EDITOR'S PERSPECTIVE

Decentralized AI: Edge Intelligence and Smart Blockchain, Metaverse, Web3, and DeSci

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Centralization has dominated classic scientific, social, and economic developments. Decentralization has also received increasing attention in management, decision, governance, and economics, despite its incomparability in AI. Going beyond centralized and distributed AI, this article reviews and delineates the conceptual map, research issues, and technical opportunities of decentralized AI and edge intelligence. The complementarity and metasynthesis between centralized and decentralized AI are also elaborated. We further assess where decentralized AI and edge intelligence can enable and promote smart blockchain, Web3, metaverse and decentralized science disciplinarily, technically, practically, and more broadly.

Decentralization[1] complements and enhances centralization for systematic, all-round, and multifold objectives, functionality, and consequences. The paradigm shift from centralization to distribution has substantially mitigated methodology, knowledge, and capability gaps in social science, management science, decision science, economics, computing, complex systems, and AI. On the other hand, open-source and science have made paramount complementary achievements and contributions, and blockchain is transforming and inspiring finance to decentralized finance (DeFi), and the World Wide Web to Web3. In contrast, decentralizing AI is still an open area. By reviewing decentralized movements, systems, and technologies, including the recent movements on the blockchain, Web3, and decentralized science (DeSci), we paint a research picture of decentralized AI (DeAI), the research issues in edge intelligence, and the tasks of synthesizing centralized AI (CeAI) and DeAI. These further envisage and inspire the opportunities of DeAI-enabled smart blockchain, Web3, metaverse, and DeSci.

DECENTRALIZATION

Decentralization is not a buzzword, hype or myth, although such concerns have been widely raised on decentralization-oriented initiatives, such as Web3 and the metaverse. Decentralization is also not a new or mysterious concept.[1] It has a 200-year history and is grounded in political science (such as subsidiarity, democracy, liberty, equality, and the decentralist movement), management and decision science (e.g., systems theory, self-organization, and self-determination), and economics (e.g., decentralized free markets and fiscal decentralization). Decentralization (with forms, such as devolution, deconcentration, delegation, etc.) is complementary or an alternative to centralization (and concentration), such as decentralized organizations, infrastructures, administration, operations, and services, corresponding to their centralized counterparts. In contrast to centralizing resourcing, manufacturing, and supply, *globalization* partitions, distributes, and decentralizes industrial, manufacturing, and supply chains to usually isolated and local economies and productivity. Open society, open government, and open science further promote the decentralization of administration, governance, governmentality, and scientific activities.

Distributed to Decentralized Systems

In technology, the thinking and conceptualization of technological decentralization have evolved for over half a century. A flagship decentralized IT movement is the open and shareable initiatives and programs, represented by open source, open data,

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open access, and open science.[a] A representative early stage distributed and decentralized computing flagship is the formation of Linux operating systems and their ecosystems. This movement has been further intensified by public and private cloud services for decentralized infrastructures, storage, sharing, computing, applications (DApps), and services. In IT practices, a recent trend is that an increasing number of organizations have removed or are decentralizing their existing centralized IT divisions, substituted by subscribing to vendor-centralized cloud-based infrastructures, computing, applications, and services. Furthermore, *edge computing*[2,3] emerges to connect isolated end-level devices and the Internet of Things (IoT) through edge nodes (networks) rather than centralized cloud infrastructures and to support decentralized computation, communication, storage, sharing, and management at end devices or edge nodes.

However, the early version of decentralized computing, systems, and services is also not new. They have been built on the conceptual systems and success of distributed systems, computing, algorithms, and services and more recent successes, such as in distributed AI (DAI) and peer-to-peer (P2P) and device-to-device (D2D) systems. P2P, D2D, and team-driven activities, such as open science, crowdsensing, crowdsourcing, and crowdfunding, further relax distributed couplings between nodes and with centralized or shared facilities (such as shared memory or databases). Here, peers and end devices replace shared central controllers, servers, mediators, or matchmakers. P2P and D2D authentication, collaboration, and communication at running time replace the design-time protocols and specifications for authentication, collaboration, cooperation, communication, and governance. This shift from distributed loose couplings to *ad hoc* and running-time P2P interactions enhances the effect of decentralization. Blockchain, Web3, and DeSci thus emerged, and the metaverse upgrades the initiatives of digital twins and virtual reality.

Blockchain, Metaverse, Web3, and DeSci

Blockchain and Web3 further decouple the dependence on and interactions with central or intermediary authentication, organization, computation, communication, and mediation. Decentralized operations, authentication, communication, and collaborations engage scalable decoupled and loosely connected individuals and local nodes to form decentralized ecosystems physically, virtually, mentally, or jointly, resulting in evolving blockchain, Web3, the metaverse, and DeSci movements.

Blockchain: A blockchain[b,4,5] is a decentralized network where cryptographically hashed blocks (digital records) are chained one to another, and each node replicates its previous blockchain. A blockchain is a P2P network for DeFi, where each node replicates, stores, and updates an identical ledger (called a distributed ledger). The distributed ledger database thus records, validates, manages and shares the consensus of the chained digital information across the blockchain ecosystem. *Proof-of-work* allows new blocks to join, secures a blockchain, and serializes changes in the chain. *Proof-of-stake* builds consensus over a blockchain. Transactions of digital assets (called cryptocurrencies) are recorded by blockchains, and *smart contracts* allow asset contracting between entities to be executed on blockchains without human interaction. In blockchain ecosystems, blockchains transfer assets between chains through blockchain interoperation. Consequently, blockchain is decentralized without a central administrator, server, or trusted authority for authentication, governance, communication, management, and mediation, etc. Accordingly, the blockchain architecture, identity, communication, contracting, interoperability, management, governance, security, and privacy differ significantly from centralized networks and present unique decentralized characteristics, properties, challenges, and opportunities.

Web3: The Web3 movement[c] aims to transform the static, consumer-oriented Web 1.0 and the dynamic, producer and platform-oriented Web 2.0 into a decentralized web ecosystem. Some initial Web3 trials are typically implemented in terms of decentralized autonomous organizations (DAOs), blockchain technologies, cryptocurrencies, and other decentralized technologies for exchanging digital assets over the web. It is envisaged that Web3 may evolve to be a decentralized web ecosystem, which could 1) mitigate issues in the existing Web 2.0, such as overcentralization and domination, by big tech companies, network vulnerability, misinformation and information disorder; 2) provide more secure, private, scalable, and free information creation, exchange, sharing, and transfer; 3) enable the creation, identification, contracting, exchange, trade and management of public or private content, products (such as digital assets), and services (e.g., financial services); and 4) supporting immersive web development and experience by the decentralized end, and edge devices.

