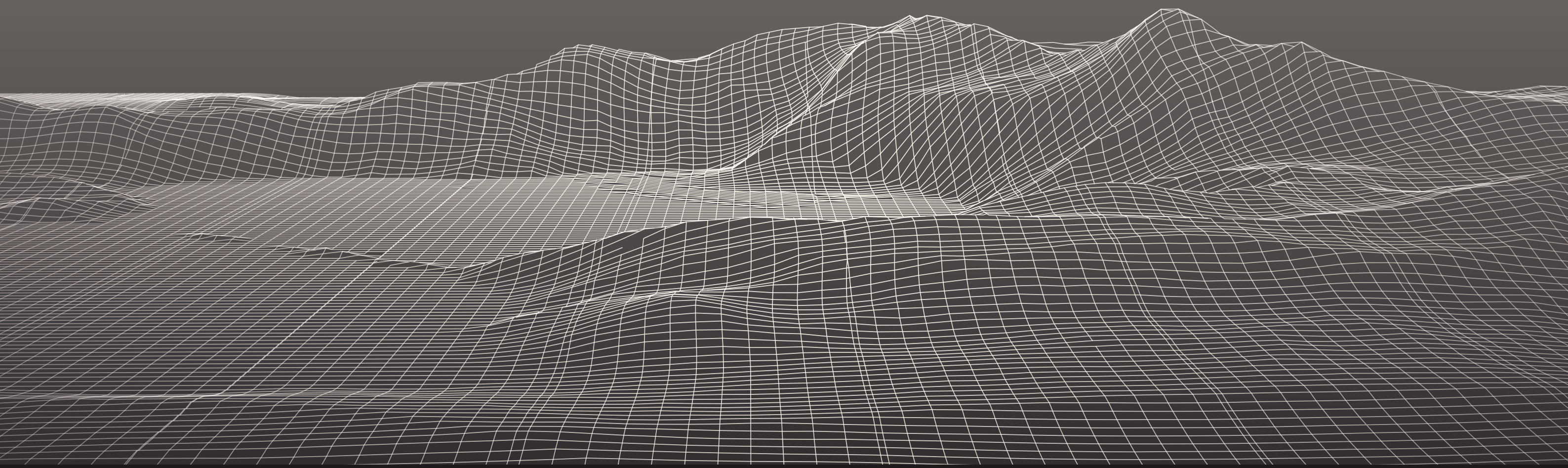
SPATIAL WEB
FOUNDATION

## SWF STD-1:2025 (3.3.2)

# The Spatial Web

# Spatial Web Protocol, Architecture, and Governance

September 26, 2025



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Spatial Web Foundation
5877 Obama Blvd
Los Angeles, CA 90016
USA

E-mail: info@spatialwebfoundation.org

# Abstract

This standard describes the services, hypergraphs, protocols, and languages that enable interoperable, semantically compatible connections between etwork-connected hardware (e.g. autonomous drones, sensors, IoT devices, robots) and software (e.g. user agents, services, platforms, applications, artificial intelligence systems) and includes specifications for:

- a functional layer stack capable of fulfilling spatially defined real-world and virtual requests for digital content respectful of governance authorities and self-sovereign identity
- a spatial range query and response format for requesting content or data about assets within a dimensional range
- a data ontology for describing objects, relationships, and activities
- a verifiable credentialing and certification method for permissioning create-retrieve-update-delete access to devices, locations, users, and data
- a human and machine-readable contracting language that enables the expression and automated execution of legal, financial, and physical activities

# Introduction

This standard defines requirements for the interoperability and governance of cyber-physical systems at (potentially global) scale, including autonomous devices, applications, spatial content and operations.

The Spatial Web provides a fusion of the physical and virtual worlds, transcending geographic and national boundaries to create a global commons for expression and imagination. This convergence, enabled by decentralizing technologies, artificial intelligence, autonomous vehicles, robots, and the Internet of Things, heralds a new era of interconnectedness. It's built on the foundations of the Internet's evolution over the past half-century, characterized by user-generated content, mobile internet, and IoT. The Spatial Web, facilitated by the Hyper-Spatial Transaction Protocol, enables stakeholders to integrate normative values into a seamless digital-physical reality, leveraging augmented and virtual reality.

As a reference model, this document provides three viewpoints of the Spatial Web: Value for stakeholders, Knowledge modeling and Distributed computing. The architecture defined in the viewpoints results in a set of requirements on components of the Spatial Web system. The concepts and requirements of the reference model guide subsequent development of Spatial Web Implementation standards and domain-specific Spatial Web architecture developments.

# Acknowledgements

This Spatial Web Foundation standard is identical in technical content to the document published by the IEEE Standards Association on May 28, 2025 as IEEE 2874-2025: IEEE Approved Draft Standard for Spatial Web Protocol, Architecture and Governance.

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# 1. Scope

This standard provides the key concepts of a Spatial Web framework, the relevant terms and their definitions, and a generalized system protocol, architecture, and governance that together serve as a reference model for Spatial Web components, systems, services and specifications.

As a reference model, this standard establishes the set of required modules and sub-modules and their minimum functions, the associated information content and the information models to be provided and/or supported by a Standards-based Spatial Web compliant implementation.

This standard defines requirements for a set of Implementation Specifications to be developed for the Spatial Web. In addition, this standard identifies existing technologies and standards to be integrated into Spatial Web-compliant implementations.

## 1.1. Purpose

The purpose of this standard is to provide a holistic and coherent technical framework for the implementation of a collaborative, interactive Spatial Web and shared world system.

## 1.2. Structure of document

This document is structured as a reference model consistent with the approach defined in ISO/IEC/IEEE 42010:2022. This reference model provides concepts to subsequently define Spatial Web Implementation standards and to guide domain-specific Spatial Web architecture developments.

This document provides three viewpoints of the Spatial Web as an abstract system:

Value for stakeholders (Clause 5)

Knowledge modeling (Clause 6)

Distributed computing (Clause 7)

Several views are provided for each viewpoint, e.g., in the Knowledge Modeling viewpoint, the Hyperspace subclause (6.2) is a view of spatial models used in the Spatial Web.

### 1.3. Conventions used in this standard

In this document the following Spatial Web ontology entries (ENTITY, ACTIVITY, AGENT, CONTRACT, CHANNEL, CREDENTIAL, DOMAIN, HYPERSPACE, and TIME) are represented using uppercase.

# 2. Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC SRD 63188, International Electrotechnical Commission. *Smart Cities Reference Architecture Methodology*. First edition. Geneva. https://webstore.iec.ch/publication/62092.

IEEE Std 2413™-2019, Institute of Electrical and Electronics Engineers. *IEEE Standard for an Architectural Framework for the Internet of Things (IoT)*. 2020. https://ieeexplore.ieee.org/document/9032420.

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W3C NOTE-did-spec-registries-20240831, SPORNY, Manu (ed.). *Decentralized Identifier Extensions*. 2024. World Wide Web Consortium. https://www.w3.org/TR/2024/NOTE-did-spec-registries-20240831/.

W3C json-ld11, World Wide Web Consortium. *JSON-LD 1.1*. https://www.w3.org/TR/json-ld11/.

W3C REC-wot-architecture11-20231205, LAGALLY, Michael, Ryuichi MATSUKURA, Kunihiko TOUMURA and Michael MCCOOL (eds.). *Web of Things (WoT) Architecture 1.1*. 2023. World Wide Web Consortium. https://www.w3.org/TR/2023/REC-wot-architecture11-20231205/.

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# 3. Terms, definitions and abbreviated terms

For the purposes of this document, the following terms and definitions apply.

## 3.1. Terms and definitions

### **3.1.1.** ACTIVITY PREFERRED

A partially ordered set of changes effected by an AGENT.

**Note 1 to entry:** Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

**Note 2 to entry:** Attributes of an ACTIVITY can be represented using HYPERSPACE Entities.

**Note 3 to entry:** An ACTIVITY can be near-instantaneous or temporally extended and exists as either planned, ongoing, failed, or completed.

**Note 4 to entry:** ACTIVITIES are performed on, by, in, or with, DOMAINS, including other AGENTS.

### **3.1.2.** AGENT PREFERRED

An ENTITY that senses, responds, and maintains a model of its environment, while performing ACTIVITIES to achieve its goals.

**Note 1 to entry:** AGENT is a type of DOMAIN.

### **3.1.3.** artificial intelligence

AI PREFERRED

The capacity of computers or other machines to exhibit or simulate intelligent behavior.

**SOURCE**: IEEE Std 7010™-2020

### **3.1.4.** cloud computing PREFERRED

Paradigm for enabling network access to a scalable and elastic-pool of shareable physical or virtual resources with self-service provisioning and administration on-demand.

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**SOURCE**: ISO/IEC 22123-1:2023, Clause 3.1.1, modified — Notes to entry have been removed.

### **3.1.5.** commons PREFERRED

SEE ALSO: *global commons*

The resources of a community that are or ought to be collectively held, managed, shared and made accessible to all members of that community, thus balancing individual needs with sustainability and preservation.

**Note 1 to entry:** Commons encapsulates the concepts of collective stewardship and mutual responsibility, where the community members have both the right to benefit from the resources and the duty to maintain them.

**Note 2 to entry:** Based on concepts from [126].

### **3.1.6.** cooperation PREFERRED

The process of working or acting together for common interests and values based on agreement.

**Note 1 to entry:** The organizations agree by contract or by other arrangements to contribute with their resources to the incident response but keep independence concerning their internal hierarchical structure.

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**SOURCE**: ISO 22300:2021, Clause 3.1.52

### **3.1.7.** decentralized identifier

DID PREFERRED

Identifier in the format of the W3C Decentralized Identifier.

**Note 1 to entry:** Information on references can be found in Clause 2.

**Note 2 to entry:** Adapted from W3C did-core.

### **3.1.8.** digital twin PREFERRED

A virtual representation of entities and processes, synchronized at a specified frequency and fidelity.

**Note 1 to entry:** Based on concepts and definitions from [60].

### **3.1.9.** distributed computing PREFERRED

Model of computing in which a set of nodes coordinates its activities by means of digital messages passed between the nodes.

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**SOURCE**: ISO/IEC TR 23188:2020, Clause 3.1.1

### **3.1.10.** distributed ledger PREFERRED

A *ledger* (3.1.22) that is shared across a set of DLT nodes and synchronized between the DLT nodes using a consensus mechanism.

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**SOURCE**: ISO 22739:2024, Clause 3.23, modified — Note 1 to entry has been removed.

### **3.1.11.** DOMAIN PREFERRED

SEE ALSO: *ENTITY*

Sphere of knowledge, influence, or ACTIVITY.

### **3.1.12.** domain authority PREFERRED

An ENTITY that is CREDENTIALED to have the ability to define within a DOMAIN the norms and terms under which CONTRACTS are created governing: AGENTS, ACTIVITIES and CREDENTIALS within that DOMAIN.

### **3.1.13.** edge computing PREFERRED

Distributed computing in which processing and storage takes place at or near the edge, where the nearness is defined by the system's requirements.

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**SOURCE**: ISO/IEC TR 23188:2020, Clause 3.1.3

### **3.1.14.** edge device PREFERRED

Device that provides an entry point into enterprise or service provider core networks.

**EXAMPLE:** Gateways, routers, switches, multiplexers, and a variety of other access devices.

**SOURCE**: W3C REC-wot-architecture11-20231205

### **3.1.15.** global commons PREFERRED

SEE ALSO: *commons*

Global level *commons* (3.1.5) that are shared by humanity.

[example] The atmosphere and climate system, biodiversity, critical biomes, and the Internet are examples of global commons.

**Note 1 to entry:** Based on concepts from [126].

### **3.1.16.** HYPERSPACE

SPACE PREFERRED

A set of ‘points’ such that, for every ordered pair of points, there is a possibly empty set of ‘paths’ from the first point to the second, and such that there is an ‘identity’ path from every point to itself.

### **3.1.17.** Hyperspace Modelling Language

HSML PREFERRED

A human- and machine-readable modeling language and semantic data ontology schema that describes objects, relations, actions, activities and their permissions.

**Note 1 to entry:** Uses of HSML include the expression and automated execution of legal, financial, and physical activities.

### **3.1.18.** Hyperspace Transaction Protocol

### HSTP PREFERRED

Generic protocol designed to underwrite automated contracting transactions that are required for building a coherent, decentralized, secure, and privacy-respecting *Spatial Web* (3.1.31).

### **3.1.19.** Spatial Web Client PREFERRED

SEE ALSO: *peer-to-peer*

Node that communicates with Spatial Web servers in a client-server relationship, to provide users with respective views of the graphs in various forms.

**Note 1 to entry:** Spatial Web Clients can also communicate in a *peer-to-peer* (3.1.24) fashion.

### **3.1.20.** Internet of Things PREFERRED

A system of entities (including cyber-physical devices, information resources, and people) that exchange information and interact with the physical world by sensing, processing information, and actuating

**SOURCE**: IEEE Std 2413™-2019

### **3.1.21.** interoperability PREFERRED

Ability of two or more systems or applications to exchange information and to mutually use the information that has been exchanged.

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**SOURCE**: ISO/IEC 22123-1:2023, Clause 3.6.1

### **3.1.22.** ledger PREFERRED

Information store that keeps records of transactions that are intended to be final, definitive and immutable.

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**SOURCE**: ISO 22739:2024, Clause 3.54

### **3.1.23.** mereology PREFERRED

Parthood theory based on relations of ‘part to whole’ and ‘part to part within a whole.’

### **3.1.24.** peer-to-peer PREFERRED

Relating to, using, or being a network of equal peers that share information and resources with each other directly without relying on a central entity.

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**SOURCE**: ISO 22739:2024, Clause 3.70

### **3.1.25.** polycentric PREFERRED

A system of powers, incentives, rules, values, and individual attitudes that match in an ecological and social way to the issue being addressed.

### **3.1.26.** polycentric governance PREFERRED

A form of governance with multiple overlapping *polycentric* (3.1.25) nodes of nested decision making, each of which operates with a degree of autonomy.

**Note 1 to entry:** This includes special-purpose governance units that cut across jurisdictions and allow a “synthesizing and integrating” of consumption, provision, and production units operating at different scales of aggregation.

### **3.1.27.** real-time PREFERRED

Pertaining to a system or mode of operation in which computation is performed during the actual time that an external process occurs, in order that the computation results can be used to control, monitor, or respond in a timely manner to the external process.

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**SOURCE**: ISO/IEC/IEEE 24765:2017, Clause 3.3327(2)

### **3.1.28.** representation PREFERRED

Model that can be used to describe some aspect of a world.

**Note 1 to entry:** Representations can be passive or active. A passive representation reflects a possible state of affairs, typically the state of some spatiotemporally local slice of an AGENT'S environment, while an active representation changes the state of a system to conform to the representation.

**Note 2 to entry:** Representation can be probabilistic (e.g., a conditional probability distribution or Bayesian belief) and pertain to either states of the world generating data or content, at a particular moment in time, or contingencies and dynamics that could depend upon the actions of a user.

### **3.1.29.** spacetime PREFERRED

A mathematical structure that provides a framework for physics and the physical universe.

**Note 1 to entry:** In general relativity, spacetime is a 4-dimensional Riemannian manifold.

### **3.1.30.** Spatial Web Domain Server PREFERRED

Networked server that provides location-based identification of HYPERSPACE assets and ownership information to Spatial Web Domains.

**Note 1 to entry:** A Spatial Web Domain Server handles spatial content retrieval and spatial transaction validation, whereby the rules for particular areas can be described as spatial permissions in their associated assets.

### **3.1.31.** Spatial Web PREFERRED

Network structures supported by the protocol, architecture, and governance related to *HSTP* (3.1.18) and *HSML* (3.1.17) and their supporting components.

### **3.1.32.** Spatial Web Identifier

SWID PREFERRED

Identifier of a HYPERSPACE object formulated as a URL conforming to a *DID* (3.1.7).

**Note 1 to entry:** A SWID includes implicit reference ability to SWID Documents via registered "methods", which specify how to both resolve and revoke SWIDs and how to write SWID Documents themselves.

**Note 2 to entry:** The SWID is a type of pointer to the context of a resource, not just the resource itself, and utilizes the *universal domain graph* (3.1.52) to maintain a certain degree of statefulness about the resource(s) in question.

### **3.1.33.** CONTRACT PREFERRED

A binding agreement between two parties, especially enforceable by law, or a similar internal agreement wholly within an organization.

**Note 1 to entry:** The original source of this definition was ISO/IEC/IEEE 12207:2008, however ISO/IEC/IEEE 12207:2008 was superseded by ISO/IEC/IEEE 12207:2017 which no longer defines the concept "contract".

