loop configuration. Without processing or data space links providing internal relationship structures, function links in this configuration don't produce aggregation degree efficacy, and without transmission links, they don't significantly affect pervasiveness efficacy. A scientifically important exam-

ple: Nobel laureates Penzias and Wilson's 1964 microwave background radiation observation using radio detection devices belongs to typical single-loop configuration application, with information breadth covering the entire universe and delay almost as long as the universe's lifespan.

Figure 4: Single-Loop Information System Dynamic Configuration

6.3 Double-Loop Information System Dynamic Configuration

Double-loop configurations involve three different information system components, existing in multiple information movement modes. Figure 5 shows the collection-transmission-function double-loop dynamic configuration.

Collection-Transmission-Function Double-Loop Configuration

Typical scenarios include live radio or TV broadcasting. Recording/camera devices collect audio/video information, transmit via wide-area communication networks to thousands of households, then broadcast/TV devices function on audiences. Like single-loop configuration, collection devices' physical characteristics and on-site operations determine collection metrics. Transmission links affect transmitted information's capacity, delay, variety, duration, sampling rate, pervasiveness, distortion, and mismatch due to channel physical characteristics, protocols, and network distribution. Since transmission links aren't directly related to specific content, they don't affect live broadcast breadth and granularity efficacies. Final function links facing millions of audiences obviously affect capacity, delay, breadth, granularity, variety, duration, sampling rate, pervasiveness, distortion, and mismatch efficacies based on received metrics and output device characteristics.

Information systems can also fully process collected information to obtain results directly functioning on the real world, forming **collection-processing-function double-loop dynamic configuration** (Figure 6).

Collection-Processing-Function Double-Loop Configuration

Typical scenarios include supercomputers that collect input information through various peripherals, perform high-speed, large-capacity intensive computing or massive data processing, and produce result information functioning on specific users. Peripheral collection devices' physical characteristics and staff operations obviously affect supercomputer collection metrics. Supercomputer processing affects all metrics through massive CPU units, high-speed algorithms, parallel processing software, and massive data processing methods. Processing can also discover and correlate internal information relationships, changing aggregation degree metrics. Supercomputing result data naturally affects function efficacies based on peripheral output device capabilities. Although supercomputers also have transmission and storage capabilities, their core mission is supercomputing, with other capabilities subordinate, so we include them in collection-processing-function double-loop configuration.

Information systems can also directly input collected information into data

space, using data space' s powerful information resources to directly function on the real world, forming **collection-data space-function double-loop dynamic configuration** (Figure 7).

Collection-Data Space-Function Double-Loop Configuration

Typical scenarios include data center construction. With big data technology' s widespread application, various data centers play increasingly important roles in industry and regional informatization. Construction can be simplified as various information converging into data space through peripherals and interfaces. These peripherals and interfaces' functions obviously affect collection metrics. Data space' s structure design, model types, resource accumulation, and storage capacity also affect corresponding metrics. Since data space' s structural model often already implies internal relationships of converged information, it also affects all information' s aggregation degree metrics. Thus, collection-data space-function double-loop configuration' s output information has capacity, delay, breadth, granularity, variety, duration, sampling rate, aggregation degree, distortion, and mismatch efficacies, naturally also affected by data center peripheral output devices and interfaces. Similarly, any data center itself has necessary transmission and processing capabilities, but its core mission is building data space that interacts with the real world. To simplify, we include them in collection-data space-function double-loop configuration.

Figure 5: Collection-Transmission-Function Double-Loop Configuration

Figure 6: Collection-Processing-Function Double-Loop Configuration

Figure 7: Collection-Data Space-Function Double-Loop Configuration

6.4 Triple-Loop Information System Dynamic Configuration

Triple-loop configurations often involve four different information system components, with three typical information movement modes. Figure 8 shows collection-transmission-processing-transmission-function triple-loop dynamic configuration.

Collection-Transmission-Processing-Transmission-Function Triple-Loop Configuration

Typical scenarios include remote automatic control systems. Widely distributed sensors collect various information, transmit via communication networks to control centers, which after numerical calculation, state assessment, and instruction generation processing, automatically distribute control information through communication networks to corresponding control nodes, achieving process automatic control over wide-area systems. Note that in this configuration, collection links affect nine metrics except aggregation and pervasiveness, processing links affect aggregation, and the second transmission link affects pervasiveness, making this triple-loop configuration have complete eleven efficacies.