[a][Online]. Available: https://en.wikipedia.org/wiki/Open_science

[b][Online]. Available: https://en.wikipedia.org/wiki/Blockchain
[c][Online]. Available: https://en.wikipedia.org/wiki/Web3

Metaverse: The metaverse[6] coined in Snow Crash has been substantially enriched in terms of its vision, mission, conceptualization, implementation, and applications over the past 30 years. The metaverse journey has evolved from *digital twins* represented by the online virtual world Second Life[d] to *creative games* empowered by virtual and augmented reality and more recently online *virtual and multiplayer games* enabled by social interactions, training and trading creatures, and virtual economy with nonfungible tokens. The renaming of Facebook to Meta has further substantially accelerated the attention, debate and exploration as to what it is, how it works, and where it applies, etc. Technically, the metaverse pursues 1) a comprehensive virtualized or virtually-physically fused immersive experience; 2) an online or cloud-to-device 3D interactive world with human and device interfacing and teaming; 3) a vivid application for demonstrating the metaverse design, applications and services; 4) a rich ecosystem with trading markets, financial services, economic activities, and social services; and 5) a suite of enabling technologies for infrastructure, interfacing, interaction, design and development tools.

DAOs and DeSci: The early progress of decentralized blockchain and Web3 has promoted a new age of decentralized movements, initiatives, and concepts. DAOs[e] and DeSci[7] represent their new trend toward broad-reaching decentralized organizations, operations, services, and implementations. DAOs and DeSci have witnessed various initiatives, such as decentralized cryptocurrency, finance (DeFi), biomedicine, funding, review, professional services, and the metaverse. Technically and operationally, blockchain, Web3, and other decentralized technologies, platforms and services provide essential and prerequisite infrastructures, privacy and security assurance, communication, token-based assets and valuation,[8] and individual accessibility and scalability to enable DAOs and DeSci at large and at scale. Other important enablers and supporting techniques include decentralized cloud computing, edge computing, smart contracting, P2P systems, autonomous agents, distributed and cloud-based analytics, such as federated and edge learning, and technologies for the metaverse.

Despite the intensive foci on blockchain and its applications, the decentralized movements, including Web3 and DeSci, have not attracted wide scientific attention in academia. Some even believe they are hype or myth, typically driven by commercial narratives and purposes. The existing initiatives and activities are inclined to motivation, vision, conceptualization, storytelling, and specific settings and applications building on the blockchain, cloud techniques, and sometimes simple applications of AI. One critical reason lies in their ignorance of or weakened attention to identifying, defining, and exploring decentralization-centric fundamental challenges, research questions, and foundational enabling technologies. This motivates this article to discuss the concepts, aims, research issues, and opportunities of DeAI and its roles in enabling smart blockchain, Web3, the metaverse, and DeSci.

DEAI: DECENTRALIZED AI

Why DeAI?

From Centralized to DAI and DeAI: Conventional AI aims, technologies, systems, and services are centralized, static, predefined at design time, and user-neutral. CeAI presents their outputs as either a standalone system or a multiagent system. When a multiagent system carries the AI task, CeAI usually has a central controller, mediator, matchmaker, coordinator, or communicator (for message passing) to manage and govern agents and task execution. CeAI met with fundamental issues, such as inflexibility, high vulnerability, poor reliability, and low scalability and adaptability, to complex real-world demand and large-scale problem solving. The CeAI thinking does not fit the individualized nature and personalized demand/supply in the physical and social worlds. DAI then emerged, followed by DeAI to further flatten DAI.

Distributed AI involves multiagent systems for parallel or distributed problem solving. A DAI system decomposes a problem or task to subproblems or subtasks and then assigns them into specialized agents for handling; the agent-based partial solutions are then synergized to form the solution to the problem. While taking a bottom-up approach, DAI usually involves mediation, cooperation, coordination, and communication between agents for task decomposition, assignment, execution, and consensus-building. Orchestration and consensus-building mechanisms further consolidate distributed agents, logic, tasks, and results for solution aggregation or formation. Therefore, DAI is not truly decentralized, nor the classic parallel and distributed computing.

The emergence of DeAI addresses the thinking and technological gaps in CeAI and DAI for genuine AI decentralization, including decentralizing multiagents, AI tasks, task execution, resource allocation, storage and management, transaction management,

[d][Online]. Available: https://en.wikipedia.org/wiki/Second_Life
[e][Online]. Available: https://en.wikipedia.org/wiki/Decentralized_autonomous_organization

intelligence management, and consensus-building between decentralized agents and AI tasks, etc. On one hand, DeAI promotes the evolution and development of AI toward individualized, personalized, distributed, secure, privacy-preserving intelligence and intelligent problem solving. On the other hand, DeAI also aims to incorporate intelligence and intelligent problem solving into the existing decentralized systems and their enabling platforms, such as blockchain and Web3, where AI has not played a major driving role and they are not smart enough. DeAI thus will fundamentally promote the development of intelligent decentralized technologies and systems and escalate decentralized movements, including Web3, DAOs, and DeSci.

DeAI, blockchain, DAOs, DeSci, and Web3 require and take advantage of local capabilities, resources, high computation, high bandwidth, high privacy, high security, low energy, and low latency in decentralized devices and contexts. Without sharing resources, capabilities and computation with centralized servers and mediation by controlling the authority, DeAI maximizes the power of end and edge devices and resources.

What is DeAI?

Decentralization in AI: Decentralization is presented in various aspects and on different levels of AI systems.

1) Decentralized intelligent devices and agents on the edge level: referring to the lowest individualized intelligent agents. Each device alone could be an intelligent, autonomous agent with standalone universal or specific AI functions, forming edge intelligence in terms of the capabilities of thinking, emotion, perception, vision, conversation, interaction, action, and decision-making.
2) Decentralized local intelligent devices and agents on the node level: referring to edge devices in a local network area (such as the smart home) where they form a node (a local intelligent network). Nodes serve as an intelligent agent cluster to fulfill node-level AI functions.
3) Decentralized cooperation, coordination, and communication on the end level: end agents may interact, cooperate, coordinate, and communicate with each other in terms of on-device cooperation and coordination mechanisms, communication protocols, and resource management without coordinating, controlling, or authoritative management between devices.