**SOURCE**: IEEE Std 730™-2014, modified — The ISO/IEC/IEEE inline reference has been moved from the definition to a new Note. The second part of the original multi-part definition has been removed.

### **3.1.34.** norm PREFERRED

A standard or principle of right action serving to guide, control, or regulate proper and acceptable behavior, which can be specified in terms of (a) the conditions under which it is binding on AGENT'S actions and (b) the conditions under which such actions conform or fail to conform to it.

### **3.1.35.** ENTITY PREFERRED

that which is perceived, known, or inferred to exist, has existed, or is anticipated to exist.

**Note 1 to entry:** An ENTITY can exist whether data about it are available or not.

**Note 2 to entry:** ENTITY is the base item in the Spatial Web Ontology. 6.6

**EXAMPLE:** An event, idea, object, person, process, etc.

### **3.1.36.** augmented reality PREFERRED

Type of mixed reality system in which virtual world data are embedded and/or registered with the representation of physical world data.

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**SOURCE**: ISO/IEC 18039:2019, Clause 3.1.2

### **3.1.37.** mixed reality system PREFERRED

System that uses a mixture of representations of physical world data and virtual world data as its presentation medium.

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**SOURCE**: ISO/IEC 18039:2019, Clause 3.1.13, modified — The admitted term has been removed.

### **3.1.38.** virtual reality PREFERRED

An artificial environment presented in the computer.

**SOURCE**: ISO/IEC TR 18121:2015, Clause 3.6

### **3.1.39.** autonomous AGENT PREFERRED

An AGENT that is capable of modifying its intended DOMAIN of use or goal without external intervention.

### **3.1.40.** CHANNEL PREFERRED

A stream of HSML ENTITIES that are related to an ACTIVITY of a specific context that does not itself warrant a DOMAIN or hierarchy.

**EXAMPLE:** A CHANNEL contains HSML messages that relate to an HSML ACTIVITY.

### **3.1.41.** cognitive computing PREFERRED

A paradigm for complex computational systems designed to sense, comprehend, act and adapt in ways comparable to the human brain.

**SOURCE**: IEEE Std 2755™-2017, modified — The original definition format has been simplified. The phrase "A paradigm for" has been added to the start of the definition.

### **3.1.42.** concern PREFERRED

A matter of relevance or importance to a stakeholder.

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**SOURCE**: ISO/IEC/IEEE 42020:2019, Clause 3.8, modified — The Example has been removed.

### **3.1.43.** CREDENTIAL PREFERRED

A set of one or more claims made by a DOMAIN.

**Note 1 to entry:** Examples of claims include: identity of a DOMAIN, membership in a DOMAIN, ability of a DOMAIN to perform an ACTIVITY.

### **3.1.44.** dimension PREFERRED

The number of degrees of freedom of a physical quantity.

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**SOURCE**: ISO/IEC/IEEE 21451-1:2010, Clause 3.44, modified — The embedded Example in the definition was removed.

### **3.1.45.** Euclidean space PREFERRED

Real vector space or real point space for which a scalar product is defined for any two vectors.

**Note 1 to entry:** The usual geometrical three-dimensional space is a Euclidean point space. Four-dimensional vectors used in special relativity are elements of a non-Euclidean point space because the scalar product of a vector by itself may be negative.

**Note 2 to entry:** Euclidean space is a type of vector space.

**SOURCE**: [42], Clause 02-03-19, modified — Note 1 has been modified. Note 2 has been added.

### **3.1.46.** geographic information PREFERRED

Information concerning phenomena implicitly or explicitly associated with a location relative to the Earth.

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**SOURCE**: ISO 19101-1:2014, Clause 4.1.18

### **3.1.47.** geographic coordinate reference system PREFERRED

Coordinate reference system that has a geodetic reference frame and an ellipsoidal coordinate system.

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**SOURCE**: ISO 19111:2019, Clause 3.1.35

### **3.1.48.** graph space PREFERRED

A set of nodes and edges such that every edge has both a source node and a target node.

**Note 1 to entry:** Graph space is a type of HYPERSPACE.

### **3.1.49.** heterarchy PREFERRED

An arrangement where the elements of the organization are unranked (non-hierarchical) or where they possess the potential to be ranked in several different ways.

### **3.1.50.** hierarchy PREFERRED

An arrangement where the elements of the organization are represented as being “above”, “below”, or “at the same level as” one another.

### **3.1.51.** register PREFERRED

Set of files containing identifiers assigned to items with descriptions of the associated items

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**SOURCE**: ISO 19135-1:2015, Clause 4.1.9

### **3.1.52.** universal domain graph

UDG PREFERRED

A distributed hypergraph which contains all relationships between all known *SWIDs* (3.1.32) in the Spatial Web.

**Note 1 to entry:** The universal domain graph is the complete *Spatial Web* (3.1.31) hypergraph.

### **3.1.53.** distributed universal domain graph system

### distributed UDG system PREFERRED

The set of coordinated Spatial Web Nodes that provide services on the distributed UDG.

### **3.1.54.** Spatial Web Node PREFERRED

Computing machine connected to the internet, capable of exchanging HSTP messages.

### **3.1.55.** stakeholder PREFERRED

A role, position, individual, organization, or classes thereof, having an interest, right, share, or claim, in an entity of interest.

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**EXAMPLE:** End users, operators, acquirers, owners, suppliers, architects, developers, builders, maintainers, regulators, taxpayers, certifying agencies, and markets.

**SOURCE**: ISO/IEC/IEEE 42010:2022, Clause 3.17

### **3.1.56.** stakeholder perspective PREFERRED

Way of thinking about an entity of interest, especially as it relates to concerns.

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**SOURCE**: ISO/IEC/IEEE 42010:2022, Clause 3.18, modified — Both the Example and Note 1 to entry have been removed.

### **3.1.57.** trust PREFERRED

An assured reliance on the character, ability, strength, or truth of someone or something.

**EXAMPLE:** Trust is required to enable anonymized data to be shared among *Spatial Web Nodes* (3.1.54) privately and securely.

### **3.1.58.** vector space PREFERRED

Type of space composed of *dimensions* (3.1.44) where each *dimension* (3.1.44) is the set of real numbers.

**Note 1 to entry:** Vector space is a type of *HYPERSPACE* (3.1.16), and *Euclidean space* (3.1.45) is a type of vector space.

## 3.2. Abbreviated terms

| | |
|---|---|
| **AI** | artificial intelligence |
| **API** | application programming interface |
| **AR** | augmented reality |
| **BFO** | basic formal ontology |
| **CRS** | coordinate reference system |
| **CRUD** | create, read, update, and delete |
| **DGGS** | Discrete Global Grid System |
| **DLT** | distributed ledger technology |
| **FAIR** | Findable, Accessible, Interoperable, and Reusable |
| **glTF** | GL Transmission Format |
| **IIC** | Industry IoT Consortium |
| **IoT** | Internet of Things |
| **MIME** | Multipurpose Internet Mail Extensions |
| **M2M** | machine to machine |
| **OGC** | Open Geospatial Consortium |
| **OWL** | Web Ontology Language |
| **RDF** | Resource Description Framework |
| **SHACL** | Shapes Constraint Language |
| **SKOS** | Simple Knowledge Organization System |
| **SPARQL** | SPARQL Protocol and RDF Query Language |
| **SWE** | Sensor Web Enablement |
| **UDG** | Universal Domain Graph |
| **UDT** | Urban Digital Twin |
| **VC** | verifiable credentials |
| **VR** | virtual reality |
| **WoT** | Web of Things |
| **W3C** | World Wide Web Consortium |

| | |
|---|---|
| **XR** | collective reference to both AR and VR |
| **ZKP** | zero-knowledge proof |

# 4. Spatial web standards

## 4.1. Spatial Web concept

This document provides the design for the Spatial Web system by specifying requirements for the interoperability and governance of cyber-physical systems at (a potentially global) scale. A networked communications system constructed according to these requirements enables all statements and interactions of the physically-oriented, socially-constructed world to be universally represented in a way that makes them amenable to computational modeling and, where applicable, simulation and automation. The system design includes a shared and linkable knowledge domain architecture (“Architecture”), a common language with which to describe domain elements and their interrelationships, a method for querying and updating the states of those elements (“Protocol”), and the ability to permission access and control of that method (“Governance”). Collectively we refer to these specifications as the Spatial Web Standards (“Standards”).

The Standards are generalizable across networks and systems, and provide substantial value over existing standards. Such value comes from the combinatorial nature of the standards as a system. Prior to the present specification, universally-applicable, common standards with which to enable the interoperation and ensure governance of multiple, disparate cyber-physical systems did not exist.

The present specification is comprehensive, seeking to encompass an entire, emerging ecosystem and reflect the trends and needs which drive its development, including but not limited to the following:

- The increasingly graph-like nature of global data
- The opportunity for automation and autonomic activities using context-aware, cognitive artificial intelligence (AI)
- The need for composable systems and applications including the governance of such systems
- The intrinsic need for secure transactions
- The rise of machine-learning and neural network computation and edge computing
- The need for explainable AI and robotic governance
- The rise of IoT and sensor mesh

For further background on the emerging ecosystem and trends, see The Spatial Web.

## 4.2. Socio-technical standards

The Spatial Web is a socio-technical system of systems. Development of the Spatial Web must address both technological as well as sociological considerations. Socio-technical standards integrate and balance the technical, social, physical, and legal use of technology. This Spatial Web standard is a socio-technical standard.

The need for socio-technical standards to govern the development of Autonomous Intelligent Systems (AIS) has been previously identified. [96] identified the need for early incorporation of socio-technical standards as crucial for aligning AIS with human values, intentions, and understanding, and for reducing the risk of behaviors understood by stakeholders to be undesirable. NIST SP 1270 called for a “broad set of disciplines and stakeholders” and warned against an over-reliance on purely technical solutions because such an approach ignores the importance of human, organizational, and societal values and behaviors in the design, deployment, and use of technology. [93] called for incorporating pertinent laws, rules, and regulations as a baseline level of management, while also incorporating ethical considerations by drawing upon interdisciplinary knowledge.

As a socio-technical standard, the normative clauses of this document establish a Spatial Web governance framework that balances the following core needs:

1. A shared understanding of meaning and context between humans and AIs
2. Explainability of AI systems, enabled by the explicit modeling of their decision-making processes
3. Interoperability of models and data that enable universal interaction and collaboration across organizations, networks, and borders
4. Compliance with diverse local, regional, national and international regulatory demands, cultural norms and ethics
5. Authentication and credentialing, to help ensure compliance and potential control over critical activities, with privacy, security, identity and transparency embedded by design

Socio-technical standards allow Spatial Web agents, including AI agents, to become trustworthy, to network, and to participate in governance, while also granting those who manage agents the ability to define the desired level of human oversight and involvement.

## 4.3. System architecture standard

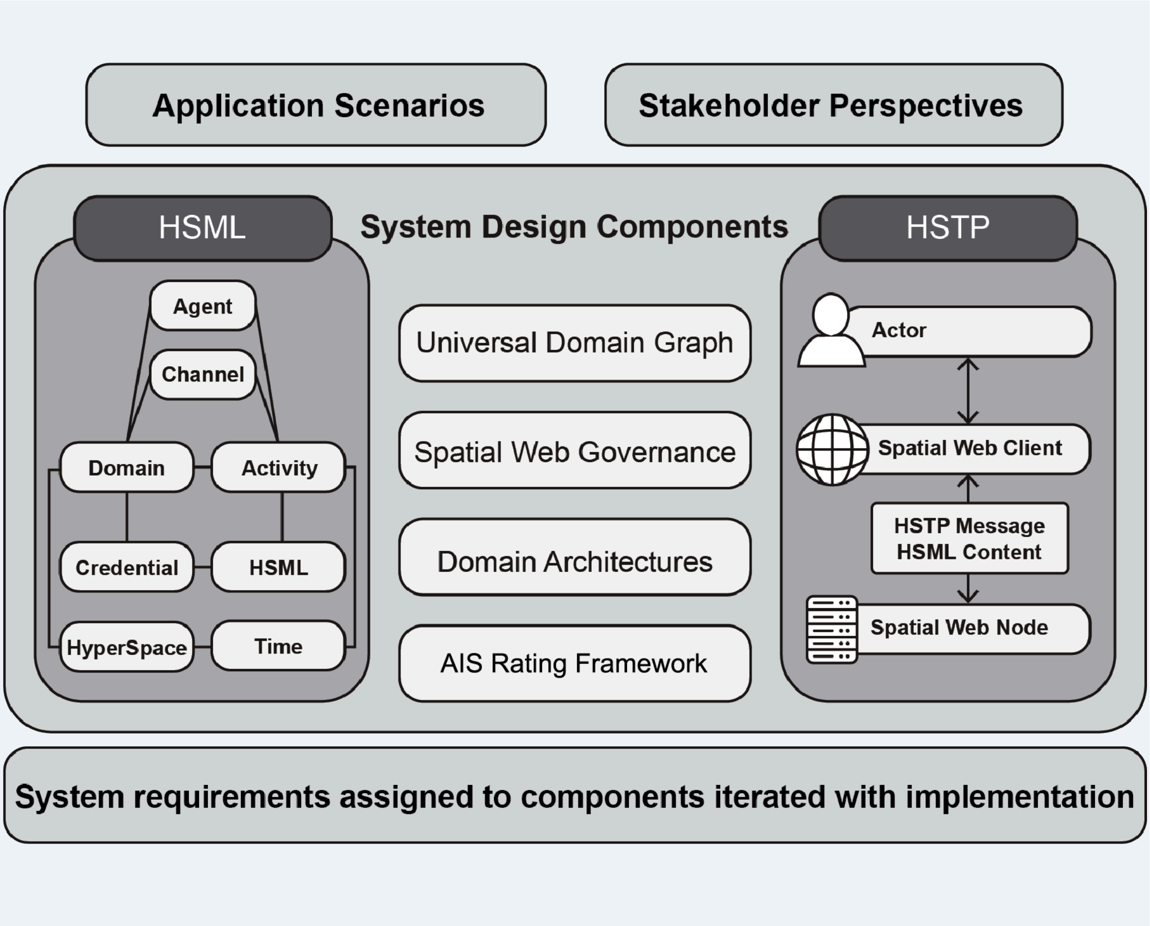
This document provides an architectural design of the Spatial Web System (See Figure 1). The Spatial Web is a distributed information system composed of computing nodes that interact using HSTP and HSML. The system design identifies requirements to be addressed in the development of the system components. The requirements in this specification are identified by examining stakeholder perspectives and application scenarios. By design synthesis, architecture components include a Hyperspatial Modeling Language (HSML), Hyperspatial Transaction Protocol (HSTP), Spatial Web Nodes and associated use cases, and other components. The coherence of the design is demonstrated by the use cases meeting the needs of the scenarios and resulting in requirements for the components as compliance targets.

The engineering approach to implement the system design is based on iterative development practices ([104]). The application scenarios show expected value of the system based on capabilities offered by a set of emerging technologies. To meet the scenarios, elements of the architecture are synthesized. Use cases show how the architecture elements will achieve the scenarios. Implementation of the architecture elements proceeds through iterations of implementation, specification, and architecture refinement. This iterative development leads to a mature system concept and implementation requirements. The iterative approach provides a grounded expectation that the benefits stated in the scenarios will be achieved by the Spatial Web implementation.

This architecture design specification defines requirements for architecture elements. To support iterative development, the requirements are assigned to compliance targets. Requirements of this Spatial Web conceptual model shall be met by the compliance targets as listed in Annex A.

- HSML
- HSTP
- Universal Domain Graph
- Spatial Web Governance
- Domain Architectures
- AIS Rating Framework

**FIGURE 1:** System architecting process overview



# 5. Value for stakeholders

## 5.1. Guiding principles

This document defines the Spatial Web architecture. The architecture for a system includes all the fundamental concepts of the system and its environment along with guiding principles for the realization and evolution of the system. The guiding principles of the Spatial Web are shown in Table 1.

