Internet of Realities

Beyond IoT to Bridge Human Understanding

Challenges and Opportunities

Version 1.0 (English)

JST CREST
Internet of Realities Project
https://www.internet-of-realities.org

Contents

Preface

We live in an age of paradox. The same technologies that promised unprecedented global connectivity have also become powerful engines for societal fragmentation. Algorithmically-driven information streams create deeply personalized echo chambers, leading to a profound divergence in understanding. While we may inhabit a common world of observable **facts**, we increasingly live within disparate and often conflicting subjective **realities**. This divergence in **interpretation**, fueled by our unique **personal histories** and contexts, erodes the very foundation for empathy and collective action.

In response to this critical challenge, this white paper proposes a new paradigm: the **Internet of Realities (IoR)**. We envision a next-generation internet that moves beyond connecting devices (Internet of Things) and instead focuses on creating a trusted infrastructure for **inter-reality communication**. The purpose of the IoR is not to enforce a single, monolithic truth, but to enable the difficult yet essential process of building **shared reality**, the recognized commonality of our **internal states** with others. By leveraging advancements in AI and immersive technologies, we can create the conditions for a deeper, more embodied form of mutual understanding.

This white paper is based on the extensive discussions and research activities from the JST CREST Internet of Realities Project, which commenced in October 2022 and is scheduled to run until March 2028. Within this project, members have engaged in foundational debates on "*what is reality, and what is the Internet of Realities*," while also discussing these concepts with a wider audience through technology exhibitions at events like Interop. In December 2023, we held our First Symposium, featuring seminal lectures from Professor Jun Murai of Keio University on the essence of the "Internet" and from Professor Shinsuke Shimojo of Caltech on "Shared Reality." Furthermore, in March 2025, we hosted our Second Symposium, welcoming Professor Olaf Blanke from EPFL to explore complex topics extending even to subjective "hallucinations." Each of these symposia was further enriched by panel discussions featuring project members and the invited speakers, which served to deepen our collective understanding. The project's advancement and the insights that have led to

this white paper also owe a great deal to the invaluable guidance from Professor Yasuo Okabe of Kyoto University, the JST CREST Area Director, and our other esteemed advisors.

This document, ***Internet of Realities: Beyond IoT to Bridge Human Understanding***, represents a foundational step in articulating this vision. Born from an interdisciplinary dialogue between computer science, cognitive science, sociology, and ethics, it puts forth the core research questions we believe are most urgent for the global research community to address. These are not merely technical inquiries; they are fundamental questions about the future of human cognition, identity, and governance in an increasingly complex world.

Our goal is to guide the development of this new paradigm toward a more **coexistent**, **emergent**, and **adaptive** global society, one built not on the simple exchange of information, but on a deeper capacity for understanding. We invite researchers, developers, policymakers, and citizens to join us in this vital exploration and to help shape an internet designed for the challenges of our time.

Takuro Yonezawa, Nagoya University
Akira Kanaoka, Toho University
Soko Aoki, Kadinche
Manabu Tsukada, The University of Tokyo
September, 2025

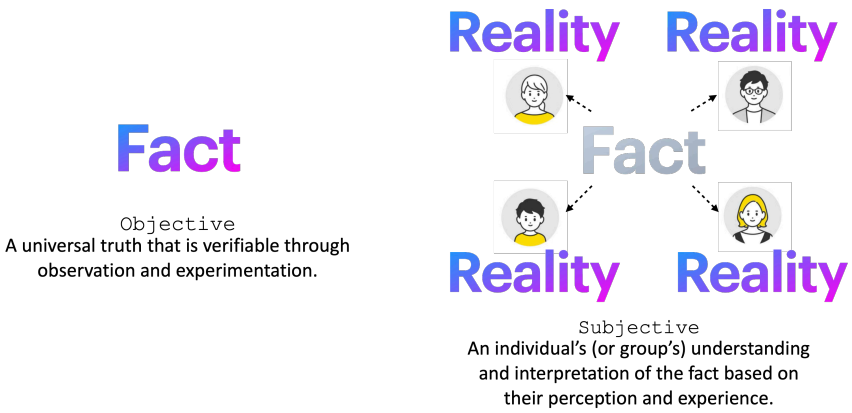
Introduction to the Internet of Realities (IoR)

“Reality” and the Fragmentation of Society

The meaning of the question “What is reality?” has varied across historical, political, cultural, and technological contexts. Contemporary information technologies—VR, digital twins, the metaverse, and AI—enable novel forms of experience, space, and agency, thereby heightening the relevance of this question for human and planetary well-being.

“Reality” is often discussed in contrast with “facts.” Facts denote propositions verifiable through observation, experiment, and evidence. By contrast, reality can be understood as the subjective totality through which individuals and groups interpret those facts, shaped by perception, experience, and social consensus. Prior to the internet, such realities likely formed more proximate clusters due to mass media regimes and shared routines. Personalization in digital platforms now accelerates exposure to preference-congruent content. While this affords autonomy, it also risks filter bubbles, attenuated community attachment, and diminished mutual understanding.

Consequently, societies may share a physical environment and many facts, yet diverge in interpretation. Technologies that could cultivate shared awareness may also scaffold individualized realities. The divergence arises less from the facts themselves than from interpretive processes—memory, culture, and internal states. As subjective realities become siloed, opportunities for coordination decline and the probability of misunderstanding increases.



A New Computing Paradigm: Internet of Realities (IoR)

We propose the **Internet of Realities (IoR)** as a new computing paradigm oriented toward bridging heterogeneous realities rather than merely exchanging data. Its core mechanism is **inter-reality communication**: the intentional externalization of internal states and interpretive frames, and the reciprocal acquisition of others' sense-making processes. Even if realities differ, empathy and collaboration are possible by creating a **shared reality**.

Whereas the Internet of Things (IoT) connects devices to sense and analyze objective states for productivity, efficiency, and safety, IoR extends this logic to the realm of interpretation. It aims to support mutual understanding and social harmony by recognizing and interconnecting diverse realities as they are interpreted in personal, group, and societal contexts.

IoR is guided by three principles:

- **Coexistent:** The IoR should constitute an ecosystem in which markedly different realities can coexist without enforced consensus. It must provide a trusted milieu for inter-reality communication that manages friction among conflicting interpretations and enables authentic disclosure.

- **Emergent:** By combining insights derived from distinct realities, the IoR should catalyze forms of collective intelligence that yield solutions intractable from any single perspective.

- **Adaptive:** The IoR must remain robust and evolvable in light of shifting human realities. Its design should anticipate ethical dilemmas and societal risks inherent to networking subjective experience, ensuring alignment with human flourishing.

These principles are the foundation of IoR research and a compass for a future centered not only on "knowledge" but on deeper "understanding."

Use Cases of the IoR

The Internet of Realities (IoR) represents more than a technological paradigm shift; it proposes a new way of engaging with human subjectivity to foster mutual understanding and address critical societal issues. To articulate its practical value, this section presents use cases organized along two axes: self-oriented applications, which support individual growth and decision-making, and other-oriented applications, which enhance communication and collaboration. Furthermore, we emphasize how these use cases can be extended to societal challenges such as the prevention of social isolation and loneliness, issues increasingly recognized as urgent in aging societies.

Utilizing One's Own Reality

- **Deepening Self-Recognition:** By embedding and reflecting an individual's internal states, IoR systems can provide tools for self-recognition. Through the visualization of patterns in thoughts, emotions, and behaviors, individuals gain insight into their cognitive tendencies and personal history. This reflection process enables people to understand how past experiences shape present interpretations, fostering a sense of continuity and identity.

- **Improving the Quality of Information Intake:** IoR-mediated personalization does not simply curate content, but contextualizes information against the backdrop of an individual's subjective reality. For example, when consuming news or academic materials, the system can highlight potential cognitive biases or suggest alternative framings. In this way, IoR promotes balanced and diversified knowledge acquisition, reducing the risks of echo chambers.