On the edge level, nodes perceive, reason, and act on their own goals, tasks, and expectations and coordinate, cooperate and communicate with other nodes in proximity to share, exchange, and assist in tasks, resources, and intelligent capabilities. Nodes act on their own, and there are no controlling, authoritative, or coordinating nodes in the node network.

Decentralized AI: DeAI refers to the AI thinking, methodologies, technologies, systems, and services for developing, managing, and deploying decentralized intelligence in decentralized settings; storing, updating, sharing, and exchanging decentralized intelligence between decentralized agents, nodes, or devices; and integrating decentralized intelligence from local agents and across decentralized ecosystems (with their services, and environments) for higher level intelligence and intelligent problem solving.

DeAI aims: Accordingly, the research aims and objectives of DeAI include but are not limited to:

- studying fundamental and unique characteristics and properties in making decentralized systems intelligent, for example, enabling smart blockchain, Web3, DAOs, and DeSci systems, and services; their characteristics and properties may influence the decentralized architectures, functions, operations, production, services, quality assurance, and risk mitigation, etc.;
- quantifying decentralized interactions, complexities, and intelligence in DeAI systems, which form some of the most fundamental system characteristics and properties in DeAI systems, and drive and enable smart blockchain, Web3, DAOs, and DeSci. Interaction, complexity, and intelligence cause or influence their fundamental frameworks, working mechanisms, evolution, performance, and risk; quantifying them thus makes it possible to characterize, compute and manage decentralized systems in a quantitative manner;
- developing key enabling techniques for designing and producing intelligent decentralized systems and services, and making blockchain, Web3, DAOs, DeSci, and their ecosystems intelligent with smarter autonomy, self-organization, and resilience;
- enabling the integration and integrity of plugging in third-party AI systems, tools, and services to decentralized platforms, services and DApps;
- identifying and addressing systematic issues, risks and exceptions of decentralized platforms and services in an adaptive and autonomous manner to enhance their reliability, resilience, integrity, and adaptability;
- enabling, driving, and delivering new value propositions (e.g., economic and social benefits) of

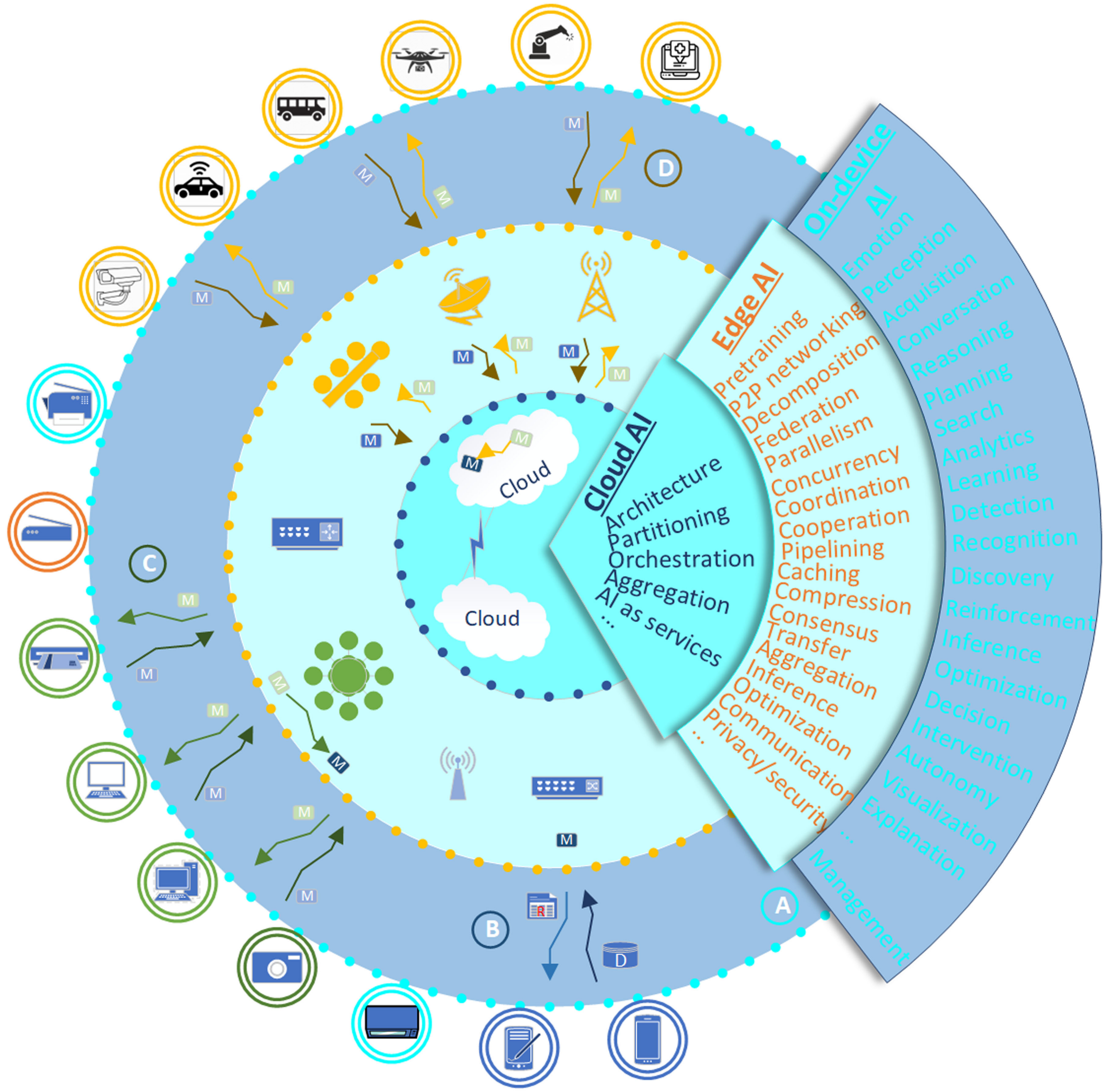

FIGURE 1. DeAI: Synthesizing on-device AI, edge AI, and cloud AI. Ⓐ P2P on-device AI. Ⓑ Data-sharing edge AI. Ⓒ Model-sharing edge AI. Ⓓ Device-edge-cloud hybrid edge AI.[f]

decentralized technologies, platforms and services by advancing their intelligence, personalized services, autonomous decisions, and optimal performance, etc.