**TABLE 1:** Guiding principles of the Spatial Web

| Principle | Description |
|---|---|
| Spatiality | Representing information as locations and relations in hyperspace with well-defined metrics enables cognitive computing to be performed based on context. |
| Ownership | Users can own their data and digital property and choose with whom they share this data. Moreover, they are able to retain control of it when they leave a given service provider. |
| Security | Secure data collection, transmission, and storage enables interactions and transactions with virtual and physical assets between any user within and across any space—physical or virtual. |
| Privacy | Individual control, trust, and security utilizing cryptographically-secured and decentrally-stored digital identity enables “trustless” complete interactions and transactions with anonymity and auditability. Previously the exchange of personal data and layers of verification were required. |
| Trust | Trust is based in reliable real-time, permission-driven validation of all users, assets, and spaces and their interactions with certifiable and verifiable records that validate various proofs of ownership, activity, traceability, and rights. |
| Interoperability | Multi-user interoperability provides searchability, viewability, interaction, transaction, and transportation of any asset or user within or across any spaces. Seamless user navigation and asset transfer is enabled within and between spaces across devices, operating systems, and locations. Governance is facilitated by the nested structure of domains. |
| Responsibility | Creating technology in a manner guided by upholding ethical principles of inclusivity, transparency and cooperation with the goal of creating a better world for all humanity. |

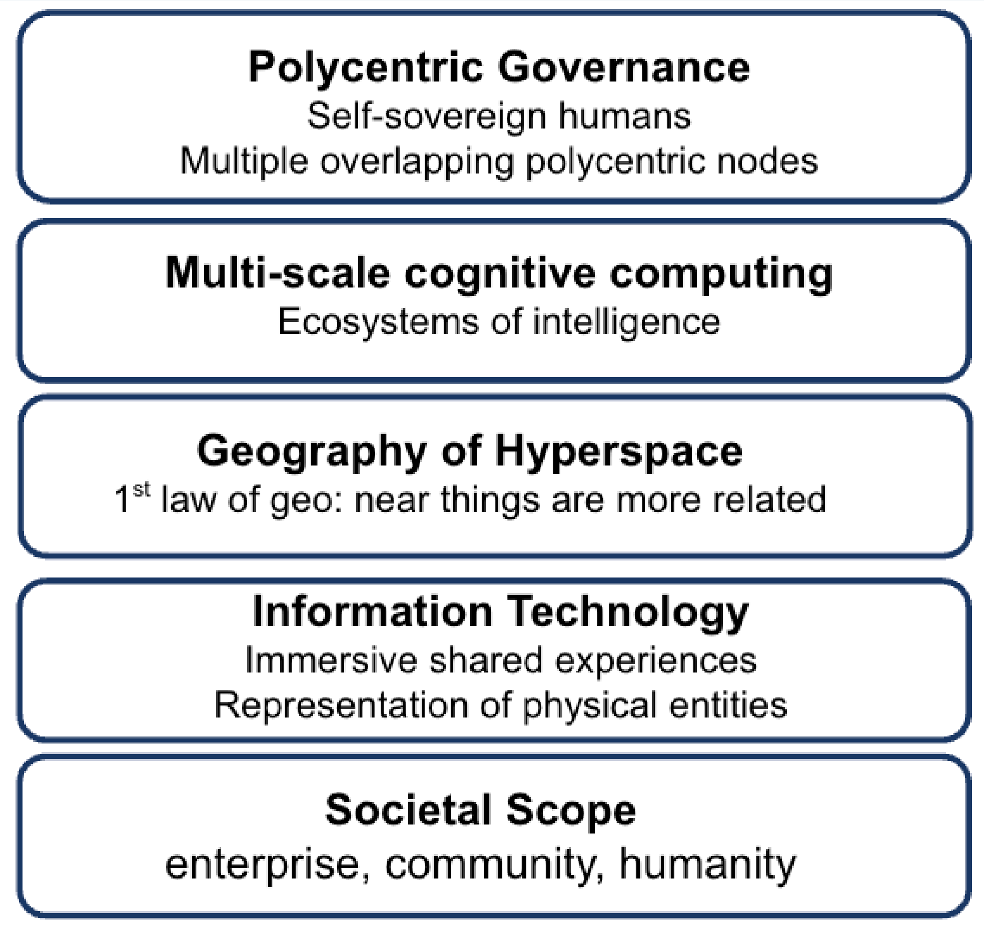
## 5.2. Stakeholders

### 5.2.1. Overview of stakeholder perspectives

Stakeholders are parties with direct or indirect interests in the Spatial Web. Stakeholder interests in the Spatial Web include matters of relevance or importance to stakeholders. Stakeholder interests include but are not limited to items of concern to the public at large as well as interests of organization. In some cases, specific organizations serve as surrogates in representing larger stakeholder perspectives.

Stakeholder perspectives are grouped as in Figure 2. Each stakeholder perspective concludes with requirements for the Spatial Web. The requirements include consideration of and building on stakeholder perspectives and resources. For example, referencing standards from a stakeholder organization can be a resource to the Spatial Web.

**FIGURE 2:** Summary overview of stakeholders of scenarios



## 5.2.2. Societal stakeholders

### 5.2.2.1. Overview

The societal stakeholders in the Spatial Web include enterprises, communities, and all of humanity. Enterprises are private groups that use the Spatial Web to conduct activities essential to the enterprise's objectives. Communities may be public or membership organizations that use the Spatial Web to support or provide services to community members. At the largest scope, the open Spatial Web serves all of humanity, similar to the open Internet.

The Spatial Web takes into consideration socio-technical standards established by the United Nations, e.g., the Universal Declaration of Human Rights (UDHR). The UN established the UDHR [80] to recognize the inherent dignity and equal and inalienable rights of all members of the human family as the foundation of freedom, justice and peace in the world.

#### 5.2.2.2. Requirements and recommendations for societal stakeholders:

- HSML shall support deployment and management of the Spatial Web by operations within organizations with defined secure boundaries, such as enterprises or communities.
- Spatial Web Governance shall consider the Universal Declaration of Human Rights as established by the United Nations.

### 5.2.3. Information and communication technology providers

#### 5.2.3.1. Overview

Information and communication technology (ICT) covers all technical means used to handle information and aid electronically mediated communications. This includes both computer and network hardware, as well as software. The Spatial Web is dependent upon ICT and the providers of ICT. Use of open standards for ICT is a strategy of the Spatial Web. While ICT includes many technologies, three areas of ICT are addressed in the remainder of this clause as vital to the Spatial Web: Virtual representations of physical entities, immersive shared experiences, and AI.

#### 5.2.3.2. Virtual representations of physical entities

#### 5.2.3.2.1. Overview

The Spatial Web interacts with real-world people, places, and objects via the Internet using HSTP, HSML and a Universal Domain Graph (UDG). Developments that provide interactivity with real-world people, places, and objects based on protocols and data models include IoT, Web of Things (WoT), Sensor Web, and Industry 4.0. Each of these systems represents people, places, and things as Internet entities, provides protocols for interaction with the real world through sensors and actuators, and anticipates autonomy of some of the connected entities.

An objective of these stakeholders is to build IoT systems in such a way that the entities are able to exchange information and mutually use the information in an efficient way as described in (ISO/IEC 21823-1:2019).

ICT Stakeholders relevant to the coupling of physical things with the Spatial Web include:

- The IEEE is developing standards for IoT and, more generally, for sensors. IEEE defines the Internet of Things as "a system of entities (including cyber-physical devices, information resources, and people) that exchange information and interact with the physical world by sensing, processing information, and actuating IEEE Std 2413™-2019.
- The W3C Web of Things (WoT) Working Group seeks to enable interoperability across IoT platforms and application domains using the Web. The WoT standards and recommendations seek to preserve and complement existing IoT standards and solutions. A key concept of WoT is a "Web Thing" defined as "an abstraction of a physical or a virtual entity whose metadata and interfaces are described by a WoT Thing Description in W3C REC-wot-architecture11-20231205.

- The Open Geospatial Consortium (OGC) Sensor Web Enablement (SWE) is a framework of open standards for Web-connected sensors and sensor systems. SWE standards provide an infrastructure for sharing, finding, and accessing sensors and their data across different applications. SWE and the SensorThings API provide an open, geospatial-enabled way to interconnect IoT devices, data, and applications over the Web.
- oneM2M standards address interoperability for Machine-to-Machine and IoT technologies. oneM2M specifications provide a framework to support applications and services such as the smart grid, connected car, home automation, public safety, and health.
- The [66] addresses cyber-physical systems of entities in the physical world that can be the subject of sensing and/or actuating. The IIC addresses industries that leverage IoT, including energy, sustainability, healthcare, manufacturing, supply chain, mining, retail, smart cities, and transportation.
- The [60] provides guidance, reference implementations and open source software for digital twin technology. The DTC defines a Digital Twin as “a virtual representation of real-world entities and processes, synchronized at a specified frequency and fidelity.”

#### 5.2.3.2.2. Requirements and recommendations for virtual representations of physical entities

- HSML shall enable virtual representation of physical entities based on the principles of spatialization and trust 5.1.
- HSTP shall be interoperable with IoT systems in such a way that the entities are able to exchange information and mutually use the information in an efficient way consistent with IEEE Std 2413™-2019.
- Domain-specific architectures shall be consistent with IEEE Std 2413™-2019.
- HSML shall enable digital representation of physical entities synchronized at frequencies and fidelity needed for applications based on considerations of OGC 07-165r1, W3C REC-wot-architecture11-20231205, [73], [123].
- HSTP shall provide interoperability of observations coming from physical sensors based on considerations of OGC 07-165r1, W3C REC-wot-architecture11-20231205, [73], [123].
- HSTP shall provide interoperability of robotics and other physical actuator devices.
- UDG shall enable discovery of the virtual representation of physical entities.
- HSML shall be able to represent real-time data from sensors and actuators. The data may subsequently be used to control remote processes.

### 5.2.3.3. Immersive shared experiences

#### 5.2.3.3.1. Overview

An immersive experience is three-dimensional wherein a person’s engagement with the environment is enhanced, including socializing with others and interacting with objects and assets within the space in which the user is immersed. The Spatial Web enables immersive experiences that use a mix of representations of the physical world and the virtual world. It is anticipated that the user experiences feature a sense of immersion, real-time interactivity, user agency, and interoperability across platforms.

According to ISO/IEC 18039:2019, Mixed and Augmented Reality (MAR) systems use a mixture of representations of physical world data and virtual world data as its presentation medium.

ICT Stakeholders relevant to the content, interactivity and other elements for producing immersive shared user experiences with the Spatial Web include the following:

- The [69] aims to encourage and enable the timely development of open interoperability standards essential to an open and inclusive Metaverse.
- The [78] seeks to bring high-performance Virtual Reality (VR) and Augmented Reality (AR) (collectively known as XR) to the open Web via APIs to interact with XR devices and sensors in browsers.
- The [67] analyzes technical requirements of the metaverse to identify fundamental enabling technologies in areas from multimedia and network optimization to digital currencies, Internet of Things, digital twins, and environmental sustainability.
- The [76] drives development of open and interoperable AR Cloud technology, data and standards to connect the physical and digital worlds.
- The [72], developed with the Open AR Cloud, standardizes geographic pose: a geographically-anchored pose with 6 degrees of freedom referenced to one or more standardized Coordinate Reference Systems (CRSs).
- The [125] activity seeks to simplify AR/VR software development, enabling applications to reach a wider array of hardware platforms without having to port or re-write their code and subsequently allowing platform vendors supporting OpenXR access to more applications.

### 5.2.3.3.2. Requirements and recommendations for immersive shared experiences:

- HSML shall provide representation of physical and virtual entities using 3D encoding standards, i.e., glTF, USD or Web3d.
- HSML shall enable the use of OGC 21-056r11.
- HSML shall enable discovery of physical and virtual entities via discovery services.
- HSTP shall enable discovery of physical and virtual entities via discovery services.
- UDG shall enable discovery of physical and virtual entities via discovery services.
- HSML shall provide an open, multi-domain universal domain graph suitable for immersive shared experiences across multiple Spatial Web nodes and domains.
- HSML representation of entities shall include multiple modes of sensing, e.g., vision, touch, and smell.
- HSML hyperspace semantic modeling, extending beyond four spatial-temporal dimensions, shall be suitable for immersive experiences.

#### 5.2.3.4. Artificial intelligence (AI)

##### 5.2.3.4.1. Overview

AI is an overarching concept that encompasses an array of ICT-based capabilities that make predictions, recommendations, or decisions influencing real or virtual environments. AI-enabled systems perceive real and virtual environments, abstract such perceptions into models through analysis in an automated manner, and use model inference to formulate options for information or action.

ICT Stakeholders relevant to the application of AI to the Spatial Web include the following:

- [68] develops standards in the area of AI
- [64] develops standards that enable the governance and practice of AI as related to computational approaches to machine learning, algorithms, and related data usage.

##### 5.2.3.4.2. Requirements and recommendations for AI

- HSML shall enable representation and messaging of AI AGENTs in the Spatial Web.
- Spatial Web Governance shall address societal-technical considerations regarding AI as defined in standards developed by [68] and [64].

### 5.2.4. Hyperspace geography

#### 5.2.4.1. Overview

Hyperspace geography is an ecology of humans and autonomous agents interacting as complex adaptive systems in physical space and extended to hyperspace. The First Law of Geography states that “everything is related to everything else, but near things are more related than distant things” [89]. Traditional geography calculates this distance in physical space. The Spatial Web extends the First Law by calculating distance in hyperspace. In hyperspace, entities may be physically distant while being strongly coupled in other dimensions.

Geographical concepts extended to hyperspace can be used to address resilience and sustainability. By identifying strong relations between entities that are close in hyperspace but may be physically distant, the Spatial Web defines hyperspace geography. Such a hyper-geography provides new perspectives on social and societal interactions and trade-offs between local and global sustainability.

Stakeholder communities who are addressing issues relevant to the Spatial Web concerning the extension of geography to hyperspace include the following:

- Geographic information concerns features of the earth and its atmosphere, and of human activity, as it affects and is affected by these, including the distribution of populations and resources, land use, and industries. Organizations like ISO TC 211 and OGC publish standards in the field of digital geographic information. Geographic features are a key concept for modeling objects and phenomena that are directly or indirectly associated with a location relative to the Earth.

Features in geographic information play a role similar to DOMAINS in the Spatial Web (see 6.3 for a description of how DOMAINS represent real world ENTITIES). Geographic information uses Spatial Referencing Systems (SRS) for location referencing including Coordinate Reference Systems, Discrete Global Grids, and civic addressing. The Spatial Web extends SRSs to include graph referencing systems.

- Sustainable earth system science is a key application of hyperspace geography. To support sustainability, the geographic and earth system communities are creating systems to integrate observations and other data using common standards. Digital twins of the Earth are being constructed as replicas of various aspects of the Earth's system to monitor, analyze, predict, and safeguard various aspects including climate dynamics, natural disasters, food and water security, ocean circulation, and biodiversity.
- Sustainable society is a key application of hyperspace geography. These developments are merging spaces described entirely in digital terms with physical space, to balance economic advancement with the resolution of social problems by providing goods and services that granularly address manifold latent needs regardless of locale, age, sex, or language" ([111]).
- The UN's Sustainable Development Goals are a call for action for sustainable development to provide a shared blueprint for peace and prosperity for people and the planet, now and into the future.
- Smart Cities bring operational efficiency, sustainability and resilience to the city infrastructure to improve its citizens' quality of life. ISO 37101:2016 helps communities define their sustainable development objectives and implement strategies to achieve them. IEC SRD 63188 defines a Smart City as "a city (re)built as a digital system to integrate by design various views on the city for better life of its citizens, easier doing of business and sustainable improvement."

### 5.2.4.2. Requirements and recommendations for hyperspace geography:

- HSML shall define representations of hyperspace which include representations of physical space.
- HSML shall provide a globally unique index for any geographic domain listed in the Spatial Web using a DGGS as defined in ISO 19170-1.
- HSML shall provide for metrics in the compound space of physical dimensions and semantic dimensions.
- HSML shall enable the application of information from diverse domains, e.g., geographic, digital earth, economic and social systems, in order to assess the complex interactions of relevant systems.
- Domain-specific architectures for Smart Cities shall extend the Spatial Web using concepts from IEC SRD 63188.

### 5.2.5. Multi-scale cognitive computing

#### 5.2.5.1. Overview

The Spatial Web plays the role of a collective nervous system for a smart infrastructure. It hosts cognitive computing, i.e., inference (perception, learning, action selection). By combining and abstracting distributed information, the Spatial Web enables the formation of complex ideas and facilitates decision-making.

Cognitive computing occurs at multiple scales in the Spatial Web. Individual nodes of the Spatial Web may host cognitive computing functions. Networks of nodes may also collectively perform emergent cognitive computing functions.

[85] describes the Spatial Web as a cyber-physical ecosystem of natural and synthetic sense-making, in which humans are integral participants—in some cases referred to as "shared intelligence". HSML enables such an ecosystem of intelligences in the first — and key — step towards this ecology.