- **Supporting Self-Esteem and Mental Well-Being:** By mapping strengths, values, and meaningful life experiences, IoR applications can provide affirming feedback that reinforces self-worth. Rather than relying solely on external validation, individuals can rediscover intrinsic motivators, which supports resilience against psychological stressors and loneliness.

- **Decision-Making Assistance:** Complex choices, ranging from career changes to health-related behaviors, can be augmented by objective analyses of subjective states. IoR systems are capable of presenting decision scenarios that incorporate both factual data (e.g., statistical outcomes) and personalized interpretations (e.g.,

emotional comfort, past preferences). This dual framing enables individuals to pursue decisions that are rational yet authentically aligned with their lived reality.

- **Enhancing Creativity and Inspiration:** By analyzing the conditions under which past creative ideas emerged—whether through environmental cues, emotional states, or interpersonal interactions—IoR can identify personalized sources of inspiration. Coupled with interactive brainstorming tools, it can provide real-time prompts and divergent perspectives that foster creativity in artistic, academic, or professional domains.

Utilizing Others' Realities

- **Facilitating Mutual Understanding:** IoR enables individuals to share internal states, from emotions to cognitive framings, with unprecedented fidelity. For instance, in intercultural dialogue, participants can not only exchange linguistic content but also perceive how the same statement resonates differently across cultural realities. This fosters empathy and nuanced interpretation.

- **Constructing Empathy Maps and Shared Experiences:** Interactive empathy maps can be dynamically generated, illustrating overlaps and divergences between participants' realities. Shared VR/AR experiences—such as walking through each other's neighborhoods or re-enacting significant memories—provide immersive avenues to recognize common ground. These tools support relationship-building across divides of culture, profession, or ideology.

- **Supporting Communication and Collaboration:** Whether in negotiations, academic presentations, or daily conversations, IoR can optimize message framing by adapting delivery to the recipient's cognitive and emotional states. In collaborative settings, it can curate group-level perspectives, highlight synergies, and suggest balanced solutions. The result is improved dialogue quality, smoother consensus formation, and enhanced group creativity.

- **Enhancing Entertainment and Cultural Exchange:** IoR technologies expand entertainment beyond passive consumption. Audiences can experience performances through multiple perspectives, interact with narrative realities, and

co-create cultural meaning. This not only revitalizes traditional arts but also offers novel intercultural encounters that reduce distance and foster curiosity.

Addressing Societal Challenges: Preventing Social Isolation and Loneliness

A particularly promising domain for IoR applications lies in public health and community well-being, specifically the prevention of social isolation and loneliness. These issues are strongly correlated with physical and mental health risks, and their mitigation requires both individual engagement and systemic support.

- **Personalized Pathways to Social Connection:** IoR can integrate personal health data (e.g., from wearable sensors or body composition monitors) with information on local community activities. By situating self-recognition within broader social opportunities, individuals can be guided toward meaningful participation—whether in sports clubs, cultural workshops, or volunteer groups. This transforms self-discovery into a direct motivator for community involvement.

- **Creating Shared Realities in Communities:** Through shared platforms, residents can visualize the overlapping elements of their realities—common concerns, hobbies, or aspirations—making invisible connections tangible. Such “anticipatory spaces of connection” reduce barriers to participation and strengthen local bonds, addressing the root causes of isolation.

- **Scaling Support Through Hybrid Models:** While digital tools can suggest pathways and foster awareness, human interpretation remains essential. IoR-based community systems can therefore operate in tandem with social workers, educators, or health professionals, enabling large-scale outreach while preserving personalized care. This hybrid model ensures not only efficiency but also authenticity in fostering belonging.

These use cases illustrate that the IoR is not a purely technical infrastructure but a socio-technical framework. For individuals, it supports reflection, creativity, and balanced decision-making. For groups, it facilitates mutual understanding, collaboration, and cultural enrichment. And for society, it offers pathways to combat pressing challenges such as isolation and loneliness. Together, they exemplify the IoR’s capacity to create a coexistent, emergent, and adaptive global society, built not merely on information exchange but on the cultivation of genuine shared realities.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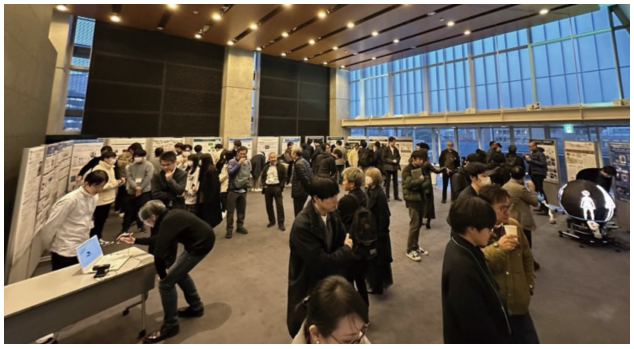

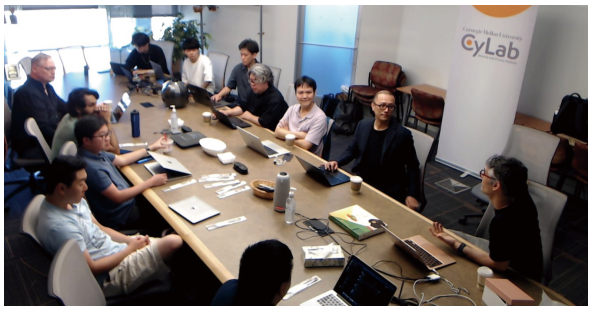
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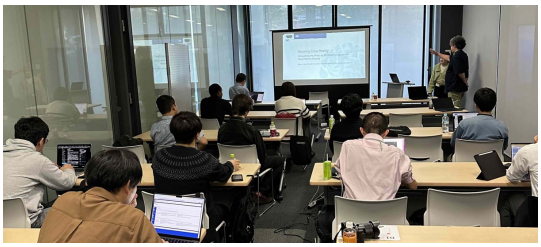
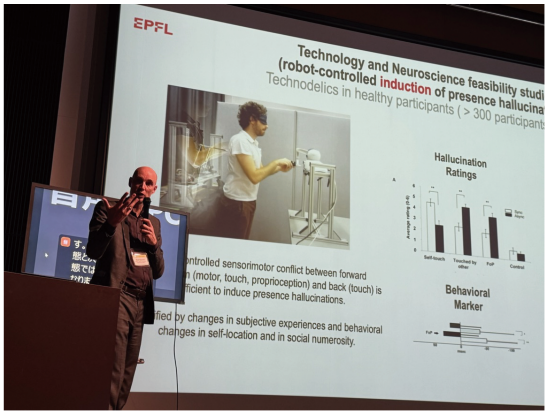



JST CREST 領域横断 シンポジウム
CREST マルチセンシング領域
「幻覚スペクトラムの操作と可視化」
研究代表
高橋 英彦
CREST S5基盤ソフト領域
「多様な形態の現実を安心・安全に創り・繋ぐ
Trusted Inter-Reality基盤」
研究代表
米澤 拓郎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IoR Related Terminology

Fact: A universal truth that is verifiable through observation and experimentation.

Reality: An individual's (or a specific group's) understanding and interpretation of the fact (world) based on their perception and experience.

Shared Reality[1]: The process of sharing internal states (e.g., judgments, beliefs, emotions, attitudes) with others regarding a specific object, either between two people or within a group, and the recognition of this shared state.

Entity: An object, being, or system that exists independently. It can be the subject of a ***fact***, the object of perception within an individual's ***reality***, or the focal point around which a ***shared reality*** is formed.

Physical Space: The three-dimensional environment where ***entities*** exist and interact. It is a primary source of observable ***facts*** and the foundational context for an individual's sensory perception, which shapes their ***reality***.