In summary, DeAI aims to develop decentralized intelligent systems and services. It lightens and advances smart blockchain, Web3, the metaverse, DAOs, and DeSci, and their ecosystems.

[f]Note: some icons are from the Internet.

DeAI research issues: DeAI systems may comprise many AI agents who take different roles to achieve the abovementioned aims. Examples are local AI agents for executing local or specific AI tasks or tailoring AI algorithms or models for local AI tasks. A large DeAI ecosystem may consist of multiple DeAI edge networks, where each DeAI edge network is composed of many AI devices and edges. Each AI node may have one to multiple devices affiliated, forming a DeAI local edge network. Nodes are identified (e.g., by hashing) and connected in decentralized chains, rings, or other topological architectures.

- *DeAI architecture:* supporting decentralized agent networking, communication, collaboration, and task undertaking; connecting and communicating P2P agents, nodes and their affiliated devices in a decentralized manner, for example, by a P2P AI network;
- *Edge intelligence:* supporting edge-level AI task creation, execution, discovery, and verification; enabling edge networking, communication, and collaboration; supporting undertaking, coordinating and communicating AI tasks across devices in an edge network; managing and discovering existing and new edge networks; managing the registration or deregistration of third-party AI edge networks; and maintaining the integrity of edge networks;
- *On-device intelligence:* enabling device-level AI task creation, execution, discovery, and verification; managing and discovering existing and new devices; managing the registration or deregistration of third-party AI devices and tasks; supporting D2D cooperation, computation, and communication; and maintaining the integrity between devices in an edge network;
- *Decentralized contracting:* forming AI task contracts to allow intelligence (e.g., AI models, algorithms, resources, services, or tasks, and knowledge and findings) to be shared, executed, outsourced, or crowdsourced between edges or between devices;
- *Decentralized knowledge and intelligence federation:* storing, sharing, and federating knowledge and intelligence, such as AI models, findings, insights, and prior knowledge, to and from AI networks, edges, and devices;
- *Decentralized consensus-building:* recording, broadcasting, validating, orchestrating, securing, and managing AI agents, edges, and devices in a DeAI network; building consensus over DeAI networks in an ecosystem; and mitigating conflict;
- *Decentralized communication:* enabling secure, transparent, scalable message passing between AI agents, edges, devices, and networks, for example, in a P2P or D2D manner;
- *Decentralized governance:* enforcing the agreement, accountability, reliability, integrity, coordination, and interoperation between AI devices, edges, or between DeAI networks;
- *Decentralized security and privacy:* encrypting AI resources; maintaining the security of data, knowledge, and intelligence across edges and devices; protecting the privacy of agents, edges, and devices, such as keeping them at local when AI tasks are executed and findings, are shared to edges.

Figure 1 illustrates a conceptual map, the main functions, and research issues of DeAI systems. DeAI may be operated on 1) P2P and D2D networks, 2) an edge network, or 3) a cloud network. Accordingly, there are five DeAI architectures and patterns as follows.

A) *P2P on-device AI systems:* In D2D or P2P2 networks, end devices connect and chain with each other to form D2D and P2P2 AI systems and networks, and fulfill AI functions on devices.
B) *Data-sharing edge AI systems:* In an edge network, data from devices are shared with edge nodes (edge server, mediator, gateway, etc.), where AI tasks are executed on the device data and results are returned to respective devices.
C) *Model-sharing edge AI systems:* In an edge network, pretrained AI models are dispatched to end devices, where the AI tasks are executed on devices with their data and the reparameterized and retrained models are transferred to edge nodes.
D) *Device-edge-cloud hybrid model-sharing edge AI systems:* Device-edge-cloud networks are formed with end devices, edge nodes, and cloud servers, where pretrained cloud AI models are dispatched to edge nodes, which are customized for edge-specific functions and further dispatched to end devices for execution, and retrained models are returned to edge nodes with registration, and are then transmitted to the cloud for AI task execution with consolidated AI models.
E) *Device-edge-cloud hybrid data-sharing edge AI systems:* Device-edge-cloud networks are formed with end devices, edge nodes, and the cloud servers, where data in the end devices are transported to edge nodes for transformation and registration, which are then further transmitted to the cloud to execute AI tasks. Edge-specific AI task executive results are returned to edge nodes, which are further transformed and decomposed with end device-specific results passed to each end device.

Here, it is not possible to discuss all the functions and research issues due to the space limitation, so we refer interested readers to Cao's work[9–11] on X-interactions, X-complexities, and X-intelligences in complex systems and their data science and AI-driven solutions. X-interactions, X-complexities, and X-intelligences determine the future and challenges of the new age of AI, the X-AI age,[12] which are also intrinsic and intricate to DeAI and DeAI-enabled smart blockchain, Web3, the metaverse, and DeSci.

Edge Intelligence

Edge intelligence emerges in synergizing edge computing with AI.[13,14] *Edge intelligence* refers to the intelligent paradigms, techniques, capabilities, activities, behaviors, and problem solving of end devices by those in proximity, or jointly by the end, edge and cloud devices to achieve end, edge (cluster) or collaborative AI. AI goals, tasks, and capabilities are directly undertaken on decentralized end and edge devices for every device, every local system or organization, and devices in proximity or distributed to end/edge devices. Decentralized devices, end users, and their data, behaviors, and capabilities carry forward AI tasks and fulfill AI problem solvers locally and in proximity.

Similar to CeAI, edge intelligence also fosters and fulfills general AI capabilities, such as thinking, perceiving, communicating, reasoning, planning, analyzing, learning, behaving, acting, and decision-making. Differing from CeAI, these edge intelligent capabilities are fulfilled by individual end devices (e.g., task-specific drones) or edge devices in proximity (e.g., a cluster of nearby drones). Accordingly, edge AI studies the challenges, techniques, and opportunities of *edge vision* for sensing, perception, identification and recognition in the physical, virtual, or cyber-physical world; *edge learning*, including analytics, reasoning, inference, and optimization; *edge interfacing* between humans/brains and devices and virtual worlds; *edge conversation*, including understanding and communicating in characters, voice, text, or multimedia; *edge cooperation* for *ad hoc*, on-demand or scheduled tasking physically, virtually, or dually; *edge action and intervention*, including response, reaction, intervention, and next-best action; and *edge consensus-building*, such as task orchestration, modeling, and result aggregation, etc.

In particular, *edge learning* emerges as a frontier of applying AI and machine learning on devices, edge nodes, and over the air. New areas of cloud edge learning, federated edge learning, mobile edge learning, and blockchain edge learning will become paramount in 6G, smart cities, industrial IoT, unattended task undertaking, and the metaverse, etc.