Stakeholder communities who are addressing issues relevant to the Spatial Web multi-scale cognitive computing include:

- The Semantic Web consists of Ontologies, Linked Data, and Knowledge Graphs. The W3C describes the "Semantic Web" as a "web of data" using ontological technologies such as Resource Description Framework (RDF), SPARQL Protocol and RDF Query Language (SPARQL), Web Ontology Language (OWL), Shapes Constraint Language (SHACL), and Simle Knowledge Organization System (SKOS). Ontologies have been successful using the Basic Formal Ontology (BFO) which is a top-level ontology that provides interoperability among domain ontologies ISO/IEC 21838-2:2021. Linked open data activities define shallow schemas, used for web applications and are aimed to be less rigid than ontologies. Knowledge graphs exist both as open resources and as proprietary resources for services e.g., web searching. In general, knowledge graphs describe objects of interest and the connections between them. Constraints on the links in knowledge graphs may be enforced using a schema or ontology. The Spatial Web defines an HSML Ontology and a Universal Domain Graph based on semantic web technologies.
- AI is described as a system where computers or other machines have the capacity to exhibit or simulate intelligent behavior (IEEE Std 7010™-2020). An Artificial Intelligence System is an "engineered system that generates outputs such as content, forecasts, recommendations or decisions for a given set of human-defined objectives (ISO/IEC 22989:2022). AI Systems are built using a combination of cognitive automation, machine learning, reasoning, hypothesis generation and analysis, natural language processing and intentional algorithm mutation. These functions and abilities enable the system to produce insights and analytics at or above human capacity (IEEE Std 2755™-2017). AI Systems represent knowledge defined by (ISO/IEC 22989:2022) as "abstracted information about objects, events, concepts or rules, their relationships and properties, organized for goal-oriented systematic use." Example: Research on AI includes aspects such as "learning, recognition and prediction", "inference, knowledge and language" and "discovery, search and creation" and "active inference." Spatial Web AGENTs may be implemented using AI. (See also 5.2.3.4.2)

- Multi-scale computing is cognitive computing at multiple scales in the Spatial Web. AI systems are hosted in Spatial Web nodes ranging from small embedded computers, e.g., tinyML, up to supercomputing scale systems expanding the range of big data. Networks of Spatial Web nodes can coordinate as AGENTs to achieve a broader scale of AI.
- Ecosystems of intelligence are core to the Spatial Web. Intelligence can be understood as the capacity to accumulate evidence for a generative model of a sensed world. Formally, this corresponds to maximizing model evidence, via belief updating over several scales: i.e., inference, learning, and model selection [85]. Operationally, this self-evidencing can be realized via message passing or belief propagation on a factor graph. This same imperative underwrites belief sharing in ensembles of agents, in which certain aspects of each agent's generative world model provide a common ground or frame of reference. Active inference addresses this ecology of belief sharing—leading to a formal account of collective intelligence that rests on shared narratives and goals. Based on this perspective, levels of multi-scale cognitive computing in a Spatial Web ecosystem of Agents can be defined. The ensuing levels can be used for governance in the Spatial Web.

### 5.2.5.2. Requirements and recommendations for multi-scale cognitive computing:

- HSML shall enable a multi-scale, distributed universal knowledge graph that supports reasoning.
- HSML shall provide cross-domain interoperability which may include the use of cross-domain ontologies like the Basic Formal Ontology ISO/IEC 21838-2:2021.
- HSML shall enable the reuse of semantic terminology across domains.
- HSML may use RDF, OWL and SHACL for semantic modeling.
- Domain-specific architectures should reuse existing semantic terms from other domains.
- HSTP shall enable requests for cognitive computing such as for inference (perception, learning, action selection).
- HSTP shall enable machine learning operations on sensor data, i.e., observations and measurements, accessible in the Spatial Web.
- HSTP shall enable machine learning by providing interoperability of AGENT nodes using information accessible in the Spatial Web.
- HSTP shall enable message passing between nodes with AI functionality.
- AIS Rating Framework shall enable ecosystems of intelligence across the Spatial Web which may use [85] to enable levels of multi-scale cognitive computing.
- Spatial Web Governance shall enable multi-scale cognitive computing and shared intelligence, and may be based on [85].

## 5.2.6. Polycentric governance

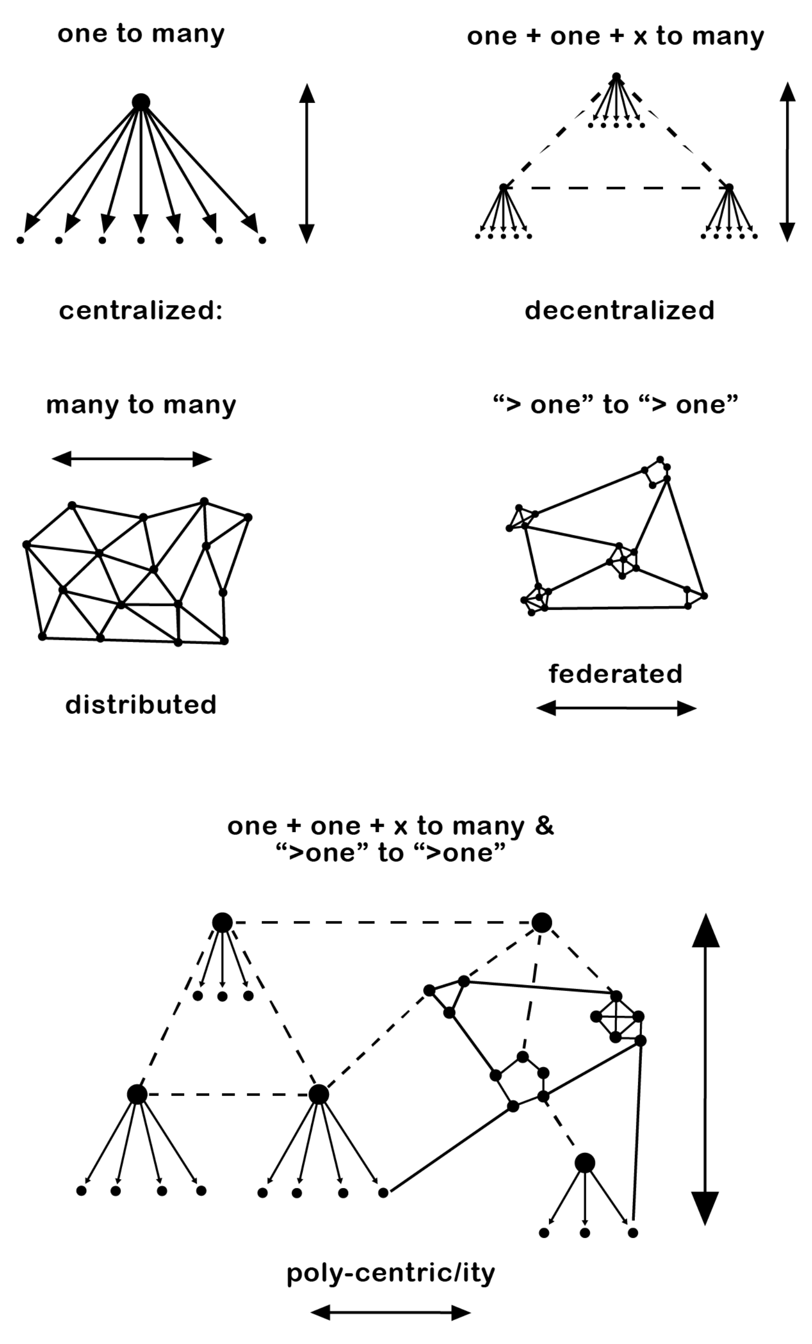
### 5.2.6.1. Overview

The Spatial Web is an information infrastructure for society. As such, societal issues will need to be addressed in the governance of the Spatial Web, e.g., privacy, location information, trust, and self-sovereign identity.

This perspective identifies stakeholder communities who are addressing governance issues relevant to the Spatial Web. IEEE Std 7002™-2022 defines governance as the process of establishing and enforcing strategic goals and objectives, organizational policies, and performance parameters. ISO 30401:2018 identifies governance as an enabler of knowledge management by providing strategy, expectations and means of ensuring the knowledge management systems is working in alignment with objectives. Considering that the Spatial Web is a network of Domains comprising multiple overlapping polycentric nodes of nested decision making, each of which operates with a degree of autonomy, then a polycentric governance framework is applicable. Several examples of governance for stakeholder concerns are addressed in the next clause.

To be a "social" agent is to associate with multiple actors in a full range of relationship forms [87]. In polycentric systems Figure 3, diverse types of agents have overlapping realms of responsibility and functional capacities. Power in these network systems does not radiate out from a fixed center, but resides in 'heterogeneous assemblages, distributed networks and circuits' that span the globe [82]. Power in polycentric systems is not centralized as it is distributed across diverse agents in a global network. AGENTs within the Spatial Web commons are not isolated individuals connected in a network; rather, they are communities of AGENTs that may constitute, enact, sustain and co-create the network.

**FIGURE 3:** Polycentric governance



Stakeholder concerns addressed by Spatial Web polycentric governance include the following:

- Governance by legal authorities. Governments define legal requirements for Artificial Intelligence. Governance of the Spatial Web, therefore, requires tracking and evaluating the impact of existing or emerging laws to determine their applicability to the Spatial Web. An example of relevant laws is the [62]. In May 2023 this communique called for AI governance based on standards by committing to “advancing multi-stakeholder approaches to the development of standards for AI, respectful of legally binding frameworks, and recognize the importance of procedures that advance transparency, openness, fair processes, impartiality, privacy and inclusiveness to promote responsible AI.”"

- Governance for ethical development. The IEEE Global Initiative on Ethics in Autonomous and Intelligent Systems seeks “to ensure every stakeholder involved in the design and development of autonomous and intelligent systems is educated, trained, and empowered to prioritize ethical considerations so that these technologies are advanced for the benefit of humanity. IEEE Std 7000™-2021 provides guidance on integrating ethical and functional requirements to mitigate risk and increase innovation in systems engineering design and development. [63] provides guidance on algorithmic bias considerations for protocols to avoid negative bias, including the use of subjective or incorrect interpretations of data like mistaking correlation with causation. IEEE Std 7007™-2021 provides an ontological standard for ethically-driven robotics and automation systems based on the Basic Formal Ontology.
- Governance for privacy. Messages transmitted on the Spatial Web will include Personally Identifiable Information (PII). The quantity and types of PII processed are increasing, as is the number of situations where domains need to cooperate regarding the processing of PII. Protection of privacy in the context of the processing of PII is a societal need, as well as the topic of dedicated legislation and regulation all over the world. Requirements and guidance for PII protection vary depending on the context of the domain, in particular where national legislation or regulation may apply. ISO/IEC 27701:2019 defines how this context can be understood and taken into account in a domain-specific, i.e., polycentric, manner. IEEE Std 7002™-2022 provides a methodological approach that specifies practices to manage privacy issues within the systems engineering life cycle processes. Polycentric governance can help domains identify and manage privacy risks to build innovative products and services while protecting each individual’s privacy. ([70])
- Governance of location information. Location information can be sensitive because PII can be gained based on the history of a person’s location. Legal requirements for handling location data are emerging spurred in part by recent activity on defining ethical handling of location data. An IETF Best Practice, IETF Best Practice, describes approaches for privacy-preserving location-based services on the Internet. The W3C Interest Group on Responsible Use of Spatial Data W3C responsible-use-spatial provides insight into relevant legislation and ethics guidelines, and also considers the principles of ethical sharing of location data.
- Governance for identity management. Identities and identity management are Spatial Web requirements 6.3.3.4. Spatial Web identities shall be decentralized. Identity management addresses the need to help ensure appropriate access to resources across increasingly heterogeneous technology environments and to meet increasingly rigorous compliance requirements.

#### 5.2.6.2. Requirements and recommendations for polycentric governance:

- Spatial Web Governance shall establish strategic goals and objectives, organizational policies, and performance parameters for governance of the Spatial Web.
- Spatial Web Governance shall establish a process to broadly gather stakeholder input regarding polycentric governance of the Spatial Web.
- Spatial Web Governance shall address PII, location information, and identity management.
- Spatial Web Governance shall include policy guidance for the distributed UDG system.
- Domain-specific architectures should define governance for their domains consistent with the Spatial Web governance.
- Spatial Web Governance should implement IEEE Std 7000™-2021.
- Spatial Web Governance should implement IEEE Std 7002™-2022.
- Spatial Web Governance should implement [63].
- Spatial Web Governance shall monitor emerging laws pertaining to Artificial Intelligence and, when applicable to the Spatial Web, observe and comply with those laws.
- Spatial Web Governance shall provide decentralized identity management.
- HSML shall include SWIDs that enable decentralized identity management.
- Domain-specific architectures shall design identity management that meet the requirements of the domain and are compliant with the Spatial Web system requirements.

## 5.3. Application scenarios

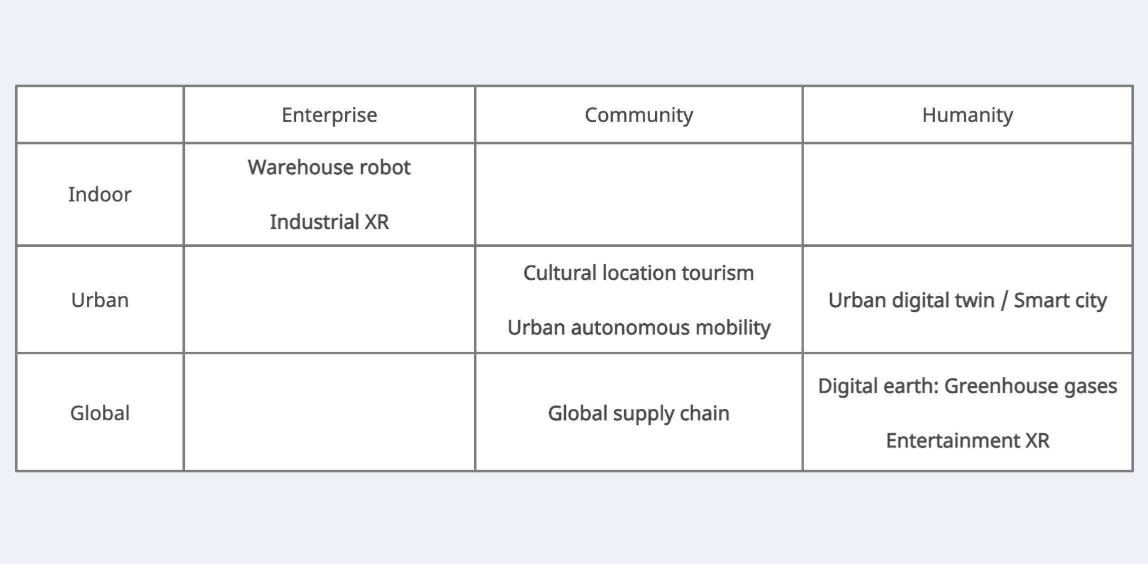
### 5.3.1. Overview

The scenarios in this clause show how the Spatial Web provides value to the stakeholders across a wide range of applications. Scenarios are written at a level that can be demonstrated for general interest. Scenarios in this section need not be as detailed as the use cases that drive code development in 7.4.

The scenarios address design elements described in further detail in other clauses, e.g., information model elements and queries, and distributed computing components at a high level. The scenarios use the terms and concepts from other clauses: HSML Elements (6.6), spatial web nodes (7.2), HSTP conceptual model (7.3), and distributed computing use cases (7.4). Terms in ALL CAPS are HSML elements.

Figure 4 is a table of a limited set of scenarios that cover the main topics of Spatial Web. The table is organized by spatial extent and societal extent. The six scenarios listed in the table are detailed in the following clauses.

**FIGURE 4:** Summary listing of scenarios



| | Enterprise | Community | Humanity |
|---|---|---|---|
| Indoor | Warehouse robot<br>Industrial XR | | |
| Urban | | Cultural location tourism<br>Urban autonomous mobility | Urban digital twin / Smart city |
| Global | | Global supply chain | Digital earth: Greenhouse gases<br>Entertainment XR |

## 5.3.2. Warehouse robot

1. Summary
   - An employee and a robot work together to retrieve a book from an automated warehouse bin and pack it for shipping. (see Figure 5)
2. Actors
   - Human employee of company
   - Robot operating in a warehouse
3. Context and pre-conditions
   - Employee (AGENT) is tasked with packing a book for shipment (ACTIVITY) that involves retrieving a book from an automated container bin in the warehouse.
   - A 3D spatial model of the indoor warehouse (SPACE) has been created in advance. The spatial model is a collection of HSML elements (and their connections) stored in a Spatial Web node for the company. The spatial model includes the coordinates of automated holding bins in the warehouse.
   - Robot (AGENT) is equipped to navigate the warehouse using a real-time location system for indoor positioning; and on-board vision sensors.
   - Automated holding bin uses advanced artificial intelligence and computer vision to select a book from a shelf, lift it, read the label, and place it on the robot.
   - Credentials in the scenario may include several claims, including identity, membership and capabilities (See Figure 21).
4. Scenario events
   - A CREDENTIAL is issued for the employee (AGENT) authorizing the employee to create a Pick (ACTIVITY) within the warehouse including tasking a robot (AGENT).
   - A CREDENTIAL is issued for the robot (AGENT) authorizing the robot to perform a Pick (ACTIVITY) within the warehouse including autonomous movement.