Figure 8: Collection-Transmission-Processing-Transmission-Function Triple-Loop Configuration

Figure 9 shows collection-transmission-data space-transmission-function triple-loop dynamic configuration.

Collection-Transmission-Data Space-Transmission-Function Triple-Loop Configuration

Typical scenarios include internet website wide-area information convergence and service processes. Currently, relatively simple internet websites rely on various information publishers using internet terminals to collect information, converge it to website databases through widely distributed internet, forming their own data space, then provide web information services to various users via internet and terminals. In this configuration, collection links affect nine metrics except aggregation and pervasiveness. Since data space content can reflect aggregation and pervasiveness metrics, and the second transmission link also affects pervasiveness, this triple-loop configuration also has complete eleven efficacies.

Figure 9: Collection-Transmission-Data Space-Transmission-Function Triple-Loop Configuration

Figure 10 shows collection-processing-data space-processing-function triple-loop dynamic configuration.

Collection-Processing-Data Space-Processing-Function Triple-Loop Configuration

Typical scenarios include centralized modeling and simulation systems. Taking electromagnetic radiation characteristic modeling as an example, specific objects are placed in microwave anechoic chambers, excited with related electromagnetic signals, and modeling-simulation systems collect partial electromagnetic radiation information at sampling points. Through computational interpolation processing, they obtain the object's omnidirectional radiation characteristics in ideal environments, then call electromagnetic field environment model information possibly existing in electromagnetic field data space to calculate the object's radiation information under simulation conditions, thereby providing sufficient simulation information support to researchers. This is a typical collection-processing-data space-processing-function application scenario. Without transmission links, this triple-loop configuration has the remaining ten efficacies except pervasiveness.

Figure 10: Collection-Processing-Data Space-Processing-Function Triple-Loop Configuration

6.5 Triple-Loop with Core Information System Dynamic Configuration

In practice, almost no information system completely lacks any of the five components: collection, transmission, processing, data space, and function. Therefore,

the seven typical configurations discussed above omit some components mainly to simplify problems and focus on key issues. Figure 11 shows the most complete, universal, and research-worthy triple-loop with core information system dynamic configuration, called the **complete configuration**.

Figure 11: Triple-Loop with Core Information System Dynamic Configuration

As shown in Figure 11, the complete configuration includes all information movement components and possible information flows between components. It's also important to note that any local part of the complete configuration may be a research object in engineering practice. Therefore, information system design and implementation need to 关注 not only the above eight configurations but also any object system maintaining information flow continuity, enabling us to analyze entire system efficacy through various component efficacies—this is the original intention of proposing information system dynamics and using it to guide information system planning, design, R&D, and integration.

In Figure 11, each information system component can affect the entire system's metric efficacy. Generally, same-type efficacies across components have 叠加 or mutual constraint effects. For example, delay efficacies across components obviously 叠加 to form system delay efficacy. Preceding components' capacity metrics obviously form capacity requirements for subsequent components—if subsequent components cannot meet them, overall system capacity efficacy is affected. Additionally, different efficacies influence each other. For instance, capacity efficacy obviously affects system distortion degree efficacy—under insufficient capacity, reflection set elements must be discarded, increasing information distortion. The first ten metric efficacies in order almost all affect overall system mismatch degree, as mismatch reflects deviation from specific user needs, and metrics like capacity, delay, breadth, granularity, duration, variety, sampling rate, and aggregation are all closely related to specific user needs—not necessarily “higher is better.” Pervasiveness needs adjustment according to user intentions; to control information knowledge scope, many measures may be needed to 充分 reduce pervasiveness, so pervasiveness doesn't correlate 单向 with adaptation. Distortion degree doesn't 正相关 with mismatch degree—for encrypted information systems, higher distortion often means lower mismatch for specific users. Therefore, studying metric efficacy mechanisms in various configurations and scenarios to reveal information systems' internal operational laws provides broad and practical development prospects for information system dynamics.

6.6 Smart Court Information System Architecture Engineering Example

Since 2013, Chinese courts have applied information system dynamics principles and methods nationwide to promote smart court construction, achieving remarkable results and attaining world leadership in judicial AI.