Critical research challenges in acquiring, discovering, and managing edge intelligence include: 1) characterizing decentralization in end devices, end-edge networks, and end-edge-cloud networks, in particular, the interaction, complexity and intelligence of end and edge devices; 2) enabling decentralized intelligent problem solving, typically, perception, data acquisition, analytics and learning, knowledge discovery, reaction, reasoning, and intervention on end devices, in edge networks, or with cloud servers; 3) supporting decentralized sharing, storage, coordination, cooperation, and communication between end devices, edge networks, and within the cloud; 4) supporting privacy-preserving, secure, distributed and collaborative AI activities across decentralized devices and edge networks without moving and sharing private data and specialized AI capabilities around and without centralizing them to a mediator, matchmaker, or gateway; 5) supporting privacy-preserving, secure transfer and exchange of intelligent capabilities, AI models, and problem-solving results between end devices, edge networks, or within clouds; 6) supporting privacy-preserving, secure consolidation, federation, orchestration, and consensus-building of collaborative AI tasks between end and edge devices; 7) supporting the efficient decomposition, splitting, parallelism, concurrency, and pipelining of resources (data), AI tasks, models, computation, optimization (e.g., learning performance), communication, etc.; 8) developing energy, bandwidth, latency, security, and efficiency-sensitive communication protocols, message-passing mechanisms, transmission mechanisms between end devices, edge networks, or within clouds; 9) developing AI system architectures to support edge AI tasks, data management, information flow, task and workflow management, optimization, computation, communication, and aggregation.

Accordingly, enabling techniques are required to empower edge intelligence. Typical enabling techniques comprise privacy-preserving data sharing and communication; smart DApp development; encrypted, P2P, and asynchronous communication; data, task and model splitting, pipelining, dispatching, coordination, orchestration, and aggregation; computation balancing, efficiency and sharing; prior and knowledge sharing and transfer; objective balancing and optimization for end devices, end-to-edge networks, edge networks, or edge-to-cloud devices.

Typical applications of edge intelligence are real-time video analytics by smartphones or drones, autonomous decision-making by driverless vehicles, crop-specific pest control and fertilization in digital agriculture, unattended mining machines, autonomous industrial robotics, automating home facilities and services in smart homes, utility and transport planning in smart cities, and unattended space exploration robots. A typical use case is to enable on-device deep learning (such as real-time videoing and analysis) on smartphones, driverless cars, or drones while also supporting collaborative

TABLE 1. Differences between CeAI and DeAI.

Aspect	CeAI	DeAI
Methodology	Top–down, holism, authority, and autocracy	P2P, bottom–up, reductionism, autonomy, and democracy
Objective	Global objectives	Local objectives
Intelligence	General and strong intelligence	Local, edge and weak intelligence
Task	Global and central task	Local and distributed task
Data/repository	Central and single resourcing and storage	Local, distributed, multiple, end resourcing and storage
Model	Central and global model	End, and local model
Architecture	Central, vertical and hierarchical control, mediation, matchmaking, gateway, and server/client structure	Horizontal, P2P, D2D, distributed, chain, and flat structure
Process	Consensus-building, aggregation, and orchestration	Partition, decomposition and splitting
Mechanism	Predefined, vertical, design-time alliance, coordination, cooperation, normalization, and standardization	*Ad hoc*, horizontal, run-time self-motivation and organization, and negotiation
Computation	Central, global computing infrastructure	Distributed, local computing systems
Communication	Broadcasting and hierarchical	P2P, D2D
Decision	Global goal-driven authority, and strategic minority	Local goal-driven personalization and majority voting
Output	Global, aggregated, and integrative	Local, individual, and personalized
Privacy	Weak protection	Strong protection
Security	Central authorization, monitoring, risk, and governance	Local or distributed authorization, monitoring, and risk
Pros	Unification, capacity, order, efficiency, stability, strategic, concentrated resources, computing, and data	Personalization, flexibility, adaptivity, resilience, transparency, autonomy, expandability, high fault tolerance, scalability, throughout, low cost, and risk
Cons	Low flexibility, adaptivity, autonomy, robustness, reliability, accountability, fault tolerance, high vulnerability, risk, cost, and catastrophic mistake	Low capacity, energy, resource, computation, and stability, high latency, and chaos

tasks (e.g., transport planning and crop pest-control) in edge networks. Here, enabling techniques for edge learning require in-device energy- and storage-efficient perception, recognition, and diagnosis by deep models,[15] energy-efficient[16] compressed communication between devices and edge nodes, knowledge transfer between devices and edges, and coordination between end devices and between end and edge devices for intervention.

SYNTHESIZING CeAI, DAI, AND DeAI

Balancing CeAI, DAI, and DeAI

In reality, natural systems, including botanical systems, environmental systems, earth systems, oceanic systems, and astronomical systems, seem to be more decentralized and self-organized, whereas human systems seem to be contradictory. It is believed our brain issues the intention and control of the behaviors of our body parts. Consequently, for the same problem, different people may have opposing opinions and responses, reflecting not only the strong decentralized intelligence of individuals but also the strong centralized intelligence of the individual mental, mind, and emotion. In contrast, artificial systems, including human-made systems, social systems, political systems, economic systems, cultural systems, and religious systems, are more or less mixed with both centralized, top–down organization, governance, and management by layered authoritative operations, governing bodies, and regulatory bodies and decentralized, individualized and lower end autonomy, self-organization, cooperation, coordination, and communication by autonomous and self-organizing individuals or individual clusters. The balance between centralization and decentralization forms the spectrum from full openness, free of control, and democracy to full close, control, and autocracy, corresponding to DeAI to CeAI in terms of their intelligence and intelligent problem solving.

AI systems are part of human-made systems, despite different AI paradigms inspired by human intelligence, natural intelligence, and social intelligence. This has motivated different AI design thinking and systems. CeAI principles and tools support global, top–down, and holistic design and development. DAI and DeAI lean toward low-end requirements and preferences with a focus on addressing their local goals, priorities, exercising their individual intelligence, and utilizing their local resources and facilities to the greatest extent. Real-world complex, intelligent systems and intelligent problem-solving heavily depend on synthesizing both CeAI and DeAI thinking, systems, and operations in both unattended and autonomous systems, such as space stations, moon rollers, drones, and autonomous vehicles, and hybrid systems, such as intelligent transportation systems, smart cities, and macroeconomic and epidemic monitoring and control. CeAI and DeAI are not a binary and exclusive choice; rather, they are inclusive and complementary, coexist and jointly contribute to complex systems and AI problem solving. The thinking, mechanisms, and techniques of CeAI and DeAI are also complementary.