Virtual Space: A computer-generated, often networked, environment. Unlike ***physical space***, its properties are defined by code, but these rules can be considered ***facts*** within its context. It provides unique perceptions that contribute to an individual's ***reality*** and serves as a medium for establishing ***shared reality***.

Internal State: The collection of an individual ***entity***'s subjective conditions, including judgments, beliefs, emotions, and attitudes. These states are the fundamental components of an individual's ***reality*** and are what is exchanged in the process of creating ***shared reality***.

Interpretation: The cognitive process by which an individual assigns meaning to perceived information. It is the crucial mechanism that transforms the raw data of observation (potential ***facts***) into the structured, subjective understanding that constitutes an individual's ***reality***.

[1] Echterhoff, G., Higgins, E. T., & Levine, J. M.,"Shared reality: Experiencing commonality with others' inner states about the world." *Perspectives on Psychological Science*, Vol. 4, No. 5, pp. 496–521 (2009)

Personal History: The cumulative record of an individual ***entity***'s past experiences and Interpretations. It acts as a unique filter that shapes how new information is processed, thereby forming the foundation of their current ***reality***.

Common: An attribute describing an element (e.g., a belief, an experience) that is present across multiple individual ***realities***. The existence of ***common*** elements can be a foundation for, or a result of, establishing a ***shared reality***.

Share: The act of externalizing one's ***internal state*** so it can be perceived by another ***entity***. This is the fundamental action required to bridge individual ***realities*** and build ***shared reality***.

Inter-Reality Communication: The exchange of information between two or more ***entities*** with the specific purpose of conveying one's own ***reality*** and understanding another's. It is the mechanism for ***sharing*** that aims to resolve differences in Interpretation and establish a ***shared reality***.

Security: The measures and state that protect ***entities*** and the integrity of information. In this context, it refers to safeguarding the verifiable nature of ***facts*** from manipulation and ensuring the channels for creating ***shared reality*** are free from malicious disruption.

Privacy: The right of an ***entity*** to control access to their ***personal history***, ***internal states***, and overall ***reality***. It is the ability to selectively determine which aspects of one's ***reality*** are kept personal and which are made available to ***share***.

Trust: The belief in the reliability, integrity, and sincerity of another ***entity***. Trust is essential for accepting another's claims about ***facts*** and for engaging in the vulnerable process of ***sharing*** one's ***internal states*** to build a genuine ***shared reality***.

IoR Research Questions

The development of the Internet of Realities requires deep, interdisciplinary collaboration. The five key research questions presented below are the result of extensive reflection and dialogue across various fields. They outline the multifaceted challenges and opportunities we face in building an internet for mutual understanding.

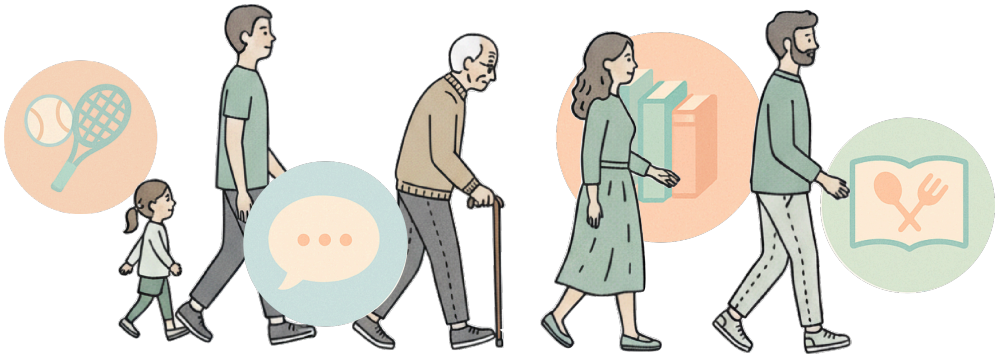
How can we computationally model and represent subjective human realities?

How can we build immersive and intuitive platforms for experiencing diverse realities and augmenting human cognition?

How can we design a secure and trust-based network for connecting different realities?

How can we create new forms of social interaction to realize the resolution of critical societal challenges and the fostering of mutual understanding?

How can we ensure the ethical development and governance of the Internet of Realities while protecting human identity and dignity?



How can we computationally model and represent subjective human realities?

A core challenge for the Internet of Realities (IoR) is to move beyond processing objective facts and begin to understand the subjective reality of an individual. This involves formalizing how a person transforms observable events into a unique, internal worldview. We call this challenge "**Reality Embedding.**"

To tackle this problem, we see two major, complementary research directions. One focuses on building models of how reality is formed internally. The other focuses on observing the external signals that reveal a person's inner state.

1. Modeling the Architecture of Interpretation:

This first direction aims to model the "internal architecture" of how we interpret the world. The goal is to understand the process by which an objective "Fact" is filtered through a person's unique "Personal History"—their memories, culture, and experiences—to produce a subjective "Reality." This research asks how we can create computational models that explain why the same event can lead to completely different internal states, such as feelings of joy or anxiety, in different people.

Key Research Questions:

- **The Architecture of Interpretation:** What computational frameworks can faithfully represent the process of "Interpretation," where a person's unique history dynamically shapes their understanding of incoming information?
- **The Formalization of Personal History:** How can we formalize a person's vast and unstructured "Personal History" into a format that a computational model can use, while ensuring ethics and privacy are protected?

2. Observing the Manifestations of Reality

This second direction is based on the principle that our internal reality creates observable signals. A person's subjective state is not purely internal; it often manifests in their body and behavior. For instance, a person's familiarity with an environment could influence their cognitive load, which might be detected through measurable changes in brain activity (EEG) or heart rate variability (HRV). By capturing these objective, real-world signals, we can open an empirical window into a person's subjective experience.

Key Research Questions:

- **The Decoding of Internal States:** What signal processing and machine learning models are required to robustly infer "Internal States", such as cognitive load, affect, and concentration, from noisy, multimodal time-series data (physiological and behavioral signals) in a context-dependent manner?
- **The Indexing of Reality:** How can we establish which patterns of physiological and behavioral responses are correlated with specific subjective experiences (e.g., "the disorientation of an unfamiliar environment" or "the anxiety from social isolation") to establish objective proxy indicators for subjective Reality?

An Integrated Path Forward

These two research paths are not separate; they are meant to be woven together. Models of interpretation can generate predictions about a person's internal state, which can then be tested and refined against real-world physiological and behavioral data. In turn, this observed data can help us build more accurate and personalized models of an individual's reality.

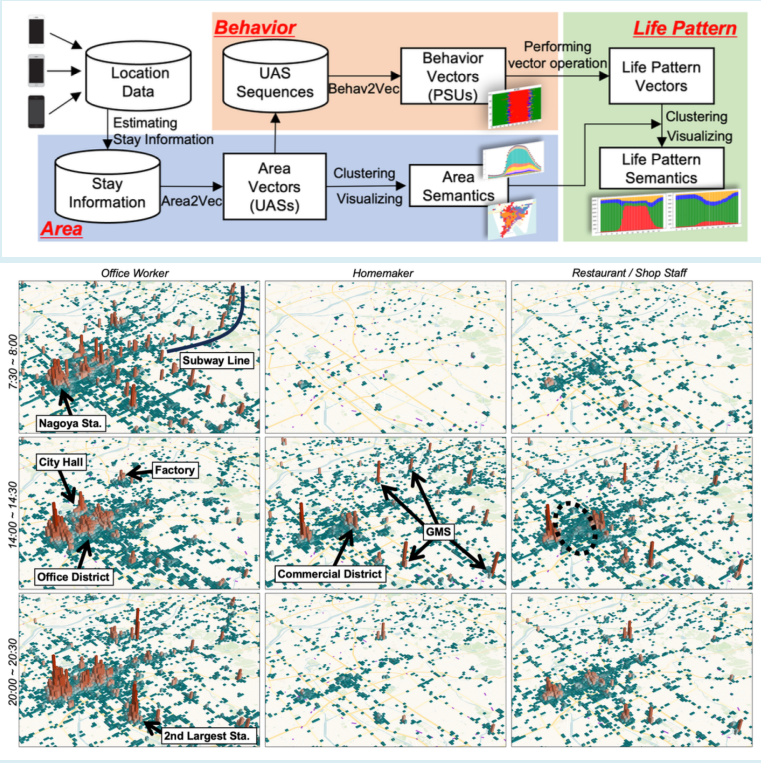
This integrated approach leads us to a central, unifying question for the research community:

“How can we build a framework that connects our computational models of subjective experience with their observable, real-world manifestations, ensuring that our models are trustworthy and genuinely aligned with a person's actual internal reality?”