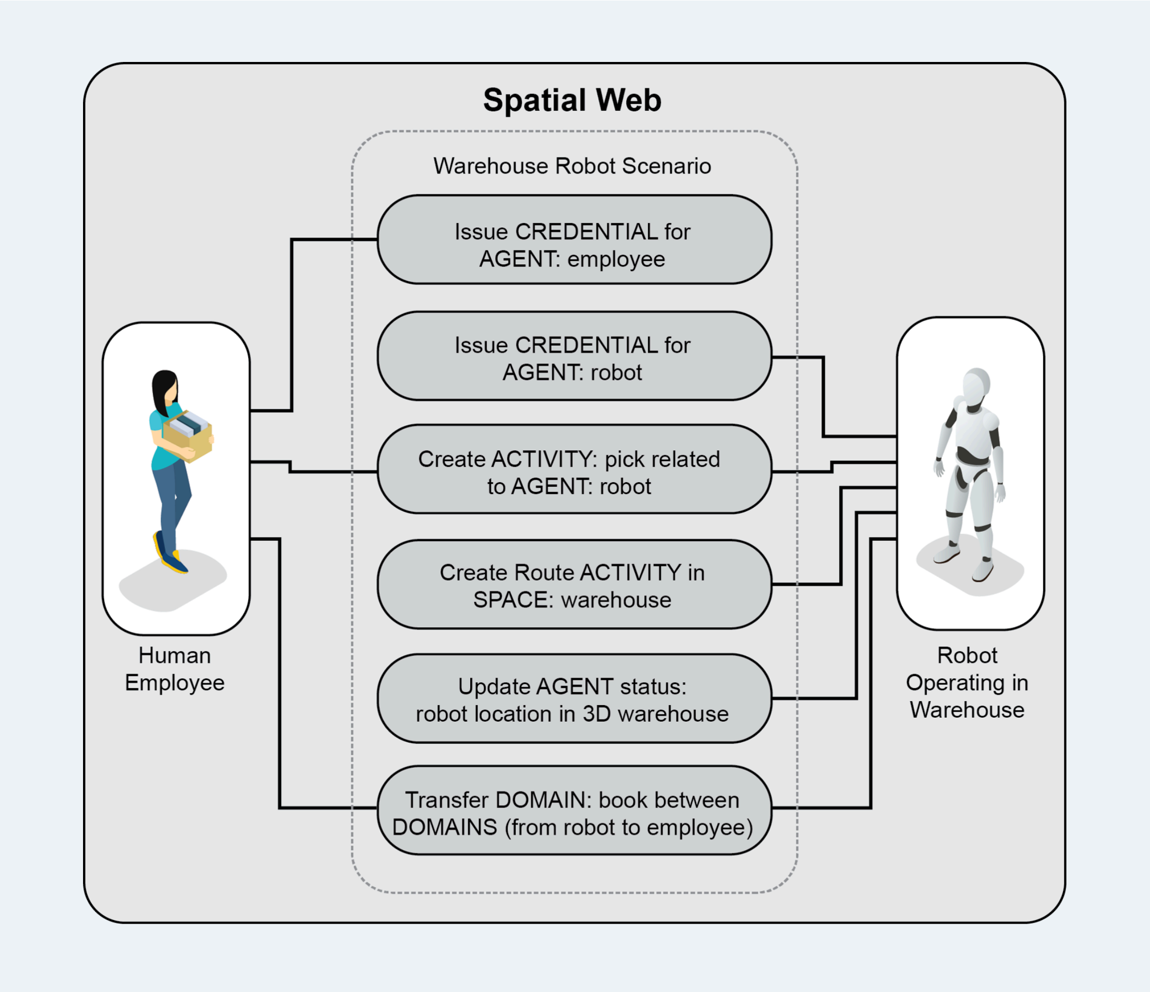
  - Employee creates a pick-and-pack (ACTIVITY) and tasks the Robot to perform the pick and deliver the book to the employee.
  - Robot receives pick-and-pack (ACTIVITY), identifies waypoints and prepares a route (ACTIVITY) in the warehouse SPACE.
  - Robot provides status updates as it performs the pick-and-pack:
    - Robot autonomously moves in a warehouse using perception and navigation technology, including obstacle avoidance based on fusion with an array of real time environmental sensors within the warehouse.
    - Robot moves safely through the warehouse, encountering humans along its route.
    - Robot interacts with the automated container bin and receives the book.
    - Robot moves to the location of the employee.
  - With the pick-and-pack activity completed the book (DOMAIN) is transferred from the robot (AGENT) to the employee (AGENT).

5. Results and post-conditions
   - Pick-and-pack ACTIVITY is completed

Bibliographic references relevant to the scenario:

- W3C REC-wot-architecture11-20231205
- [124]

**FIGURE 5:** Scenario diagram: Warehouse Robot



### 5.3.3. Industrial XR

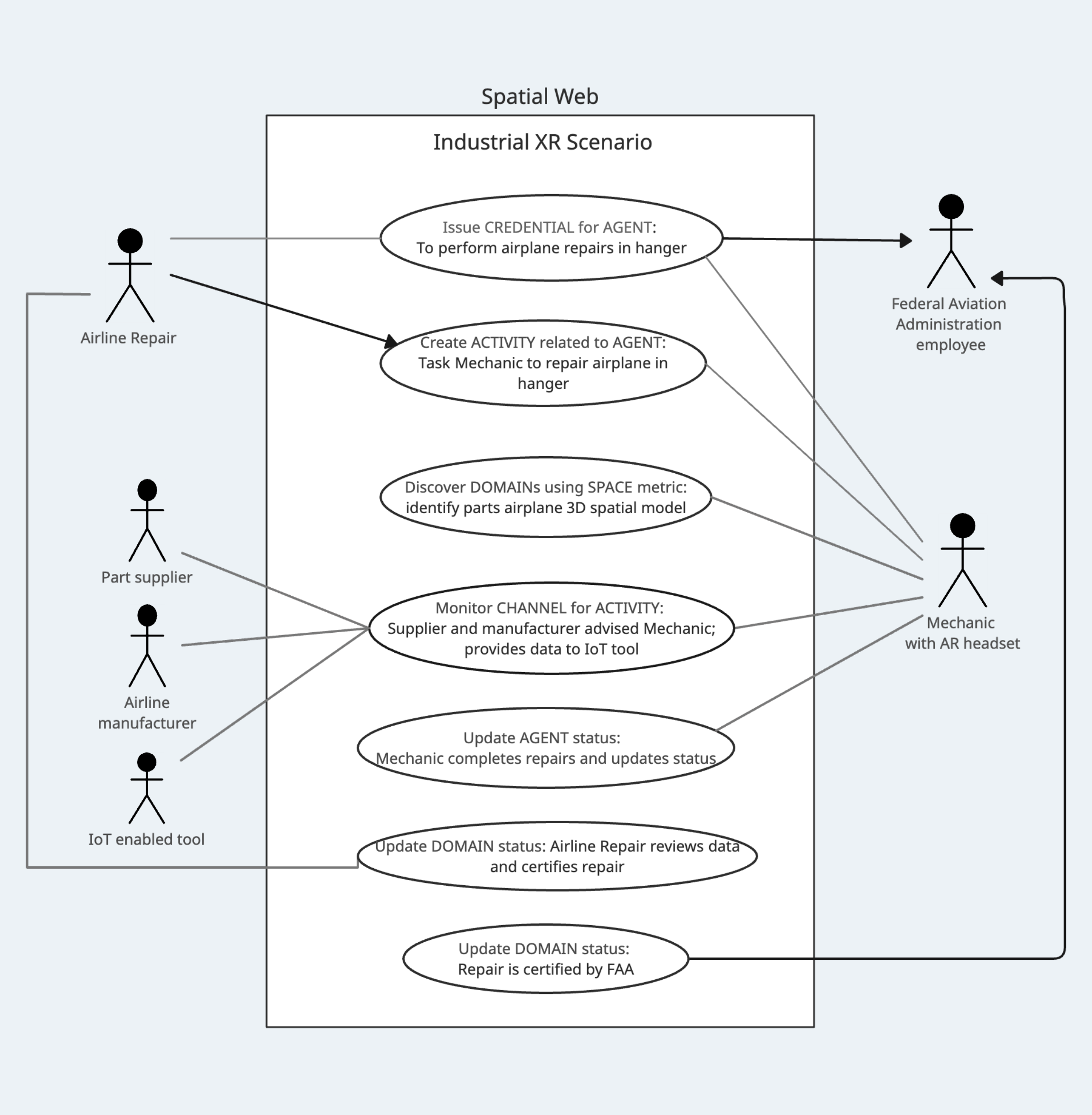
1. Summary
   - An airline mechanic can view digital content and workflows to assist their repair work (see Figure 6)
2. Actors
   - Airline Repair Inc
   - Mechanic with an AR headset
   - Commercial airline manufacturer
   - Federal Aviation Administration employee
   - Part supplier
3. Context and pre-conditions
   - A mechanic (AGENT) is tasked with making repairs (ACTIVITY) to an airplane’s landing gear.
   - The repair can only take place inside Airplane Repair Services hangar (DOMAIN).

  - The mechanic is wearing an AR headset.
  - The mechanic is using IoT enabled tools that provide location, 3D positioning and torque data.
  - A 3D spatial model of the airplane (DOMAIN) and all of its parts, systems and maintenance workflows have been predefined and created in advance. The 3D spatial model is a collection of HSML elements (and their connections) stored in a "Node Server" for the company.
  - Credentials in the scenario may include several claims, including identity, membership and capabilities (See Figure 21).

4. Scenario events
   - Federal Aviation Administration provides Airline Repair Inc with CREDENTIAL to operate and repair airplanes in their hangar
   - FAA provides the Mechanic with a CREDENTIAL authorization to complete repairs on airplanes in the United States
   - Airline Repair Inc provides CREDENTIAL to mechanic to complete repairs on airplanes within their hangar in the US
   - Airline Repair Inc creates an ACTIVITY to repair an airplane's landing gear at the company's hangar
   - The mechanic performs a query (SPATIAL) of the 3D model (DOMAIN) for the landing gear identifying components, repair history and repair workflows provided by the Airline and accessible by mechanic:
     - Mechanic approaches landing gear within the hangar and can view part data and guided workflow steps to safely complete the repair using spatially-enabled, AR headset.
     - Mechanic views the history of all previous repairs, who made them, when, where and why, along with videos of the repair work itself.
     - Mechanic views detailed 3D schematic of the parts and order them as needed from part supplier.
     - Mechanic decides they need assistance in the repair.
   - Mechanic creates a CHANNEL For the repair ACTIVITY:
     - Mechanic invites Part supplier and Airline manufacturer to join the channel (authorization not shown)
     - Mechanic calls in remote support from part supplier to aid in the repair; remote technician can view through mechanics AR headset and direct the mechanic to complete specific tasks through AR.
     - Airline Repair Inc system observes and records work being done by the mechanic to ensure it's properly and safely completed
     - Mechanic adds an IoT enabled tool to the channel (authorization not shown).
     - As the repair is completed, the IoT enabled tool reports the torque, position and location to ensure the right torque is being applied to the correct part at each step.

  - Mechanic completes the repair and updates the DOMAIN on all data recorded during the repair
  - Airline Repair quality checks the data and certifies the repair
  - Repair is remotely reviewed and certified by Federal Aviation Administration employee
5. Results and post-conditions
  - Repair ACTIVITY is completed
  - Spatial Web nodes contain data of the repair and certification

**FIGURE 6:** Scenario diagram: Industrial XR



## 5.3.4. Urban autonomous mobility

1. Summary

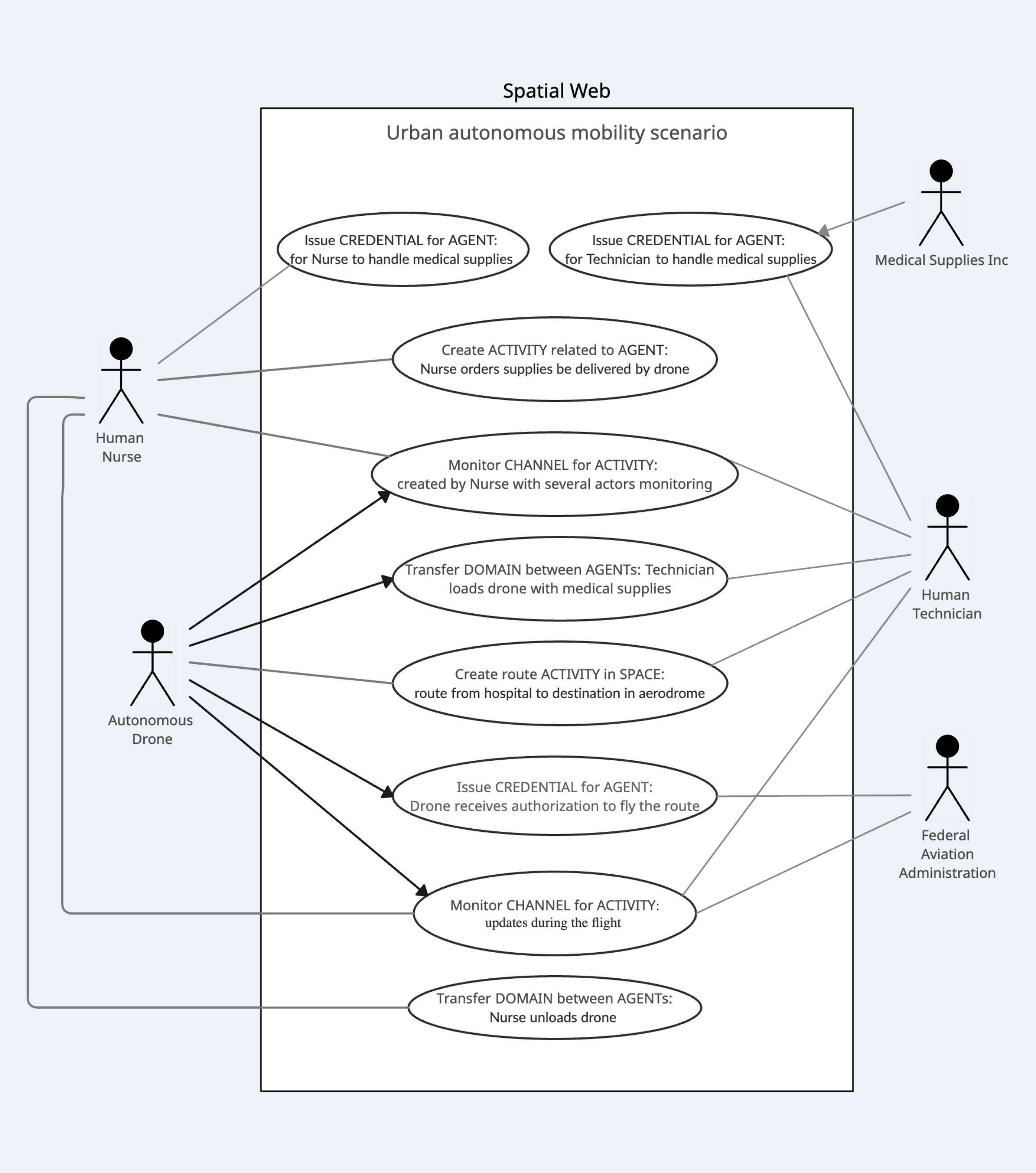
- An autonomous drone makes an emergency medical delivery across town to a hospital (see Figure 7).