Table 1 compares the properties, characteristics, pros, and cons of CeAI and DeAI in terms of the major AI aspects of methodology, objectives, intelligence, tasks, data and resources, models, architectures, processes, mechanisms, computation, communication, decision-making, output, privacy, and security. This comparison also shows the need to integrate and balance CeAI and DeAI in complex AI systems and intelligent problem solving.

Hybridizing CeAI, DAI, and DeAI

What would an AI system integrating CeAI and DeAI look like? How would synthesizing CeAI and DeAI promote AI developments? What are their major research challenges and issues? This section briefly discusses these questions.

First, the integration of CeAI and DeAI is problem- and requirement-driven. It does not aim to enable all-round and omniscient intelligence and functionality and incorporating and integrating all individual intelligent paradigms and objectives, such as human-level AI, social AI, and natural AI into one system. On a high level, synergizing CeAI and DeAI seeks to enhance the inclusivity, complementarity, harmony, sustainability, and balance between CeAI and DeAI thinking, methodologies, functionalities, and strengths. On the low level, integrative AI aims to consolidate the respective thinking, design powers, working mechanisms, and functional modules of CeAI and DeAI, and to build consensus between maximizing global and local objectives simultaneously and minimizing conflicts in understanding complex systems and pursuing effective problem-solving solutions. Harmonic, sustainable, and balanced *integrative AI* involves and integrates top–down and bottom–up human intelligence in mind, emotion, vision, conversation, action, and natural and social intelligence inspired by nature and society. This thinking has been widely applied in hybrid intelligent systems by integrating two-to-multiple AI paradigms, techniques, objectives, tasks, or models, from research areas, such as neural translation and ethical AI, to specific aims and tasks, such as deep Bayesian learning and explainable AI.

Second, synthesizing CeAI and DeAI can inspire new AI thinking, methodologies, research questions, and developments. New perspectives and opportunities include systematic AI thinking, inclusive AI, integrative AI systems, intelligence metasynthesis, and conflict mitigation. Each is affiliated with new research challenges and issues.

- *Systematic AI thinking:* New AI thinking, paradigms and methodologies of integrative AI, inclusive AI, and sustainable AI; quantifying significant interactions and complexities; metasynthesizing major AI paradigms, such as human cognitive, emotional and imaginary intelligence, behavioral intelligence, algorithmic intelligence, natural intelligence, social intelligence, etc.
- *Inclusive AI:* Developing AI thinking, paradigms, methodologies, architectures, processes, mechanisms, and tools to complement, consolidate, harmonize complementary, conflicting, or competing CeAI and DeAI thinking, capabilities, and advantages; developing inclusive AI optimization, decision-making theories, and methods to complement and consolidate global and local objectives.
- *Integrative AI:* Enabling both centralized and decentralized working mechanisms, integrating different AI techniques and tools driven by diverse objectives, problems, and requirements; hybridizing specific AI techniques and tools for integrative problem solving.
- *Metasynthetic AI:* Developing the representation, modeling, and metasythesis of qualitative to quantitative human intelligence, domain intelligence, data intelligence, network intelligence, and machine intelligence in complex intelligent problem-solving.

- *Conflict mitigation:* Developing methodologies and tools to mitigate the respective advantages, disadvantages, and conflicts of coexisting intelligence, interactions, and complexities; developing resolution mechanisms for tolerant, inclusive, and resilient open AI systems.

SMART BLOCKCHAIN, METAVERSE, WEB3, AND DESCI

How would DeAI and synthesizing CeAI and DeAI make blockchain, Web3, the metaverse, and DeSci smart or smarter? In decentralized settings, DeAI is a critical enabling technique for smart blockchain, Web3, the metaverse, and DeSci.

Smart Blockchain

Existing blockchain technology and systems concentrate on the smartness of digital contracts; hence, smart contracts that can securely, fault and risk-tolerantly and automatically codify, transfer, execute, audit, and manage cryptographically signed transactions or an agreed value on a blockchain network or distributed ledger. However, the smartness of contracts is typically predesigned and precoded without autonomous adaptation and intelligence. Other important components, such as a block, ledger, token, cryptocurrency, and chain and the P2P network infrastructure, networking, computing, consensus-building, and management, are not necessarily smart. In addition, although it is claimed that blockchain systems can make other systems, such as a city or Industry 4.0 smart, enabling smart blockchain, is an open issue, and smart blockchain represents a new generation of blockchain 2.0.

Cao *et al.*,[17] introduced the concept of *smart currencies*, *smart cryptos*, and *smart blockchain* in the context of *smart FinTech* enabled by data science and AI. Various opportunities are illustrated to enable smart blockchain, such as in pricing, trading strategy, portfolio management, bitcoin mining, risk analytics, fragility detection, governance, and regulation.

Here, I discuss the fundamental roles of DeAI in enabling smart blockchains through making smart infrastructure, smart networking, smart computing, smart consensus-building, smart governance, and smart transaction, currency, block, and ledger. This relies on 1) incorporating and strengthening on-device intelligence into blockchain components and edge intelligence into chain nodes, ledgers, and the network; 2) intelligent infrastructure to partition, pair, and virtualize computing and communication for end devices and edge nodes and facilities to decentralize resource management and the orchestration of AI devices, models, and tasks; and 3) intelligent computing platforms and tools for programmable edge computation, communication, and AI modeling on devices and by average users.

First, on-device intelligence may be incorporated into blockchain transactions, currency, blocks, tokens, and ledgers on demand and to make them more active, personalized, secure, adaptive, autonomous, fault tolerant, risk tolerant, and resilient. For example, blocks could be empowered with task-specific intelligence, such as intrusion and alternation detection. Hashing codes may be embedded with functions to monitor and detect the order, intrusion, and integrity of chains. In specific applications, blocks and chains may be customized with intelligent functions, e.g., video recording and analysis for encrypted drone chains to detect environmental, climate or agricultural change. Cryptocurrencies may be encoded with price monitoring and manipulation detection. Distributed ledgers could be incorporated with various functions to enforce the integrity and consensus of blocks, prevent illegal or unexpected permission, access, replication, sharing, and the approval of ledgers over chains.