Research Highlight

Our research [1] provides a compelling example of observing the manifestations of reality. In a study with Surgical Intensive Care Unit (SICU) nurses, we used wearable sensors to capture physiological signals, such as heart rate variability (HRV), during their clinical activities. We discovered that specific tasks, like "Patient Transfer," induced distinct and measurable stress signatures in the body. By combining this physiological data with activity context, a machine learning model identified high-stress states with 80% accuracy. This work demonstrates that subjective experiences like occupational stress have tangible, decodable manifestations, connecting an individual's internal reality to their objective physiological state.

Another of our research [2] demonstrates a scalable way to model a key aspect of human reality, a person's social role and lifestyle, using only raw GPS data. The goal was to overcome the need for manually labeled data, like Points of Interest, to understand life patterns. Our framework, LPSeL, first learns the functional purpose of different urban areas (e.g., "office," "residential") by analyzing the collective stay patterns of thousands of users. It then represents an individual's life as a sequence of movements between these semantically-defined areas. By clustering these life patterns, we successfully identified distinct groups like "office workers" and "shop staff". This work shows that by observing long-term behavioral manifestations, we can embed and infer meaningful human attributes from large-scale, unlabeled mobility data.



How can we build immersive and intuitive platforms for experiencing diverse realities and augmenting human cognition?

Once a Reality is computationally embedded, it must be rendered into a perceivable experience for another entity. This process, which we term Reality Hosting, is a challenge of translation: converting the complex, multi-layered data of one person's worldview into an intuitive and impactful immersive experience. The goal is not merely to display another's world, but to create platforms that facilitate the act of Sharing, moving beyond observation to a state of embodied understanding. Critically, these platforms should not be passive displays; they must be designed as cognitive tools that augment and enhance our own mental processes.

This vision requires pioneering work in human-computer interaction, immersive technologies, and cognitive science. The platforms must be carefully designed to foster empathy and deep understanding while simultaneously serving as a seamless extension of our own cognitive capabilities.

The primary research questions include:

- **The Interface for Empathy:** What are the fundamental principles for designing interfaces that allow a user to navigate another's Reality without causing cognitive overload or disorientation? This involves leveraging technologies like VR and AR not just to display information, but to foster a state of presence and embodiment, creating the conditions for genuine perspective-taking.

- **The Sensory Translation Problem:** How can the abstract components of an Internal State—such as a feeling of trust, a cultural value, or a deeply held belief—be translated into sensory information? This requires foundational work in areas like affective haptics, spatial audio, and even olfaction to convey the non-verbal, often subconscious, dimensions that constitute a Reality.

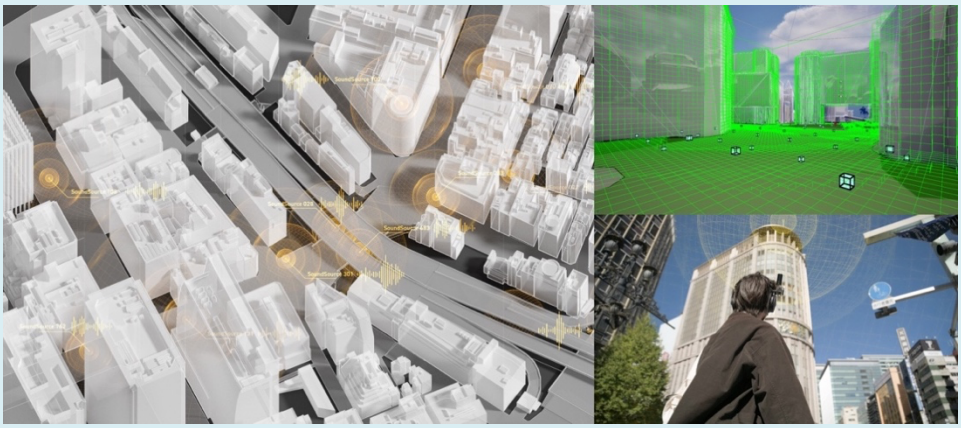
- **The Co-evolution of Cognition:** As these platforms become powerful tools for thought and perspective-taking, how do we design them to augment human cognitive processes like memory, creativity, and critical thinking? The goal is to

avoid creating cognitive dependency or deskilling, and instead foster a synergistic relationship where the technology enhances our innate human capabilities.

- **The Challenge of Scalable Coexistence:** How can a platform host millions of unique, dynamic Realities simultaneously, allowing them to coexist and be explored within a shared Virtual Space? This question addresses the fundamental architecture of the metaverse, requiring new solutions for distributed computing that ensure coherence, performance, and scalability on a global scale.

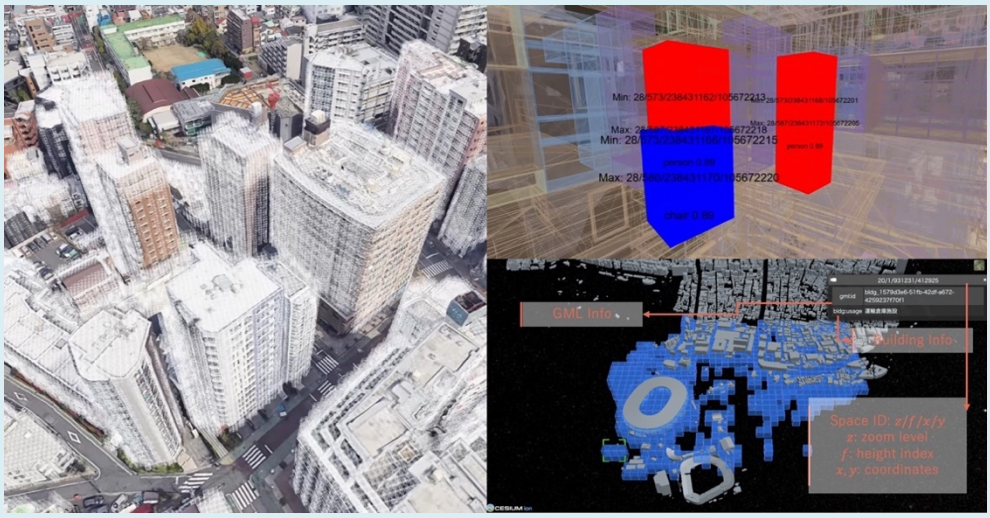
Research Highlight

'PLATONE' [3,4], a digital twin–based infrastructure, demonstrated real-time 3D audio spatialization within a georeferenced urban context. The Ministry of Land, Infrastructure, Transport and Tourism of Japan's PLATEAU 3D building models drive cloud-based wave propagation simulations—capturing occlusion, diffraction, and reverberation—while a lightweight pedestrian tracking unit fuses RTK-GNSS, inertial sensing, and barometric altitude to suppress drift and ensure absolute positioning at city scale. Combined, these technologies allow virtual content and sound to remain stably anchored to the physical world with sub-decimeter accuracy, even in complex outdoor or urban canyon environments. Prototype deployments have shown not only immersive audio experiences but also the feasibility of pedestrian navigation and context-aware MR interactions. This work establishes a foundation for platforms where localization and sensory augmentation converge, enabling cultural applications, construction support, and real-time urban exploration through sound.