(1) Overview of China's Smart Court Architecture Engineering

China's smart court construction involves over 3,000 courts, more than 10,000 派出法庭, and over 4,000 collaborative departments. 各地 courts simultaneously operate relatively independent basic support, business application, data management, network security, and operation maintenance information systems totaling over 13,000, making it a massive information system architecture 工程 with huge scale, broad spatial distribution, 参差不齐 survival time, heterogeneous technical systems, different functional tasks, numerous collaborative departments, and close sharing linkages.

In smart court information systems, smart service, smart trial, smart execution, smart management, and judicial openness systems are information systems directly facing users, undertaking information collection and function tasks. Smart service includes China Mobile Micro Court, People's Court Mediation Platform, litigation service network, 12368 hotline, electronic delivery, online preservation, online appraisal, etc. Smart trial includes trial process management, electronic file circulation, intelligent trial assistance, etc. Smart execution includes execution command, case process management, execution investigation/control, dishonesty punishment, online judicial auction, case fund management, mobile execution, etc. Smart management includes online office, trial supervision, electronic archives, etc. Judicial openness includes China Trial Process Information Open Network, Court Hearing Open Network, Judgment Document Open Network, and Execution Information Open Network. Internet, court dedicated network, mobile dedicated network, and external dedicated network connect internal and external users, undertaking information transmission tasks. Electronic file automatic cataloging, case information automatic 回填, legal knowledge services, similar case intelligent push, court audio/video intelligent inspection, judgment deviation intelligent analysis, file material one-click archiving, etc., undertake information processing tasks. The Judicial Big Data Management and Service Platform converges national courts' trial execution data, judicial personnel data, judicial administrative data, external data, judicial research data, and informatization operation data, forming the core data space reflecting national courts' trial execution and operation management states.

(2) Key Efficacies of Smart Court Information System Architecture

Smart court architecture engineering's construction and application effectiveness depends on various information movement efficacies generated by integrated information systems. Although almost every system and information affects some users' experience and effectiveness, key performance indicators of some key systems have more important impacts on the eleven metric efficacies of the entire architecture. Although these performance indicators' common names may not completely align with ISD-defined metric efficacies, their substantive content has decisive influence on these metric efficacies. In practice, we have formed the key efficacy distribution of smart court architecture shown in Table 4, continuously monitoring these key indicators' changes to improve overall smart court architecture operation quality.

Table 4: Key Efficacy Distribution of Smart Court Information Sys-

tem Architecture

Metric Efficacy	Key Indicators
Capacity	• Internet access bandwidth • Court dedicated network bandwidth • Mobile dedicated network bandwidth • Video information transmission bandwidth • File information transmission bandwidth • Big data platform converged judicial data resources total volume • Big data platform converged case data total volume • Judicial big data daily full-volume data convergence volume
Delay	• Big data, AI computing processing delay • Legal knowledge service system processed laws/regulations/cases response delay • Application system operation response delay • Legal knowledge service system service data delay • Video information display delay
Breadth	• Legal knowledge decomposition breadth • Application system unit time input data types • Application system unit time output data types • Case file information upload delay • Case handling system coverage of national courts • Case handling system coverage of national courtrooms • Smart service system user distribution and quantity
Granularity	• Judicial statistical information item granularity • Case information item granularity • Video information resolution • Application system input data, text, file, video, audio information types and methods quantity • Application system output data, text, file, video, audio information types and methods quantity

Metric Efficacy	Key Indicators
Variety	• Internet, court dedicated network, mobile dedicated network, external dedicated network transmission data, text, file, video, audio information types quantity • Network system average failure-free time • Application system average failure-free time
Duration	• Application system input data sampling rate • Application system unit time data output rate • Network load utilization rate
Sampling Rate	• Application system input data sampling rate • Application system unit time data output rate • Network load utilization rate
Aggregation Degree	• Application system output data aggregation degree • Big data platform judicial statistical information item correlation • Big data platform national court case coverage correlation • Big data platform data text, file, video, audio information type quantity correlation • Big data, cloud computing, AI, blockchain system processed data, text, file, video, audio information type correlation
Pervasiveness	• Application system user coverage quantity • Application system user coverage scope • Case-case correlation types • Big data platform data volume • Big data platform average failure-free time • Big data platform data access cycle