Second, edge intelligence may be incorporated into P2P and D2D blockchain nodes, networking, communication, computation, and infrastructure to enhance their intelligence.[18,19] Opportunities include 1) incorporating intelligent behaviors and functions, such as perception, acquisition, analysis, learning, reasoning, reaction, and intervention into block nodes and chains; 2) enhancing secure, risk/fault-tolerant registration, access, replication, sharing, discovery, storage, validation, and transfer of currencies and ledgers on the chain; 3) automatically monitoring and regulating currency pricing, price stability, trading strategies, and portfolios; 4) improving the efficiency, energy consumption, and latency of bitcoin mining, blockchain infrastructure, computation, and communication; 5) improving the automatic detection and prevention of security and privacy violation in smart contracting processing and contracts; 6) analyzing exceptional behaviors and activities of and between blocks, nodes, ledger, and contracts over time; and 7) promoting, innovating and regulating blockchain businesses and services.

Smart Metaverse

The metaverse forms a virtual society and a virtuality-reality continuum. The smart metaverse is thus essential to make the digital or dual world smarter and incorporate AI success in the physical world with the metauniverse. This includes enabling digital agents and society with intelligent capabilities of understanding, perceiving, reasoning, communicating, analyzing, learning, optimizing, planning, and reflecting on their self and societal behaviors, activities and consequences in the digital world and intelligent interactions, cooperation, communication and problem solving between agents, between agents and humans, and through teaming and alliance in the cyber-physical-social world over time, space, and episode.

Perspectives and opportunities of producing the smart metaverse include enabling the following.

- *General intelligence in virtual societies:* such as empowering agents with abilities of perception, recognition, detection, identification, conversation, behavior, and action-taking, reasoning, planning, search, retrieval, and optimization in their virtual communities.
- *Human-like intelligence in digital worlds:* mimicking and replicating human intelligence in digital avatars and agents for them to better interact, interface, communicate, and team with humans in the dual worlds and agent-human cooperation.
- *Embodied and immersive agent-human interaction, communication, teaming and cooperation in the dual world:* supporting mind, haptic, vision, action and device-based cyber-physical interfacing, communication, and feedback for telepresence, and agent-human teaming and cooperation.
- *Rational and sustainable virtual economy:* ensuring the rationality and sustainability of business models and economic activities in creating a virtual economy, currency, payment, cost, and utility models in the digital worlds.
- *Virtual safety and security:* ensuring information order, user safety and mental health, and information security in interfacing and communicating with agents in virtual communities.
- *Ethical virtual society:* ensuring social intelligence in virtual interactions and agent-human teaming; enforcing rationality, norms, privacy, trust, and accountability in social interactions, virtual marketing, trading, and competition.

We further illustrate some specific general intelligence, human-like intelligence, and agent–human-teaming intelligence in creating intelligent avatars and agents in the metauniverse.

- *Duality:* supporting predictive, active and proactive interaction, cooperation, and response between digital avatars in the cyberspace and humans (or devices and vehicles) in the physical world.
- *Reasoning and planning:* for agents to reason about and plan their behaviors, actions, activities, and responses.
- *Teaming:* enabling agents to select and team up with other agents for team tasks.
- *Vision:* for agents to perceive, track, detect, identify, recognize, analyze and predict the behaviors of teaming agents, competitors or defenders.
- *Communication:* enabling agents to communicate with team players about their goals, intentions, beliefs, and plans in private chatbots, queries, or instant messaging.
- *Search:* enabling agents to search historical transactions, results, and resources.
- *Learning:* enabling agents to analyze, predict, and optimize their behaviors, states, and objectives.
- *Reinforcement:* enabling agents to reinforce their objectives and optimize their goals and actions by optimizing policies, strategies, and actions.
- *Environment:* enabling agents to sense, perceive and predict their environment.
- *Personalization:* enabling agents to personalize their preferences, objectives, states, strategies, behaviors, and actions.
- *Reflection:* enabling agents to receive feedback and to evaluate and reflect on their prior states, behaviors, actions, and strategies and to improve them during planning, action-taking, and interactions.
- *Automation:* enabling agents to automatize their behaviors, actions, and decisions.
- *Risk:* enabling agents to proactively detect, analyze and predict harm, risk, intrusion, attack and automate reactive actions and strategies.
- *Assistance:* enabling agents to make enquiries and ask for instant help from peers.

Smart Web3

Web3 is deemed to be a new edition of the World Wide Web enabled by decentralized blockchain technology, tokens, and DeFi for trustworthy, secure, and immersive decentralized web platforms, content, and services. It contrasts with the centralized content, services, and technology in Web 2.0 for user interaction and social media and Web 1.0 for static consumer-oriented content listing. However, the Web3 movement has not made much progress and mainly stays at the conceptual level.

Grounded on decentralized thinking and technology, Web3 has the potential to 1) support and favor the preference, friendliness and concentration of scalable, heterogeneous, individualized and personalized end and edge devices, users, and services; 2) offer and enhance individual engagement, security, privacy, and scalability; 3) connect to and interact with large-scale and heterogeneous end devices, and diversified low-level edge nodes and networks; 4) operate in secure, privacy-preserved, and P2P networking, communication, token and cryptocurrency-based financial services, and ecosystems; and 5) provide immersive, personalized, cyber-physical-social-human interactive experience, services, and ecosystems.

DeAI can play a foundational role in enabling and shaping open, secure, trustworthy, privacy-preserving, and end user/device-oriented Web3 and make it smart.

- *Web3 intelligence:* enabling Web3 end users, devices, and edge networks to develop and deploy on-device and edge intelligence.
- *Web3 metaverse:* developing immersive capabilities, experience, and services in Web3 and incorporating virtual-physical interaction, teaming and cooperation.
- *Web3 protocols:* supporting encrypted, traceable, P2P, D2D, edge networking, and edge-cloud networking protocols for connection, content exchange, message passing, data sharing, coordination, etc.
- *Web3 infrastructure:* supporting efficient, energy-sensitive, trustful, latency-sensitive P2P, D2D, edge, edge-cloud networking, computing, resourcing, programming, and servicing, etc.
- *Web3 operation:* supporting decentralized operating systems, device registration and identification, access control, resource management, task decomposition, computation offloading, function virtualization, search and discovery, resource and activity orchestration, regulation, consensus-building, etc.
- *Web3 communication:* enabling secure, privacy-preserving, P2P and D2D communications between heterogeneous end devices, between personalized end users, with heterogeneous devices in proximity, and in the ecosystem with heterogeneous communication protocols, networking connectivity, etc.
- *Web3 services:* enabling end/edge-oriented real time, active, adaptive, personalized and trustworthy services, personalized content, P2P and D2D interaction, communication, instant messaging, and encrypted economic activities, which may be provided by end users, from end devices, and through edge networks, etc.
- *Web3 development toolkit:* supporting open source, end user, end device, edge network-oriented DApp programming, and interactive and workflow-oriented interfacing.
- *Web3 security:* protecting, tracing and monitoring information security, order and authenticity, and enabling active and proactive detection and prevention of intrusion, manipulation, and misuse, etc.
- *Web3 privacy and ethics:* preserving and protecting individual privacy of their accountable, valid, and trustworthy content, communication, and activities in the Web3 network and ecosystem, etc.