Spatial ID [5] is a government-backed, hierarchical 4D voxel identifier that turns 3D space into an addressable, queryable database, so heterogeneous datasets and live datastreams can interoperate at multiple resolutions. Building on this specification, our research has demonstrated various use-cases for Spatial ID, such as an edge–cloud pipeline that encodes static PLATEAU city models and real-time IoT detections into Spatial IDs, enabling low-latency, database queries and datastream discovery and subscription (vector tiles for static data; pub/sub for dynamics). In the same identifier

space, we also demonstrate a 4D drone path-planning stack to schedule safe corridors through urban canyons as constraints evolve over time. Together these deployments show Spatial ID functioning as the “network layer” for reality: consistent addressing, efficient routing of updates, and composable access across domains. Next steps emphasize the querying side at scale—high-throughput Spatial ID indices, multi-tenant access control and audit, stream compaction/aggregation policies per zoom/time level, and deployable APIs for third-party services—so that spatial computing workloads can share a common, trustworthy backbone.



How can we design a secure and trust network for connecting different realities?

We call the process of connecting individual Realities into a functional network Reality Networking. This serves as the infrastructure foundation for the Internet of Realities (IoR) and enables a new form of communication we define as Inter-Reality Communication—the exchange of information aimed at conveying one's own Reality to another and understanding the other's Reality.

For this to be possible, Security, Privacy, and Trust must be established as inherent properties that the system is built upon. It is believed that without this foundation of trust, the IoR's goal of "mutual understanding through authentic sharing" cannot be achieved. Therefore, the construction of this network requires networking and platform technologies that facilitate the understanding of others while simultaneously solving fundamental challenges related to distributed systems, cryptography, and data governance. The primary research questions include:

- **Protocols for Decentralized Trust:** What protocols are necessary to establish trust between two entities involved in inter-reality communication without reliance on a centralized authority? This requires a mechanism to peer-to-peer verify the legitimacy of shared internal states using verifiable credentials and digital signatures.

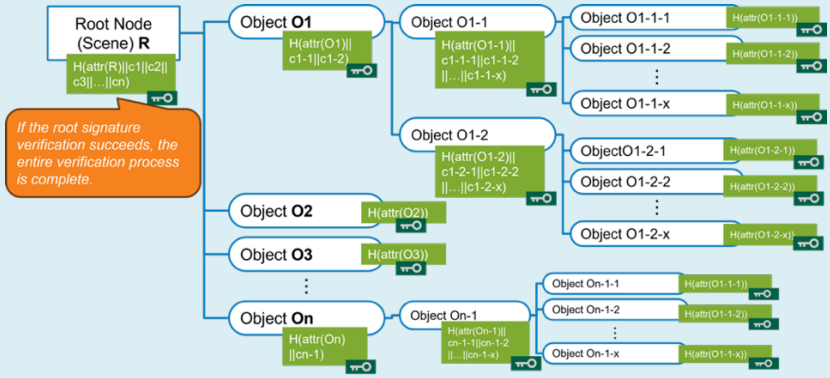
- **Preservation of Contextual Integrity:** How should the network be designed to ensure that when a component of a Reality is shared, its context and nuance (the product of a unique interpretation and Personal History) are not lost or distorted? This includes addressing the deep semantic challenge of conveying meaning across different subjective worldviews. At the same time, it is crucial to selectively share only the information necessary for mutual understanding (activities and objects related to the internal state) according to the context, while protecting individual privacy.

- **Context Understanding on Lightweight Devices:** It is essential to determine how MR/VR devices, including those with limited computational power, can maintain a rich context of Reality by coordinating with edge and cloud resources with low latency, allowing them to perform advanced visual inference and environmental recognition (e.g., object detection, pose estimation) beyond their on-board capabilities.

- **Seamless Connection Between Physical and Virtual Spaces:** It is necessary to explore platforms and connection methods that can realize telepresence, where entities in physical and virtual spaces feel as if they are in the same location, without spatial or sensory discontinuity.

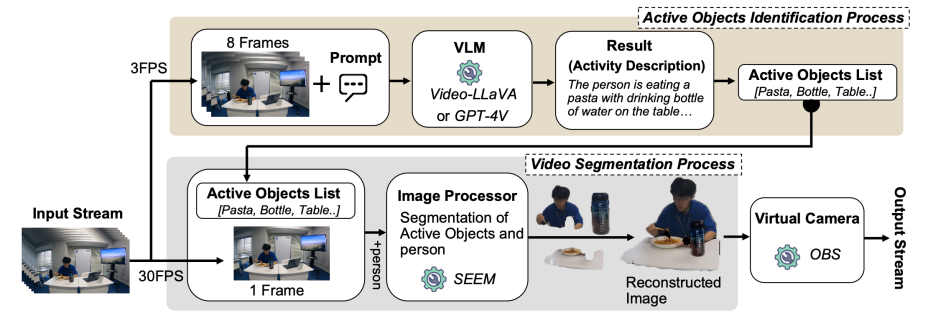
Research Highlight

TrustWeave [6] secures 3D assets by mapping scene graphs to Merkle trees, allowing subtree integrity to be confirmed with a single parent signature. Integrated into Unity and tested on large-scale VR/AR scenes, it demonstrated near-constant latency in event-driven partial verification, ensuring rapid checks without breaking immersion. By combining fine-grained authenticity with efficient performance across platforms such as Unreal, ARKit, Android XR, and WebXR, TrustWeave offers a practical trust layer for IoR's Reality Networking in multi-user, multi-service environments.

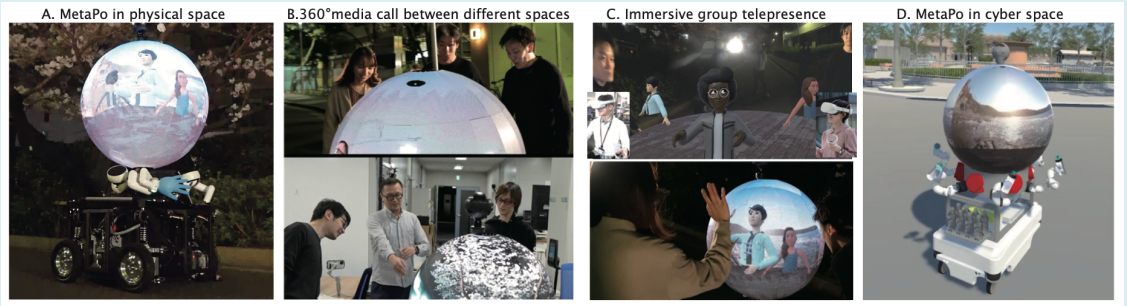


Scene context understanding is essential for mixed reality. A co-processing framework [7] has been implemented to provide MR headsets with egocentric scene context by offloading visual inference tasks to compact edge AI accelerators. These co-processors perform object detection and classification, human pose estimation, semantic segmentation, and facial recognition, returning structured outputs—bounding boxes, masks, and labels—to the headset with minimal latency. By enriching the internal model of the environment, virtual objects can attach to recognized furniture, avatars can respond to real people, and navigation cues can adapt to dynamic crowd flow. This division of labor allows MR devices to remain lightweight while benefiting from models that exceed onboard capacity. Early deployments confirm that sub-100 ms round-trip inference enables smooth interaction, positioning edge co-processing as a key enabler of Spatial AI—where geometric mapping, semantic interpretation, and human-centered interactivity converge.