Metric Efficacy	Key Indicators
Distortion Degree	• Application system input information accuracy rate • Application system output information accuracy rate • Court dedicated network coverage • Mobile dedicated network coverage • External dedicated network coverage • Communication system transmission information distortion degree • Communication system transmission information format type adaptation • Data-user association calculation accuracy • Big data platform storage space and region • Big data platform full-volume data confidence • Big data platform shared data confidence • Big data platform data model accuracy
Mismatch Degree	• Application system input data format type, content quantity adaptation • Application system output data format, type, content, quantity adaptation • Information system user satisfaction • Case-object correlation types • Case-fund correlation types • Information encryption effectiveness • User permission control • Network security isolation • Processing system information processing precision

(3) Growth Curves of Key Metric Efficacies for Smart Court Information System

Figure 12 reflects changes in some key metrics of smart court information systems in recent years. Among them, the total volume of judicial big data platform data resources reflects the Supreme Court's convergence of national court judicial big data, with stable growth showing increasingly abundant judicial big data resource accumulation. Court office platform average response delay directly affects almost all staff's operation experience—thanks to technical improvements, this metric dropped below 0.8 seconds since November 2020, winning staff praise. The tech court monitoring system uses video technology to 实时 connect courts

nationwide, with its court coverage reflecting breadth metrics of national court video information. The figure shows that since November 2021, the Supreme Court has stably connected over 93% of national tech courts through video networks. A single case can be considered the smallest granularity of court judicial information. The figure shows that since August 2015, national courts' case information coverage has basically reached and remained stable at 100%, fully demonstrating that management of national courts' judicial big data has reached very fine granularity. The variety of information converged by judicial big data platform reflects information management completeness. The figure shows that since the platform's official launch in December 2013, information variety has steadily increased, basically achieving convergence, management, and application of all information types. Information system average failure-free time reflects average duration of real-time collected information. The figure shows that since March 2018, court information systems' average failure-free time has basically stabilized above 700 hours—significant drops in certain periods inevitably shorten real-time collection information duration. The Fayeian platform monitors national court information systems' operation quality, with information sampling rate needing reasonable settings based on monitored objects' characteristics. The figure shows 53% of monitoring information has sampling rate higher than 1 time/hour, and 73% higher than 1 time/day, reflecting Fayeian platform's monitoring density. Judicial big data platform data aggregation degree reflects internal data correlation. The figure shows that since January 2019, information aggregation degree has remained above 80%, indicating good levels of information correlation processing and application. Information system output information pervasiveness can be represented by visit volume. The figure shows that since February 2020, China Mobile Micro Court, the unified window serving the public, has seen monthly visits steadily increase, exceeding 100 million by December 2021, fully demonstrating its significant effectiveness in serving the public. Data confidence is the negative expression of information distortion degree. The figure shows that since January 2018, judicial big data platform's judicial statistical data confidence has remained above 97%, currently stable above 99% long-term (distortion degree below 1%), thus laying a credible foundation for various big data analyses and services. User satisfaction is also the negative expression of information system output information mismatch degree. The figure shows that since January 2020, information system user satisfaction has remained above 98%, fully demonstrating smart court architecture engineering's remarkable achievements.

Figure 12: Examples of Eleven Categories of Metric Efficacies for Smart Court Information System

7. Summary

Addressing key issues affecting information science research paradigms—lack of universally recognized mathematical foundation for information concepts, lack of clear and rich measurement systems for information value, lack of scientifically

reasonable framework structures for information space, and lack of clear efficacy analysis for information functions—this paper proposes information space framework structure, information models, properties and metrics, and information systems' metric efficacies and dynamic configurations, constituting the technical and mathematical foundation theoretical system of information system dynamics, applied and validated in China's smart court information system architecture engineering practice.

The mathematical foundation describing information space and information movement laws is set theory, measure theory, relation algebra, and topology. Although relatively abstract, they have direct and clear correspondence with widely used statistical and computational methods in daily life, and are fully compatible with classical IT principles like Shannon information entropy and Nyquist sampling theorem, thus being completely applicable to value analysis, mechanism research, and design evaluation of currently 关注的大数据, streaming media, metaverse, and other information systems.

Moreover, based on the information dynamics foundation formed by this research, we can supplement and enrich from aspects like compatibility between information metrics and various IT classical principles, interaction relationships among information metric efficacies, and refined decomposition of information system dynamic configurations. The completeness and practicality of information system dynamics will also be tested and improved through subsequent extensive applications, as any theory only demonstrates its value and continuously improves through practice.

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