2. Actors
    - Autonomous Drone (AGENT): Owned by Medical Supply Inc., is equipped for autonomous air deliveries.
    - Human Nurse (AGENT): Places and accepts the order for emergency medical supplies, authorized by City Hospital.
    - Human Drone Technician (AGENT): Loads the medical supplies onto the drone (AGENT), as authorized by Medical Supply Inc., and supervises the autonomous drone during its operations.
    - Federal Aviation Administration (FAA) Authority (AGENT): Governs federal aviation regulations, manages airspace and ACTIVITIES within the airspace, and issues necessary credentials for the drone technician (AGENT) and the autonomous drone (AGENT) for autonomous flight.
3. Context and pre-conditions
    - Nurse (AGENT) is tasked with ordering emergency supplies for a medical operation, authorized through a credential (CREDENTIAL) issued by City Hospital (DOMAIN).
    - Drone technician (AGENT) has a Remote Pilot Certificate (CREDENTIAL), which was issued by the FAA Authority (AGENT), in accordance with the requirements of the Federal Aviation Regulations (DOMAIN).
    - A predefined 3D spatial model (DOMAIN), encompassing the aerodrome (also known as an airfield), the hospital building, and the landing zone, has been created in advance. The aerodrome model (DOMAIN) is stored within a Spatial Web node for the company.
    - Autonomous drone (AGENT) has a registered list of Activities that it is capable of performing and has read-access permission to the aerodrome model (DOMAIN).
    - An IoT-enabled storage container affixed to the autonomous drone (AGENT) provides status updates on location, state, and internal temperature of the medical package (DOMAIN).
    - Credentials in the scenario may also include several claims related to identity, membership, and capabilities verification (See Figure 21)
4. Scenario events
    - Nurse (AGENT) initiates a request for an emergency medical package (DOMAIN) delivery to the City Hospital (DOMAIN) by the medical supply drone delivery company (DOMAIN).
    - The request for autonomous urban air delivery (ACTIVITY) is instantiated as a Medical Supply Delivery Contract (HSML CONTRACT), and is signed by the autonomous drone (AGENT) and the drone technician (AGENT).
    - The drone technician (AGENT) loads the medical package (DOMAIN) onto the autonomous drone (AGENT).
    - The autonomous drone (AGENT) has access to the start and endpoint of the delivery route and a digital map of the aerodrome (DOMAIN).

  - The FAA Authority (AGENT) issues an Operation Approval Certificate (CREDENTIAL) to the autonomous drone (AGENT), which provides real-time operational approval for autonomous drone's (AGENT) activity.
  - During the flight, the autonomous drone's (AGENT) location data, time-of-arrival data, compliance reporting data is referenced in a designated air traffic communication CHANNEL.
  - The status, location, and time-of-arrival of the medical package (DOMAIN) in the IoT container is referenced in the designated contract communications CHANNEL.
  - Upon arrival, the autonomous drone (AGENT) locates the landing pad using real-time location services and optical sensors, safely delivering the medical package (DOMAIN) to the designated location.

5. Results and post-conditions
   - The delivery is successful and the CONTRACT status is updated as fulfilled.

**FIGURE 7:** Scenario diagram: Urban autonomous mobility



## 5.3.5. Cultural location tourism

1. Summary (see Figure 8)
   - Tourist uses a Cultural AI Bot for context awareness and for social mediation with a Resident
   - The tourist meets a resident of the location. The two engage in a conversation mediated by a Cultural AI Bot. The facilitation provided by the Cultural AI Bot considers social norms and cultural differences. The Bot not only translates languages, but also provides historical meaning and current context about the location.

2. Actors
   - Tourist in a location foreign to them
   - Resident of the location
   - Cultural AI Bot able to mediate conversations across languages and cultures.
3. Context and pre-conditions
   - A tourist (AGENT) prepares to visit a cultural site, e.g., museum, monument, natural park, by interacting with Cultural AI Bot.
   - The Bot (AGENT) is developed in advance using quantitative analysis of millions of digitized, published works spanning the location's culture, humanities and sciences. Social insights are identified about fields as diverse as the evolution of language, collective memory, adoption of technology, history of individuals and groups in the location, and political events. For more information, see Annex B.
   - The tourist seeks to maximize understanding of culture by interacting with a resident.
4. Scenario events
   - Tourist creates a route (ACTIVITY) by identifying waypoints in a culturally significant location. A 3D Digital Twin model of the location has been spatially represented in (SPACE).
   - Tourist creates a tourism ACTIVITY; tasking the Cultural AI Bot to provide cultural experiences along the route.
   - A CHANNEL is established for the ACTIVITY. As the tourist travels the route, the Bot identifies relevant cultural items and provides information to the tourist.
     - The Bot's analysis of a corpus for the location enables quantitative investigation and representation of cultural artifacts, concepts and trends
     - The Bot identifies linguistic and cultural phenomena reflected in the corpus that are relevant to the Tourist's route.
     - The tourist uses an AR viewer for an immersive experience of the spatially registered information and artifacts coming from the Bot.
   - The Tourist asks the Cultural AI Bot to perform a spatial query of a specific area along the route.
     - Tourist's headset provides a video image of the space to the Bot.
     - Bot returns information about artifacts in the space: such as, terms and concepts associated with the artifact and how they have changed over time; Cultural differences from varieties of groups for which the artifact is relevant; Comparison of words across time about the artifacts coming from specific communities; Research available from different cultures and how they compare.
   - Tourist identifies a resident along the route and invites the resident to join the CHANNEL for the tourism ACTIVITY.
     - Bot identifies the language and some cultural affiliations of the resident.
     - Tourist and Resident engage in a discussion about the location and artifacts mediated by the Bot.

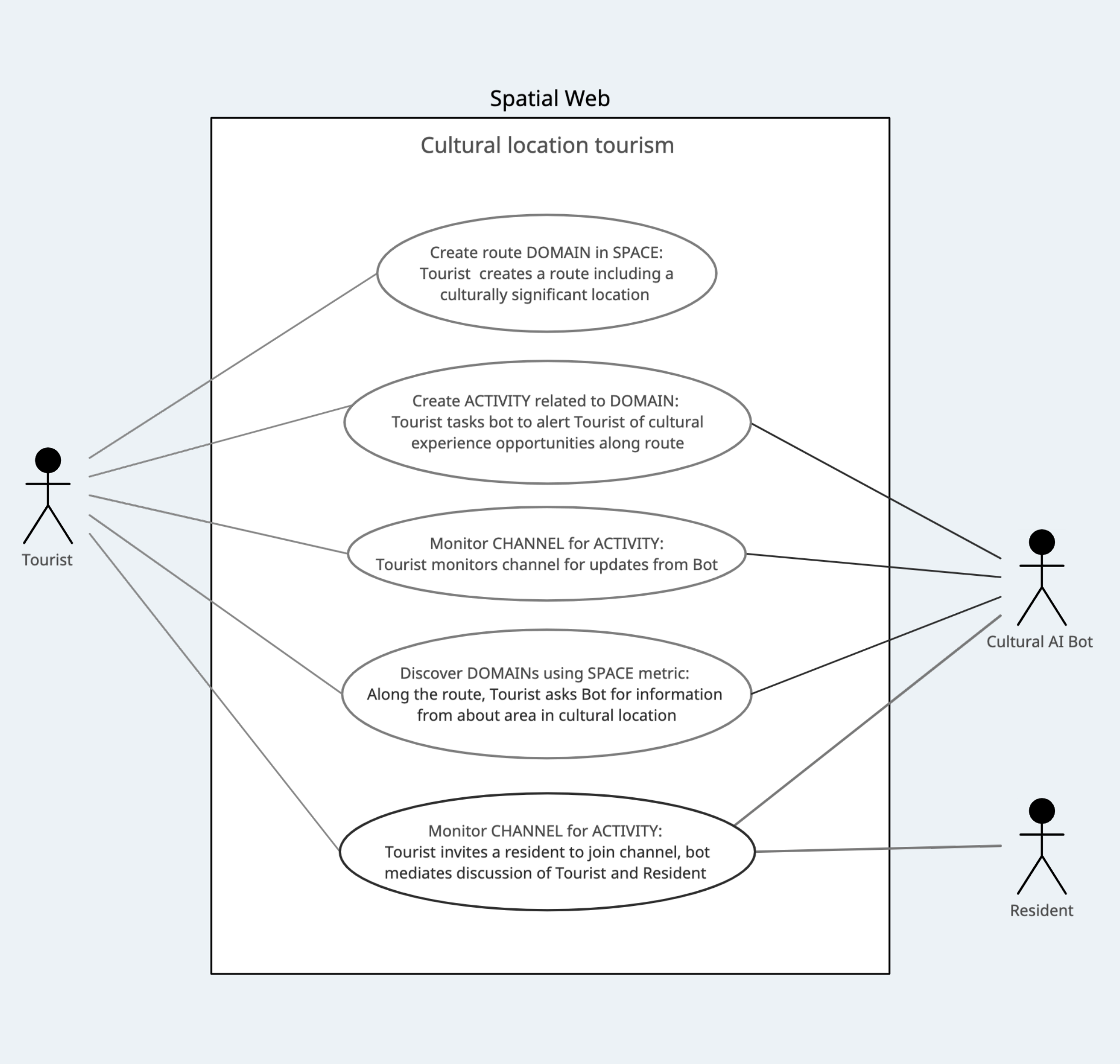
  - Cultural AI Bot provides a pathway for coordination by pulling expressions about a piece of information that can be recontextualized for another individual graph.

5. Results and post-conditions
   - Tourist and Resident conclude a rich and pleasant social interaction. The tourist's visit is enhanced through an immersive experience revealing details about the location and artifacts. Through a mediated conversation, empathy is increased between the tourist and resident in areas of culture, perhaps along racial and cultural lines.

Bibliographic references relevant to the scenario

- Quantitative analysis of culture using millions of digitized books
- Giving shape to large digital libraries through exploratory data analysis

**FIGURE 8:** Scenario diagram: Cultural location tourism



### 5.3.6. Global supply chain

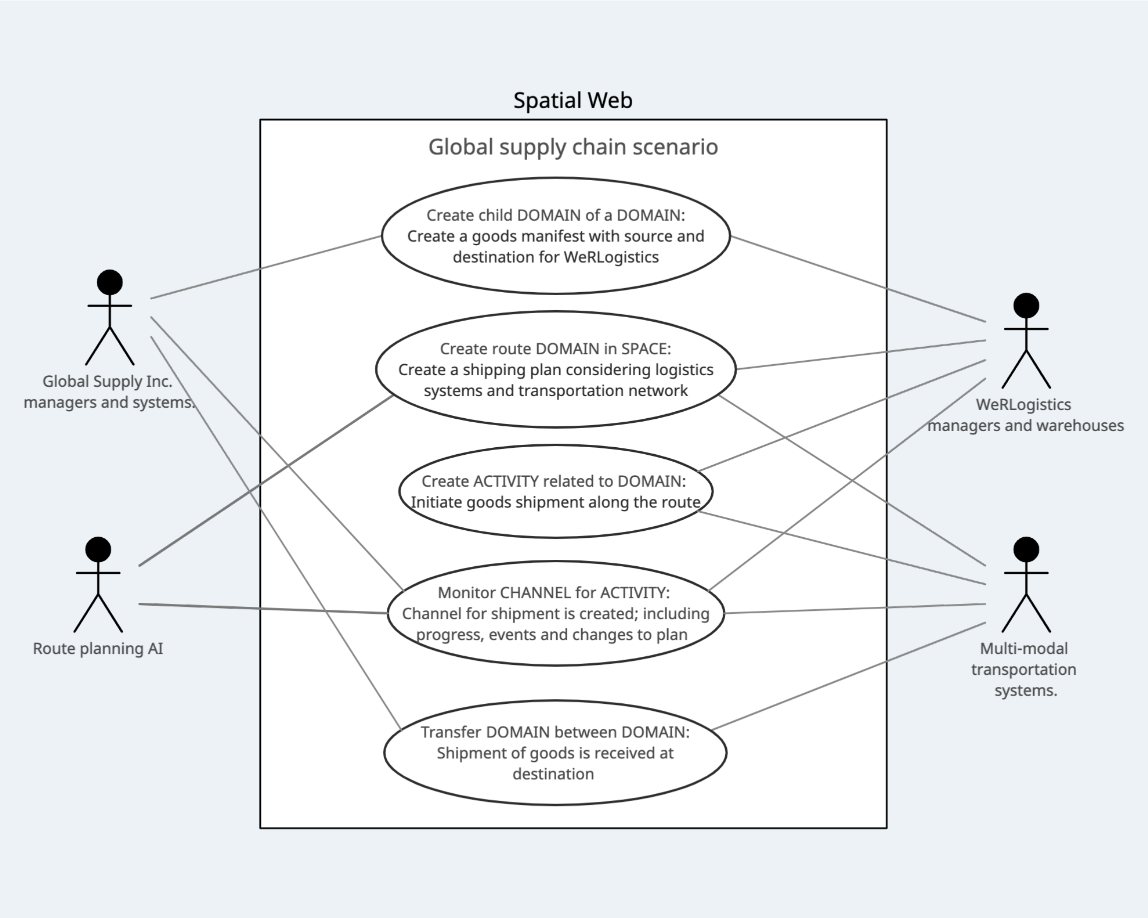
1. Summary (see Figure 9)
   - The Spatial Web improves global supply chains by increased insight, prediction, and real-world optimization throughout the distribution center and warehouse to modernize the traditional approach to worker performance and experience, inventory and capacity planning and facility management and space utilization.
2. Actors
   - Global Supply Inc. managers and systems.
   - WeRLogistics managers and warehouses
   - Multi-modal transportation systems.
   - Route planning AI
3. Context and pre-conditions
   - Global Supply Inc. needs to arrange for shipment of goods.
   - Route planning AI has been trained to create optimized shipment routes based on previously obtained information about logistic systems, multi-modal transportation systems and potential events affecting the shipment. The Route planning AI is able to provide updates for an in-transit route based on events.
   - The transportation systems provide real-time visibility into all aspects of the supply chain
   - WeRLogistics has an established ability to intelligently orchestrate human and robotic workers' real-time ACTIVITIES and assignments along the supply chain.
4. Scenario events
   - Global Supply Inc. creates a goods manifest (DOMAIN) and registers the manifest as a child domain of WeRLogistics (DOMAIN)
   - WeRLogistics creates a route (ACTIVITY) in with a spatial representation (SPACE):
     - Potential routes are created by the Route Planning AI based on models of the logistics systems and transportation networks
     - Current status reports from the systems, networks and additional information are used to optimize the shipment route
   - WeRLogistics creates a shipment (ACTIVITY) and initiates the shipment:
     - Resources in the logistics systems and transportation networks are reserved by WeRLogistics
     - HSML messages contract for the movement of goods from source warehouse, through transportation domain, to destination
   - The shipment ACTIVITY is added to existing supply chain CHANNEL:
     - WeRLogistics invites all DOMAINS involved with the shipment ACTIVITY are part of the CHANNEL
     - Notification is sent by WeRLogistics to the CHANNEL to initiate the shipment
     - During the shipment, events occur which require replanning the shipment. Events could involve more material to be moved, less drivers available, or

weather events disrupting transportation. The Route planning AI detects the events and suggests a new optimized plan. WeRLogistics accepts the new plan, reserves the resources, and announces the new plan to the channel

- Goods on the manifest reach their destination and are transferred from the WeRLogistics (DOMAIN) to the receiving site (DOMAIN)

5. Results and post-conditions
   - Use of Spatial Web increased supply chain performance and lowered costs
   - Resilience is provided by the Route planning AI based on data interoperation using HSML and HSTP
   - WeRLogistics orchestration is achieved using the Spatial Web interoperability and multi-scale cognitive computing

**FIGURE 9:** Scenario diagram: Global supply chain



### 5.3.7. Urban digital twin / Smart city

1. Summary (see Figure 10)
   - Digital twin technology coupled with AI is improving how cities function, meeting major challenges of human civilization including health, climate change, and sustainability. Urban Digital Twins (UDTs) move us toward the UN goal to make cities and human settlements inclusive, safe, resilient and sustainable

  - This scenario shows how the Spatial Web enables digital twin technology for addressing urban sustainability with a focus on energy. Using urban energy system modeling and analysis developed in the Spatial Web multi-scale cognitive computing ecosystem will benefit next generation cities and the globe. Considering climate change it is vital that more cities deploy energy UDTs to address energy consumption and climate sustainability

2. Actors
   - Metropolis residents and visitors
   - Urban authority: executive function of the metropolis
   - Urban Sustainability Officer for the metropolis
   - Urban energy utility for the metropolis
   - Energy Management AI node
   - Spatial Web registrar
3. Context and pre-conditions
   - Urban authority has charged the Urban sustainability officer to create and implement an energy plan aiming to bring resilience considering climate change for the metropolis.
   - The Sustainability officer has been trained in creating an energy plan with policies modeled as Spatial Web HSML entities.
   - For simplicity in the scenario, the urban energy utility includes all forms of energy production and distribution in the metropolis.
   - Urban energy utility has created an Urban Digital Twin (UDT) for the energy system and energy consumers of the metropolis:
     - The Energy UDT includes real-time data sensing with predictive modeling for dynamic energy management.
     - The Energy UDT has access to a weather and climate UDT for predicting both real-time and long-term weather.
     - The UDTs are HSML enabled both to accept energy policies and to communicate energy system status.
     - The metropolis has deployed IoT networks for real-time data about devices, location, weather, traffic, people movement, etc., that are made available to the UDTs.
   - Energy Management AI nodes have been trained based on the metropolis urban utility system:
     - AI methods, e.g., machine learning techniques, in the node enable accurate forecasting, benchmarking, building optimization, demand response, and anomaly detection to lower costs and meet sustainability goals across the metropolis.
     - Use of AI supports reduction of energy expenditure, waste and GHG emissions, and improves operations through real-time tracking, analytics, and optimization.