With the rapid spread of online meetings and personal livestreaming, video-mediated communication faces a growing challenge: users often expose private aspects of their environment unintentionally. Conventional techniques such as background blurring or virtual backgrounds can mitigate this risk, but they also obscure activity-relevant objects, which are often essential for mutual understanding. ActStream [8] introduces a new method of selective video sharing. By combining Vision–Language Models (VLMs) with real-time segmentation, ActStream automatically identifies and shares only the user and the objects relevant to their ongoing activity (Active Objects). For example, when a user is looking at a monitor, the system transmits only the user and the monitor, hiding the rest of the background. This approach enables a unique balance between contextual awareness and privacy protection. ActStream exemplifies a new design principle of “context-aware selective sharing”, offering a concrete implementation that aligns with the IoR vision of fostering mutual understanding while respecting subjective realities.



MetaPo [9] is a robotic portal system designed to unify communication across physical and cyber spaces. Equipped with a spherical display, 360° cameras and microphones, and robotic hands, MetaPo functions as a gateway between distributed environments, enabling both panoramic communication and immersive interspace migration. The system defines two core communication modes. In Mixed Link, users remain in their respective environments but connect through panoramic audiovisual streams, enriched by MetaPo’s mobility and multi-user support. In Immersive Link, remote participants enter MetaPo’s virtual portal via VR, experiencing the remote environment in 360° immersion, enabling group telepresence beyond conventional one-to-one telepresence models. A working prototype integrates 360° cameras, spherical LED displays, VR portals, and robotic actuators, demonstrating seamless transitions between physical and cyber contexts. By offering a unified model of interspace communication, MetaPo exemplifies how cyber-physical integration can foster shared presence across heterogeneous realities, directly aligning with the IoR vision of bridging subjective worlds.



How can we create new forms of social interaction to realize the resolution of critical societal challenges and the fostering of mutual understanding?

The ultimate purpose of the IoR is to catalyze **Reality Transformation**: positive societal change driven by deeper mutual understanding. We posit that this transformation is achieved not simply by sharing information, but by leveraging the IoR to design and foster new paradigms of social interaction. These new interaction models will help people discover or construct a shared reality, the recognized commonality of their inner worlds. The challenge is to move beyond general-purpose platforms and design targeted applications that intentionally cultivate this state of connection to address real-world problems.

This requires a deep, interdisciplinary synthesis of social psychology, conflict resolution, and interaction design to create experiences that reliably lead to breakthroughs in understanding.

The primary research questions include:

- **Designing New Paradigms for Social Interaction:** How can we design IoR-mediated experiences that guide specific groups toward discovering common ground and constructing a new Shared Reality? This involves moving beyond simple communication to create structured, goal-oriented interaction protocols designed to facilitate empathy, resolve differences in interpretation, and build trust.

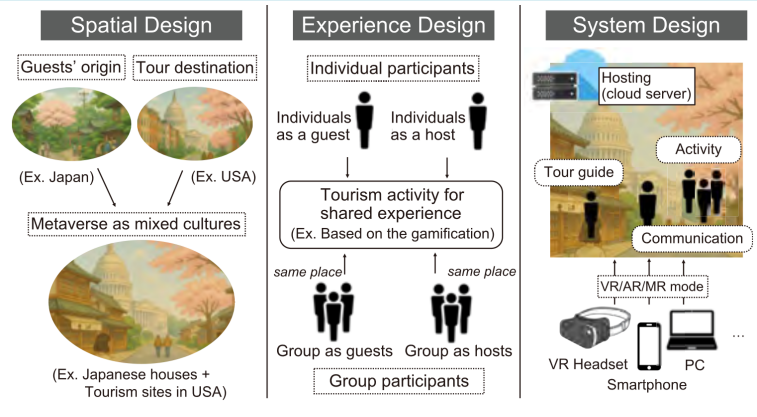
- **The Measurement of Genuine Understanding:** How do we scientifically measure the emergence of a Shared Reality? This demands a multi-modal approach, combining behavioral analysis and self-reports with objective physiological measures, such as interpersonal synchrony in heart rate or brain activity, to create a robust framework for evaluating the true impact of an IoR application.

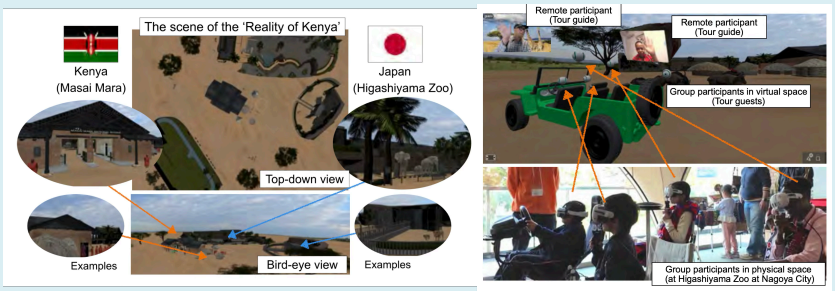
- **The Application to Intractable Problems:** What are the most effective ways to apply these principles to specific societal challenges, from political polarization to international conflict resolution and cultural education? This involves designing highly-contextualized interventions that facilitate Inter-Reality Communication

between specific groups, helping them discover or construct a new Shared Reality that was previously unattainable.

Research Highlight

MetaUniTour [10] is a core case study demonstrating the Reality Transformation capabilities of the IoR (Internet of Realities). This platform applies IoR principles to address the challenges of superficial cultural exchange common in conventional VR tourism. The system intentionally designs for real-time mutual understanding and trust between entities with differing realities by enforcing collaborative tasks (a game drive) and role assignments (on-site participants/remote guides). It builds a "Mixed Cultures Space" that fuses elements from both the guest and host cultures (e.g., Nagoya Zoo and Kenya's Maasai Mara), thereby resolving perceptual asymmetry. The experiment result showed participants experienced a strong sense of unity and an increased curiosity about foreign cultures. This validates that IoR provides a tangible path toward achieving the ultimate social value of fostering mutual understanding.





In another project, “MR Kabuki” [11] is an innovative system that enhances the traditional Japanese performing art for modern audiences using Mixed Reality (MR) headsets. To address the challenge that Kabuki’s classical language and stories can be difficult for newcomers to understand, our system provides visual aids. Spectators can see subtitles, commentary on the story and characters, and additional visual and sound effects without obstructing their view of the stage. A user study with approximately 100 participants showed this approach deepens understanding and immersion, proving particularly effective for novice Kabuki audiences.

We also presented a Mixed Reality (MR) guided tour system designed to enrich the museum experience by overcoming the physical limitations of traditional exhibits [12] . Using MR headsets and a visual positioning system, we add digital layers of content, such as 3D objects, commentary, and audio guides, directly onto existing displays. A user study at the Mizuki Shigeru Museum with 93 participants demonstrated high satisfaction, with over 80% reporting an enhanced experience and a willingness to pay additional fees for it.

Our research [13] demonstrates the advanced application of Extended Reality (XR) for complex pain management, moving beyond simple distraction. We have developed novel therapies using Virtual Reality (VR) to alleviate phantom limb pain by restoring the sensorimotor loop, a process correlated with functional reorganization in the brain. We also created an Augmented Reality (AR) home exercise system that reduces musculoskeletal pain in the elderly and improves psychological well-being by providing personalized, real-time feedback.

How can we ensure the ethical development and governance of the IoR while protecting human identity and dignity?

The power to computationally access and share the Reality of an entity carries immense ethical responsibilities. An improperly governed IoR could become the most powerful tool for manipulation or social control ever conceived. Therefore, proactive, interdisciplinary work on ethics and governance is not an optional add-on but a core requirement for its development. We must ensure the system is aligned with fundamental human values, with the protection of individual identity and dignity at its heart.

The design of the IoR's ethical and governance frameworks must anticipate and mitigate risks before they become societal harms. This requires collaboration between technologists, ethicists, legal scholars, and policymakers from the very beginning.