In addition to blockchain technology, the abovementioned areas, functions, and opportunities require advances in DeAI, smart AI chips, edge learning, on-device AI programming, interactive and visual techniques, and metaverse techniques for individuals and individual clusters to code, program, interact, and communicate with their smart devices, apps, digital avatars, and create their personalized apps, web content, pages, and services.

Smart DeSci

DeSci extends the concept of decentralization, DAO and decentralized thinking to scientific funding, publishing, operations, organizations, and inter-, multi-, and cross-disciplinary studies.[20] Complementing centralized science and developments, DeAI could play an essential role in DeSci and open science to enable and enhance bottom–up, self-organizing, self-motivated, free, open, secure, privacy-preserving, personalized, adaptive, and trustworthy scientific thinking, fields, organizations, operations, activities, and developments.

In the following, we discuss a few aspects to illustrate where and how DeAI could substantially promote the DeSci movement and make it smart.

- Enabling secure, trustworthy, privacy-preserving, and autonomous open science.
- Enabling decentralized, secure, open, and collaborative scientific infrastructures, platforms, and services.
- Enabling decentralized, P2P, autonomous, and incentive-driven scientific teaming, organization, association, and collaboration.
- Enabling transparent, and open trans-, multi-, and cross-disciplinary science and scientific programs and collaborations.
- Enabling original scientific breakthrough and innovation driven by free and open self-motivation, incentive, interest, and collaboration.
- Enabling interoperable, open, federated and collaborative scientific crowdsourcing.
- Enabling secure, privacy-preserving, and personalized scientific sharing, storage, publishing, and transfer.
- Enabling decentralized, privacy-preserving, free or priced, responsible, and accountable peer review and evaluation.

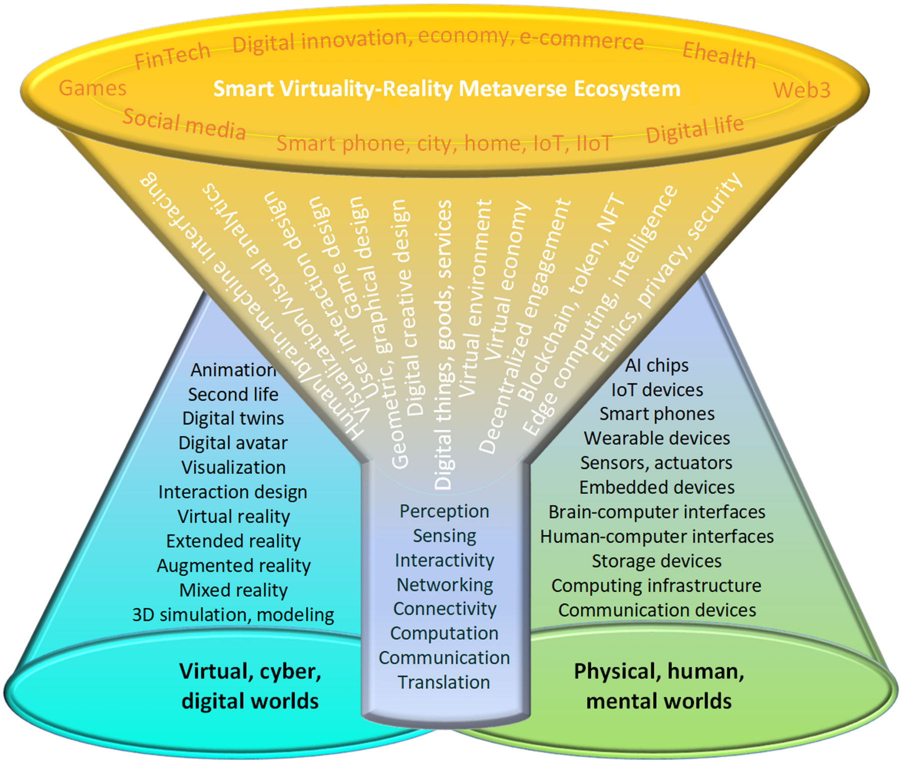

FIGURE 2. Smart virtuality-reality metaverse ecosystem: Metasynthesizing DeAI, metaverse, blockchain, Web3 and other technologies and applications.

- Enabling secure, market-driven, crowd-based valuation, protection, and the transfer of intellectual property.

CONCLUDING REMARKS

Decentralization has been widely promoted in management science, economy, and governance. Distributed and decentralized computing and systems have also demonstrated their significance. Decentralizing AI and intelligent science and technology are still in its infancy. DeAI forms a critical enabler and enhances various recent research highlights and areas, including DAI, the cloud and edge computing, blockchain, and the metaverse. This article reviews the concepts and perspectives of DeAI and their opportunities in enabling smart blockchain, Web3, the metaverse, and DeSci. Figure 2 illustrates a smart virtuality-reality metaverse ecosystem, which synthesizes DeAI, the metaverse, blockchain, Web3 and other relevant technologies for smart immersive digital and virtual-physical applications and services. The applications include FinTech, e-health, digital innovation, digital economy, e-commerce, games, digital life and society, cyberspace, and social media. The virtuality-reality continuum includes large screens, smartphones, smart cities, smart homes, and smart IoT (or industrial IoT) devices.

DeAI develops decentralized intelligence and intelligent systems by taking advantage of individualized and personalized on-device intelligence and edge intelligence. DeAI can also substantially promote smart blockchain and the metaverse and promote Web3 and DeSci movements and developments. This will inspire DeAI thinking, techniques, platforms, systems, and services. DeAI-enabled Web3 and DeSci will be substantially expanded to broad technical developments, business and economic opportunities, and intelligent decentralized ecosystems and society.

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