  - Credentials in the scenario may include several claims, including identity, membership and capabilities (See Figure 21).

4. Scenario events
  - Urban Authority registers the entire municipal government as a DOMAIN with the Spatial Web Registrar
  - Urban Authority issues CREDENTIALS authorizing the government employees and the urban energy utility to create DOMAINS as childs of the metropolis DOMAIN
  - The sustainability officer creates a CHANNEL for discussing urban energy planning
  - Urban energy utility makes the Energy UDT available as a DOMAIN on the Spatial Web
  - Urban Sustainability Officer creates a plan for achieving Urban Energy Goals:
    - The plan is developed by working with Urban residents and visitors and the Urban energy utility
    - Involving residents and visitors in development of the goals and plan is one of the most important criteria for success
    - The officer uses the Energy UDT to develop and test policies to meet the plan’s goals
    - The officer uses the Energy Management AI node to develop and test policies to meet the plan’s goals
    - Policies that are predicted to achieve the goals are implemented as Spatial Web HSML entities
  - The Sustainability officer initiates energy optimization ACTIVITY related to Energy Plan DOMAIN:
    - The activity includes the Urban energy utility providing real-time and trend data to the Energy Management AI Node
    - The AI Node reviews the plans and prepares to recommend ACTIVITIES based on the plan’s policies
    - Plan includes incentives in contracting and resident ACTIVITIES to meet the goals
    - Residents modify their ACTIVITIES based on the incentives
  - The Urban energy utility creates a secure CHANNEL for implementing the plan ACTIVITY:
    - Real-time sensor data from the Energy Utility is provided to the channel.
    - IoT and weather data for the metropolis are provided on the channel
    - The energy UDT monitors the channel and predicts energy consumption
    - The AI Mode monitors the channel and recommends ACTIVITIES for the energy utility.
    - The Energy Utility implements ACTIVITIES to best meet the goals of the plan.
  - The Sustainability Officer updates plan and policies based on usage:

    - Officer uses the previously established channel to develop revised plan with residents and visitors
    - New strategies developed, working with the Energy Management AI node.

5. Results and post-conditions
    - Energy consumption and greenhouse gas objectives defined in the Urban Energy Goals plan are met.

Bibliographic references relevant to the scenario:

Urban life: a model of people and places

Reality capture: a digital twin foundation

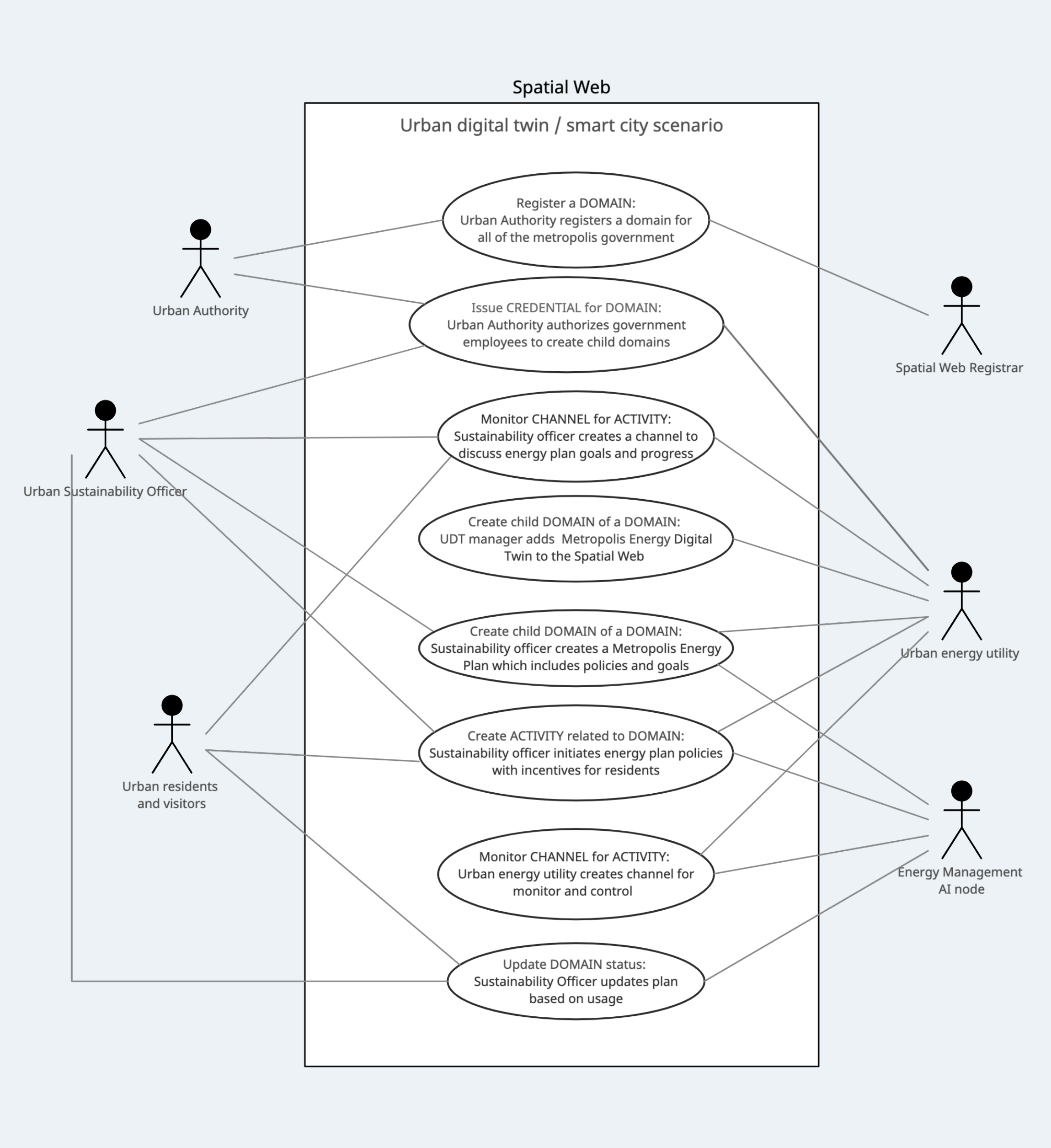
The adoption of urban digital twins

IEA EBC positive energy districts

Toward Real-Time Urban Building Energy Benchmarking

[99]

**FIGURE 10:** Scenario diagram: Urban digital twin / Smart City



## 5.3.8. Digital earth: Greenhouse Gas Monitoring

1. Summary (see Figure 11)
    - Digital Earth is a vision of an ecosystem of Earth system observation and modeling systems that support decision making about global issues. The Spatial Web delivers the vision of multiple connected infrastructures based on open access and participation across multiple Spatial Web platforms to address the needs of all Earth residents.
    - The scenario describes how the multi-level cognitive computing network of the Spatial Web can facilitate the interaction of greenhouse gas (GHG) monitoring

with emitters and goals to collectively enact plans to reduce atmospheric carbon and the resulting impact on the Earth's climate.

2. Actors
   - Earth system scientists
   - Government policy makers
   - GHG emitters
   - GHG monitoring networks
   - GHG sequestration providers
   - Spatial Web AI mediation nodes
3. Context and pre-conditions
   - Earth system scientists have:
     - Estimated the effects of GHG levels on climate, e.g., global average temperature
     - Established rigorous protocols for measuring and reporting GHG concentrations and sources
   - Multiple organizations have built elements of the Digital Earth for greenhouse gas including:
     - Space and ground-based monitoring networks for identifying the sources and amounts of greenhouse gas in the atmosphere
     - Earth-scale modeling capabilities for predicting concentration and circulation of GHG
     - Decision support frameworks for assessing policy impacts on GHG
   - Technology, systems and markets for GHG sequestration are beginning to emerge in order to remove greenhouse gas from the atmosphere
4. Scenario events
   - Government policy makers establish GHG Goals (DOMAIN) based on Earth system science and policy negotiation.
   - An international science union establishes a Digital Earth GHG modeling (DOMAIN):
     - The DOMAIN fosters the identification and advertisement of scientifically rigorous models to be available in the Spatial Web.
     - When a model is added to the Spatial Web a facade is added to make it HSML/HSTP interoperable.
     - The science union actively manages development of HSML entities consistent with standard ontologies for observations and measurements of GHG gasses and for reproducible model outputs. FAIR principles are used.
   - Government agencies create an ACTIVITY that fosters formation of CHANNELS for GHG reduction discussions:
     - Policies are defined for the channels for discussion of goals and ACTIVITIES are defined using HSML entities.

    - Different channels are formed based around communities with common interests.
  - GHG Monitoring networks are made available on the Spatial Web:
    - Similar to bringing the predictive models on the Spatial Web, HSML entities are defined for accurate communications.
    - Monitoring networks may also have specific policies and procedures for data handling.
  - CHANNELS are established for spurring responses that support a reduction in GHG:
    - Channels include the Greenhouse gas emitters, the monitoring networks, sequestration providers and AI Mediation nodes.
    - AI mediation nodes monitor the channel and recommend potential agreements for GHG reduction. The mediation nodes recommendations are in the form of contracts defined using HSML entities.
  - Government agencies working with Earth system scientists update the GHG goals (DOMAIN) based on ACTIVITIES.

5. Results and post-conditions
   - Reduction in atmospheric GHG based on a community mediated by Spatial Web AI nodes.

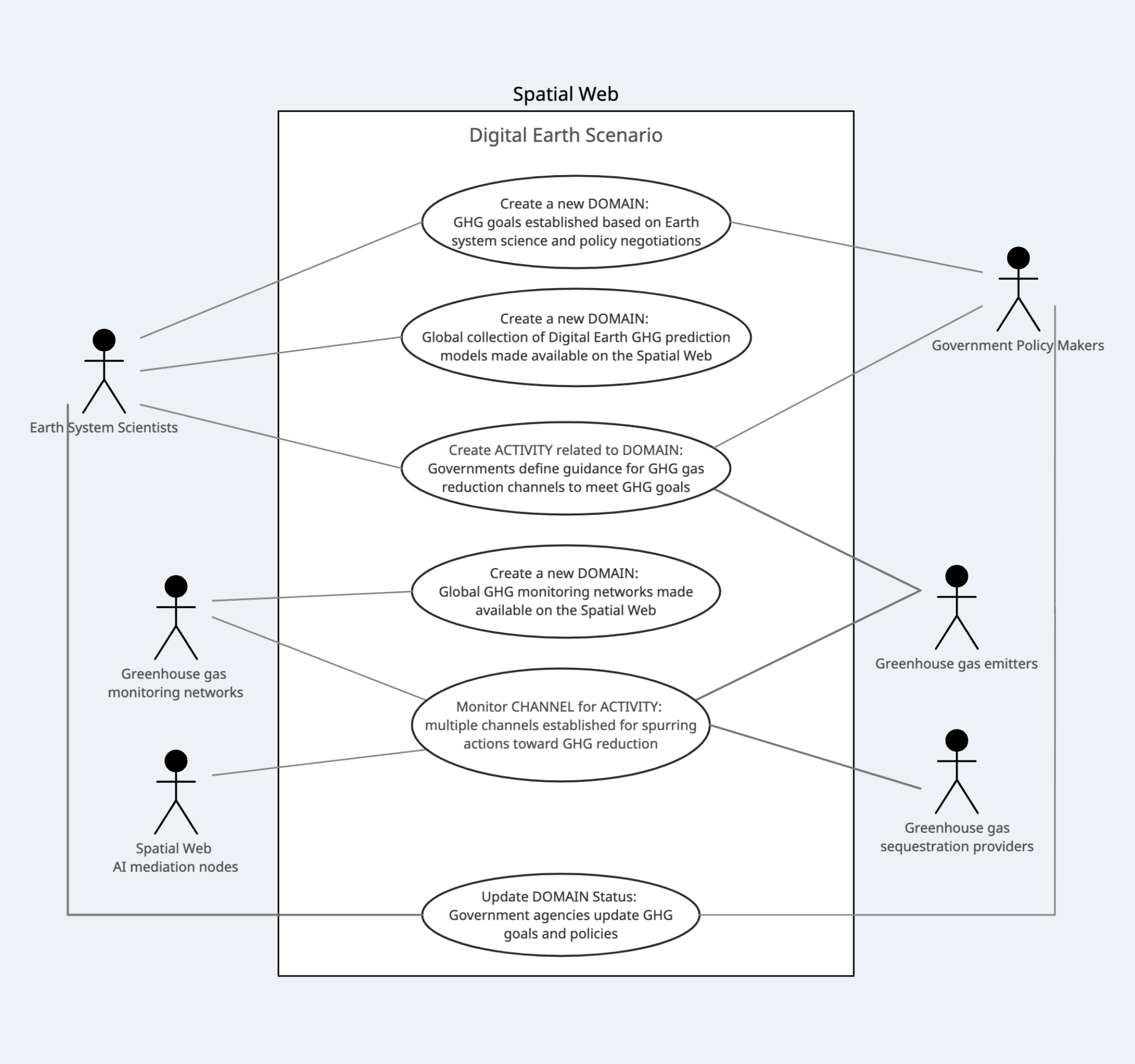
Bibliographic references relevant to the scenario:

Next-generation Digital Earth

ISDE Manual of Digital Earth

National Academies Greenhouse Gas Emissions Information for Decision Making

**FIGURE 11:** Scenario diagram: Digital earth: Greenhouse Gas (GHG) monitoring



## 5.3.9. Entertainment XR

1. Summary (see Figure 12)
   - A fan goes to a superhero movie called Fantastic Five. In the lobby of the theater they engage with a lifelike avatar from the film and win a digital asset from the movie that they can use in the movie's multiplayer game and trade with other players
2. Actors
   - Superhero fan with AR headset
   - Fantastic Five character avatar
   - A Friend of Fan with VR headset
3. Context and pre-conditions
   - The Fan and their Friends are already registered players in the Fantastic Five multiplayer online XR game