The primary research questions include:

- **The Sanctity of Identity and Dignity:** The IoR will touch the very core of what makes us who we are. What new ethical frameworks and technical safeguards are required to protect individuals from psychological manipulation, the forced alteration of their Personal History, or profound challenges to their core identity and sense of dignity?

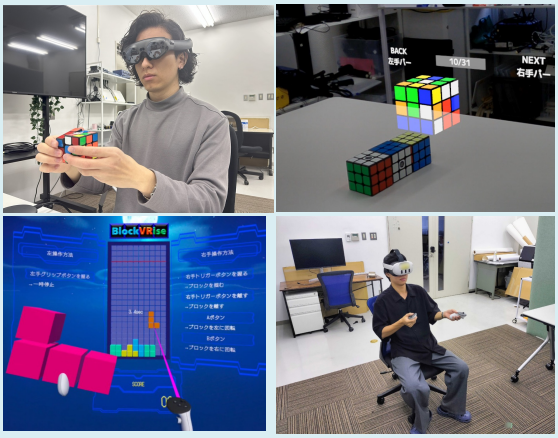
- **The Nature of Meaningful Consent:** What does consent truly mean when one is asked to share the very fabric of their subjective Reality? This requires us to move beyond simple "click-to-agree" models and design new forms of dynamic, granular, and revocable consent that give each entity continuous and unambiguous control over the privacy of their internal world.

- **Frameworks for Global Governance:** The IoR will be a global, decentralized network, transcending national borders and centralized control. What new governance models, such as decentralized autonomous organizations, multi-stakeholder oversight bodies, or new forms of digital jurisprudence—are needed to ensure accountability, fairness, and the protection of universal human rights across the ecosystem?

Research Highlight

IoR raises challenges not only of technical security but also of how to define and mitigate subjective harm. In analyzing XR threats, our work highlighted risks that extend beyond STRIDE categories, such as perceptual manipulation, psychological stress, and induced disorientation [14]. By explicitly recognizing these new harm domains, the study informs IoR's ethical agenda: establishing governance frameworks that protect users' cognitive well-being and ensure that shared realities are developed with responsibility and care.

To realize IoR responsibly, it is essential to understand how immersive technologies may influence human cognition and behavior. Our studies [15,16] on image movement attacks in optical see-through HMDs and auditory stimulus attacks in XR reveal that subtle manipulations of visual and auditory cues can guide gaze, distort attention, or alter spatial perception, often without user awareness. These findings highlight potential threats, but more importantly, they provide empirical evidence and systematic frameworks that inform safer system design. By clarifying how perception can be covertly influenced, we enable the development of XR environments that anticipate such risks and incorporate safeguards. This dual perspective, exposing vulnerabilities while guiding human-centered defense, contributes to IoR's mission of fostering trust and stability in evolving cognitive and social realities.

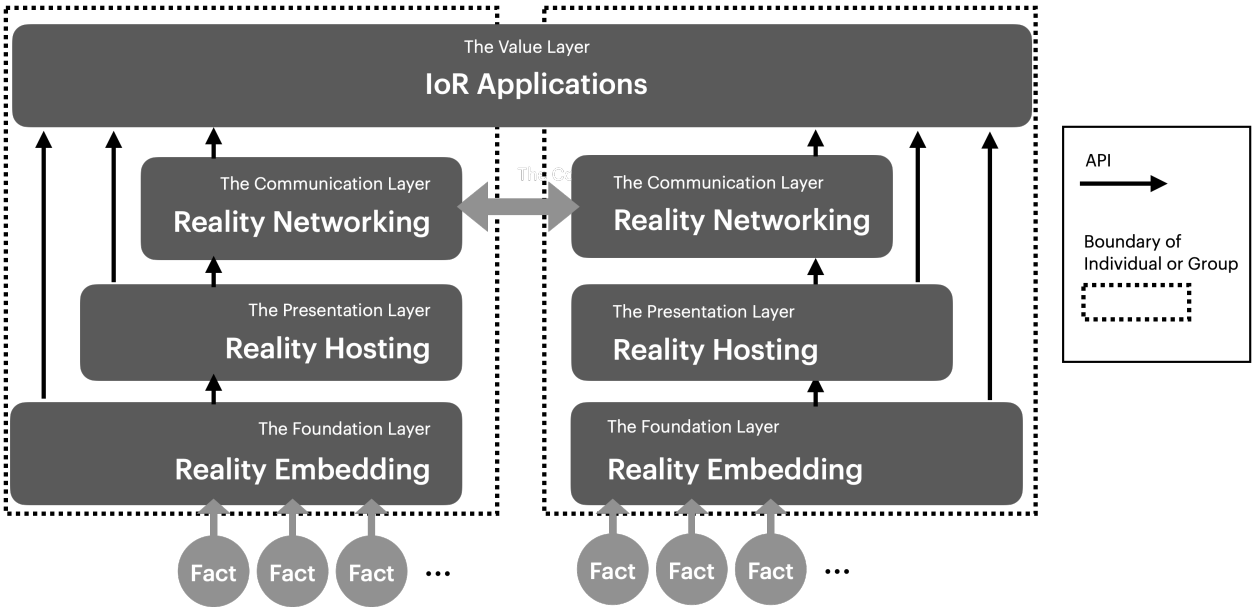


The JST RISTEX project "Service Mobility and Community Connections for Preventing Social Isolation and Loneliness" (AmPlatea Project [17]) explores how mobility can be reimagined not only as a means of transporting people but also as a way of bringing people together. Unlike conventional mobility, which focuses on movement from one place to another, service mobility refers to mobile services, such as bookmobiles, mobile markets, or health vans that themselves become destinations and opportunities for community gathering. At the core of this initiative is the concept of the Community Compass, a system designed to foster "anticipatory spaces of connection." By integrating everyday health data (e.g., body composition measurements) with information about local activities, the Community Compass leverages large language models to recommend contextually relevant community engagements. This approach transforms self-discovery, realizing one's own strengths or needs, into motivation for social participation, thus enhancing social motility. Pilot implementations in municipalities such as Oiso Town, Fujisawa City, and Toshima Ward demonstrate how the Community Compass can be deployed in public health centers, schools, or mobile service platforms, reaching citizens at scale while still offering personalized recommendations. By combining mass outreach with tailored interventions, the project illustrates a scalable model for loneliness prevention.

Our Approach:

The IoR Reference Architecture

To systematically address the multifaceted challenges outlined in our research questions, we propose the **IoR Reference Architecture**. This is not a rigid technical blueprint, but a conceptual framework designed to guide the development of a **coexistent**, **emergent**, and **adaptive** ecosystem for connecting subjective worlds. The architecture is structured in four distinct but deeply interconnected layers, each addressing a core research challenge and corresponding to a crucial function in the lifecycle of a **reality**, from its initial formation within an individual to its application in creating collective understanding.



Reality Embedding (The Foundational Layer)

This foundational layer directly addresses the first and most fundamental research challenge: the computational modeling of subjective experience. It is the architectural component responsible for the complex process of **Reality Embedding**, transforming the raw data of objective **facts**, captured through sensing, into a structured, computable representation of an **entity**'s unique **reality**. This is not mere digitization; it is a process of synthesis. The layer's models must account for an **entity**'s **personal history** and their unique cognitive process of **interpretation** to formalize the **internal states** (e.g., beliefs, emotions) that define their worldview. The output is a rich, high-dimensional model of a subjective **reality**, providing the foundational data upon which

the entire IoR ecosystem is built, while grappling with the core challenge of verifiability and authenticity.

Reality Hosting (The Presentation Layer)

This layer serves as the experiential conduit for the IoR, addressing the second research challenge of building intuitive and immersive platforms. Its function is to take the structured data produced by the Embedding layer and translate it into a navigable, sensory experience for another **entity**. **Reality Hosting** is the stage where the act of **sharing** becomes possible. It leverages immersive technologies like VR and AR to bridge the gap between an abstract computational model and the lived, perceptual experience of another's **reality**. The central design challenge here is not just technical performance, but the facilitation of genuine understanding, requiring novel interfaces and methods of sensory translation to convey the deep, non-verbal nuances of another's **internal state**.

Reality Networking (The Communication Layer)

This layer is the fabric of connection that makes the IoR an "internet," addressing the third research challenge of designing a secure and trust-based network. It provides the protocols necessary for **inter-reality communication**, ensuring that the vulnerable act of **sharing** one's **reality** is protected. This is more than a data transmission layer; it is an architecture of **trust**. It must enforce the **privacy** of an **entity**'s **internal states** and **personal history** through decentralized identity systems and advanced cryptography. Crucially, it must also be designed to preserve contextual integrity, ensuring that the meaning derived from one's **interpretation** is not lost or distorted when it is communicated across the network.

IoR Applications (The Value Layer)

At the highest level, the architecture culminates in the Value Layer, which directly addresses the IoR's ultimate purpose: applying this infrastructure to foster mutual understanding and solve societal problems. This layer leverages the capabilities of the lower layers to support applications specifically designed to cultivate **shared reality**. Here, elements from different individual **realities** are composed, compared, and synthesized to help multiple **entities** discover or construct **common** ground. This is where the societal value of the IoR is unlocked, providing tangible mechanisms for collaborative decision-making and empathy-building, as explored in the fourth research challenge. This layer is also where the ethical and societal considerations of the fifth challenges become most salient, as the design of these applications will directly shape the future of human identity and social interaction.

Together, these four layers provide a systematic roadmap, guiding our research and development from the inner world of a single **entity** to the creation of a resilient, collective **shared reality**.

Bibliography

[1] Tahera Hossain, Mohammad Saiedur Rahaman, Keiko Yamashita, Kono Aoi, Ma Guowei, Oyama Shintaro, Takuro Yonezawa, "Quantifying Work-Stress in Surgical Intensive Care Unit Nurses: A Multimodal Activity-aware Physiological Analysis", ISWC '25: Proceedings of the 2025 ACM International Symposium on Wearable Computers. Pages 118 - 124, to appear

[2] Kazuyuki Shoji, Haru Terashima, Naoki Tamura, Shin Katayama, Kenta Urano, Takuro Yonezawa and Nobuo Kawaguchi, “Unveiling Human Attributes through Life Pattern Clustering using GPS Data Only”, SIGSPATIAL '24: Proceedings of the 32nd ACM International Conference on Advances in Geographic Information Systems, Pages 621 - 624

[3] Orsholits, Alex; Qian, Yiyuan; Nardini, Eric; Obuchi, Yusuke; Tsukada, Manabu: PLATONE: An Immersive Geospatial Audio Spatialization Platform. In: The 2nd Annual IEEE International Conference on Metaverse Computing, Networking, and Applications (MetaCom 2024), Hong Kong, China, 2024.

[4] Takada, Tokio; Nakazato, Jin; Orsholits, Alex; Tsukada, Manabu; Ochiai, Hideya; Esaki, Hiroshi: Design of Digital Twin Architecture for 3D Audio Visualization in AR. In: The 2nd Annual IEEE International Conference on Metaverse Computing, Networking, and Applications (MetaCom 2024), Hong Kong, China, 2024

[5] Bao, Naren; Orsholits, Alex; Tsukada, Manabu: 4D Path Planning via Spatiotemporal Voxels in Urban Airspaces. In: 3rd Annual IEEE International Conference on Metaverse Computing, Networking, and Applications (IEEE MetaCom 2025), Seoul, Republic of Korea, 2025.

[6] Taiyo Arai, Kosei Otsuka, Akira Kanaoka, "Digital Signature Scheme for 3D Objects and Efficient Partial Verification Method Utilizing Scene Graph Hierarchy", Computer Security Symposium 2025 (In Japanese)

[7] Orsholits, Alex; Tsukada, Manabu: Context-Rich Interactions in Mixed Reality through Edge AI Co-Processing. In: The 39-th International Conference on Advanced Information Networking and Applications (AINA 2025), Barcelona, Spain, 2025, ISBN: 978-3-031-87771-1.

[8] Kaiya Shimura, Kazuma Kano, Tahera Hossain, Shin Katayama, Kenta Urano, Shun Taguchi, Hideki Deguchi, Hiroyuki Sakai, Takuro Yonezawa, Nobuo Kawaguchi,"Real-time Activity-Aware Video Streaming While Preserving Privacy", UbiComp / ISWC 2025 Posters & Demos, 2025, to appear

[9] Takuro Yonezawa, Nozomi Hayashida, Kenta Urano, Johannes Przybilla, Yutaro Kyono and. Nobuo Kawaguchi, “MetaPo: A Robotic Meta Portal for Interspace Communication”, ACM SIGGRAPH2022, Poster, Article No.: 28, Pages 1 - 2

[10] Kohei Matsumoto, Yoshiki Watanabe, Kaiya Shimura, Nozomi Hayashida, Shin Katayama, Kenta Urano, Nobuo Kawaguchi, Soko Aoki, Leleito Emanuel and Takuro Yonezawa, "MetaUniTour: Enhancing Engagement and Intercultural Understanding through A Metaverse Tourism Platform", IEEE MetaCom 2025

[11] Soko Aoki, Akinori Inada, Masashi Tomita, “MR Kabuki: Mixed Reality Enabled Performing Arts” 2024 International Conference on Intelligent Computing and its Emerging Application

[12] Soko Aoki, Naoki Itabashi, Ripandy Adha, Shinichi Sameshima, Yuki Kinoshita, Takeo Kotoku, “Mixed Reality Guided Museum Tour: Digital Enhancement of Museum Experience” IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops 2023.

[13] Yuko Otake, Michihiro Osumi, Soko Aoki, Takamichi Kogure, Masahiko Sumitani, “Usefulness of the Extended Reality（XR）Technology on Pain Management” The Japanese Journal of Rehabilitation Medicine, Vol.61 No.9 pp.812-818

[14] Akira Kanaoka, Ryota Mori, Kosei Otsuka, Shota Kurasaki, Tetsushi Oki, Toshihiro Ohigashi, Takamasa Isohara, "A Systematic Analysis of Security Threats and Attack Surface in VR/AR Environments.", SCIS2025: The 42nd Symposium on Cryptography and Information Security (In Japanese)

[15] Shodai Kurasaki, Akira Kanaoka, "Image Movement Attacks on Optical See-Through HMDs: Covert Gaze Manipulation and Privacy Risks in AR/MR System", the 3rd Annual IEEE International Conference on Metaverse Computing, Networking, and Applications (IEEE MetaCom 2025), 2025

[16] Kousei Otsuka, Akira Kanaoka, "Auditory Stimulus Attack in XR: Stimulus Characteristics and Technical Background Considerations", the 3rd Annual IEEE International Conference on Metaverse Computing, Networking, and Applications (IEEE MetaCom 2025), 2025

[17] JST RISTEX AmPlatea Project, https://internet-of-realities.org/amplatea/

[18] Societal AI: Research Challenges and Opportunities, Microsoft Research Asia, https://www.microsoft.com/en-us/research/project/societal-ai/white-paper/

Acknowledgments

The research is supported by JST CREST Grant Number JPMJCR22M4. The foundation for the vision of this paper was built upon the insightful discussions and invaluable advice we received from numerous people, both domestically and internationally, during our research activities. Microsoft Research Asia's white paper, Societal AI: Research Challenges and Opportunities [18], served as a significant reference for the structure and preparation of this document. We would like to sincerely thank them here. Please note that generative AI was partially utilized in the production and proofreading of the English and Japanese editions.