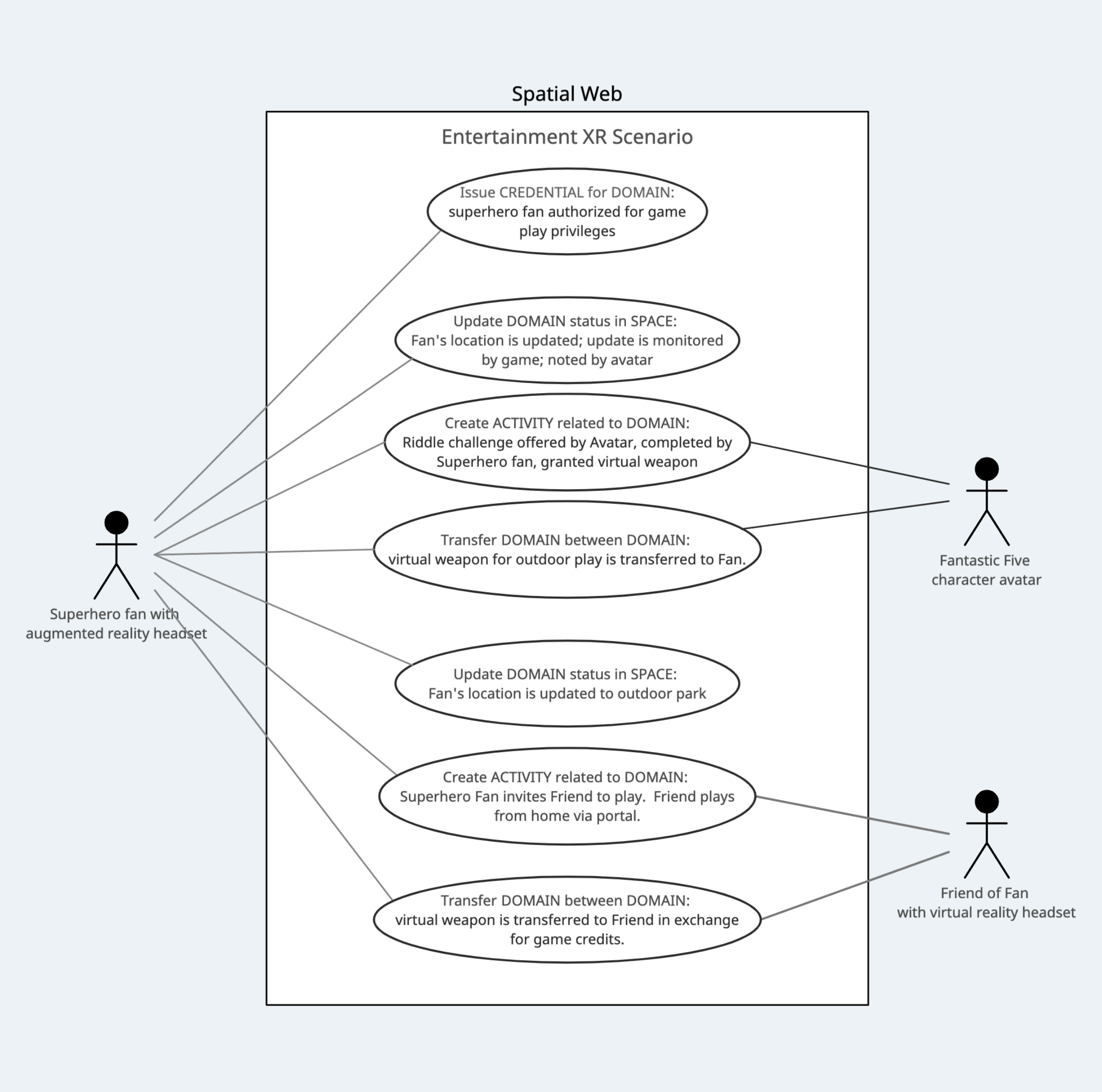
- A 3D spatial model of the theater lobby (DOMAIN) has been predefined and created in advance. The 3D spatial model is a collection of HSML elements (and their connections) stored in a "Node Server" for the company.
- A 3D spatial model of a neighborhood park (DOMAIN) has been predefined and created in advance. The 3D spatial model is a collection of HSML elements (and their connections) stored in a "Node Server" for the company.
- A 3D spatial model of the Friends home (DOMAIN) has been predefined and created in advance. The 3D spatial model is a collection of HSML elements (and their connections) stored in a "Node Server" for the company.
- Credentials in the scenario may include several claims, including identity, membership and capabilities (See Figure 21)

4. Scenario events
   - CREDENTIAL is issued to Fan by Fantastic Five game that provides their points and level in the game:
     - CREDENTIAL is possessed by the Avatar that grants them access to see any player's game profile and history
   - Fan's location is updated when entering the theater; Avatar notices and engages him:
     - The Fan buys a ticket to the movie and enters the theater lobby where several virtual Avatars are entertaining other fans wearing HMDs
     - Upon entering, an Avatar is alerted to the Fan's presence, accesses the Fan's profile and history and then flies over to them, striking up a conversation
   - Avatar creates a Riddle ACTIVITY with fan:
     - Based on the Fan's history, the Avatar challenges the Fan to a riddle and offers a prize of a special virtual weapon used in the game if they are able to solve the riddle within 5 minutes or they will lose 1000 points
     - The only catch is the weapon only works in outdoor physical or virtual spaces
     - The Fan accepts the challenge and other fans and Avatars gather around. The Avatar delivers the riddle and the Fan answers correctly within 5 min, winning the challenge and causing the observers to erupt in applause
   - Virtual weapon is transferred to the Fan (DOMAIN):
     - The Avatar produces the virtual weapon, handing it to the Fan who places it in their virtual weapons locker and then proceeds to see the movie
   - After the movie, Fan's location is updated when leaving the theater and going to a park
   - Fan creates invites a friend to play the game (ACTIVITY):
     - In the park, the Fan invites their friend to join them virtually, providing a portal in the friend's home for them to enter through into the park
   - Weapon is transferred from Fan to Friend for credits
   - During the game, the Friend is in need of a better weapon so the Fan offers to sell theirs for 10,000 credits

  - The Friend accepts the offer and they complete the transaction, automatically transferring the assets and changing ownership of the weapon
  - Once the game ends, the portal closes and the Friend is once again back at their home

5. Results and post-conditions
  - Ownership ACTIVITY is completed and updates made to:
    - Fan's Node Server
    - Friend's Node Server
    - Weapon's profile

**FIGURE 12:** Scenario diagram: Entertainment XR



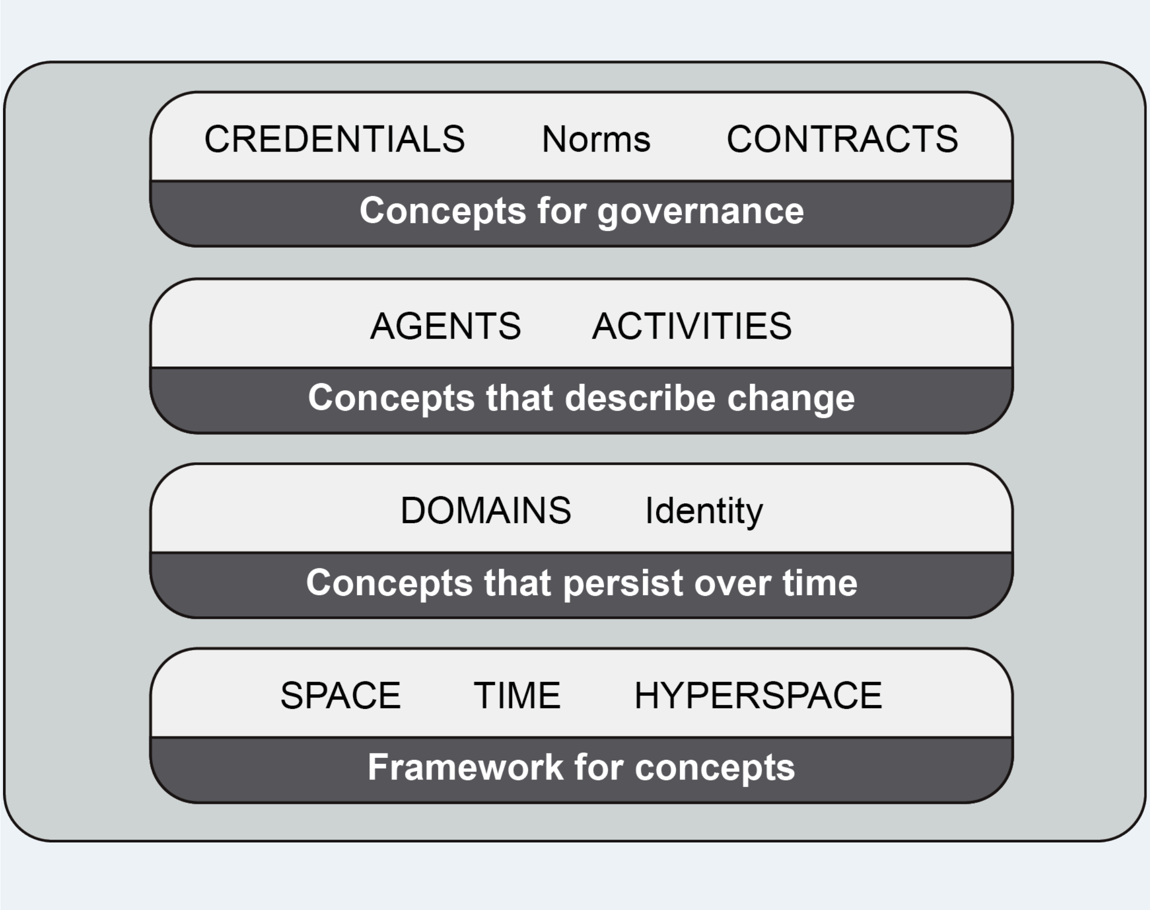
# 6. Conceptual modeling

## 6.1. Overview

A conceptual model is an abstract representation of a system using concepts and ideas. The model represents the conceptual entities that define the system and the relationships between entities.

The subclauses of the conceptual model are organized as shown in Figure 13.

**FIGURE 13:** Conceptual modeling overview



## 6.2. Space, time and hyperspace

### 6.2.1. Introduction and basic definition

The term 'hyperspace' is used to capture a generalized concept of *space*, in an acknowledgment that not only do Euclidean and geographic spaces have spatial structure, but so too do many other, more abstract data types. These spaces and types can be combined to form complex spaces that may be navigated. The concept of hyperspace is fundamental for the Spatial Web. It is incorporated in and informs many design decisions.

To support this fundamental role, this clause provides a formal definition of hyperspace, as any set whose elements are related by a formal notion of *path*. Paths may be abstract, as long as they can be 'traversed' in a fashion akin to the paths between points in familiar spaces. This clause then instantiates the definition in examples that underlie Spatial Web applications and provides useful additional structures that may be defined on hyperspaces such as *dimension*, *metrics* and *similarity measures*. These definitions and examples generate the requirements and recommendations imposed on Spatial Web implementations. By making the definition suitably general, the notion of hyperspace ensures that the Spatial Web accommodates and facilitates advances in cyber-physical and distributed computing, contextualized data, AI interoperability, and IoT Governance.

**Definition**. A *hyperspace* X is a set $X_0$ of *elements* or *points*, such that for every pair (x,y) of elements, there is a (possibly empty) set X(x,y) of *paths* $x \to y$ between them, satisfying the following conditions. 1) For every element x, there is a path $x \to x$ called its *identity* and written $id_x$. 2) Given a path $p:w \to x$ and a path $q:x \to y$, there is a path $q \circ p:w \to y$ corresponding to following the path p then the path q. 3) Paths compose associatively, in the sense that given paths $p:w \to x$, $q:x \to y$, $r:y \to z$, $r \circ (q \circ p) = (r \circ q) \circ p$. 4) Following the identity path corresponds to going nowhere: every path $p:x \to y$ satisfies the equation $p \circ (id_x) = p = (id_y) \circ p$.

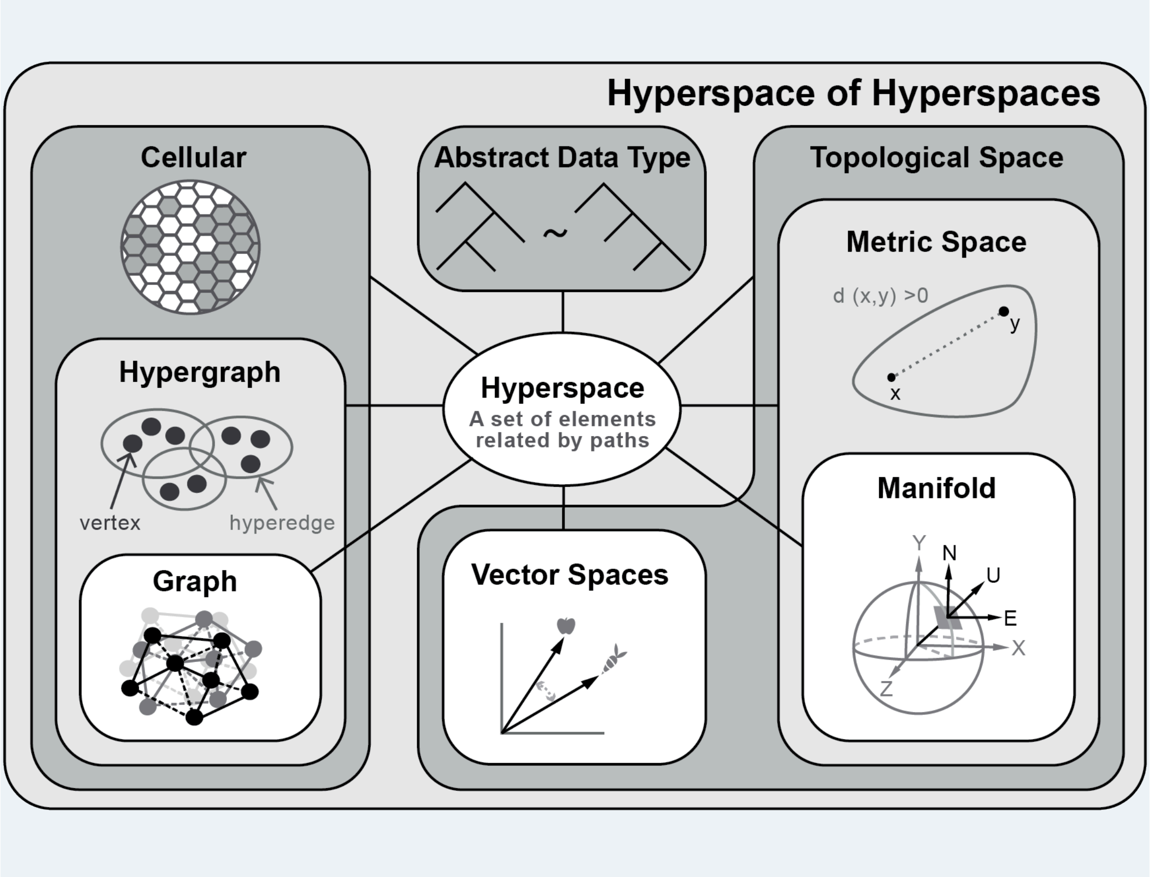
Note that in this definition, paths are *directed*, meaning that, having followed a path $p:x \to y$, it is not necessarily possible to "follow it backwards" and end up back in the starting place. This generality is important in order to capture directed graphs as spaces. However, many spaces are actually *undirected*, meaning that every path $p:x \to y$ has an associated *inverse path* $p^{-1}:y \to x$ satisfying the equations $p^{-1} \circ p = id_x$ and $p \circ p^{-1} = id_y$. These equations ensure that, in the undirected case, it *is* possible to return along a path back to the starting place.

The definition of hyperspace is equivalent to the mathematical concept of *category*, which emerged in the 20th century as a tool for modeling abstract spaces.

The motivation for defining hyperspace is to provide a foundational data layer that can be used to reason and normalize across different data schemas and data concepts. Besides offering a method to represent data points (i.e., as points in hyperspace), the additional structure that is frequently included with examples of hyperspace also provides context between data elements. For example, it may be possible to define metrics that score the distance between points of the space, or to reason about the similarity between data points. These contextual structures provide machinery for reasoning about the ambient space in which these data points are observed. Moreover, by considering how hyperspaces relate to one another—how they can be transformed or composed together—or how data can be attached to space, it becomes possible to incorporate contextual information directly and rigorously into the framework.

The remainder of this clause incorporates various types of space into the hyperspatial framework, and defines additional structures and operations that may be associated with different hyperspaces. A non-exhaustive summary view of several types of space is shown in Figure 14.

**FIGURE 14:** Basic classes of hyperspace



## 6.2.2. Basic classes of hyperspace

### 6.2.2.1. Graphs

A *(directed) graph* G is a set $G_0$ of *nodes* along with a set $G_1$ of *edges*, such that every edge e has a *source* node s(e) and a *target* node t(e). Every directed graph G defines a hyperspace $G_H$ as follows: the points of $G_H$ are its nodes, and for each pair (x,y) of nodes, the paths $G_H(x,y)$ are lists of edges such that the source of the first edge is x, the target of the last edge is y, and the target of each edge in the list is the source of the next edge. The identity path on a node x is the empty list.

An *undirected graph* is a directed graph in which every edge x→y is paired with a corresponding edge y→x. Consequently, in the hyperspace corresponding to an undirected graph, every path has a corresponding inverse path.

### 6.2.2.2. Vector spaces

The archetypal vector spaces are *Euclidean spaces*: vector spaces over the real numbers ℝ. Both these and more general vector spaces can be modeled as hyperspaces, but it is helpful to begin with the familiar Euclidean ones.

A *Euclidean space* V of *dimension* n is a set $V_0$ of *vectors* isomorphic to the n-fold Cartesian product of the real line ℝ. The dimension n is equal to the number of *basis vectors* $\{e_i\}$ and every vector x in $V_0$ can be written as an ℝ-linear combination of the basis elements: $x = \sum_{i=1}^{n} x_i \cdot e_i$, where each $x_i$ is an element of $\mathbb{R}$ and is called the $i^{th}$ *coefficient* of x. (The notation $\sum_{i=1}^{n} x_i \cdot e_i$ means the n-fold sum $x_1 \cdot e_1 + \ldots + x_n \cdot e_n$.) Considered as a hyperspace, the points of V are the vectors $V_0$ and the paths are pairs of a real number m and a continuous function from the interval [0,m] to $V_0$ (that is, continuously-indexed lists of vectors in V). Paths compose by concatenation.

More generally, every topological vector space over a (topological) field k is a hyperspace, where the field k plays the role of the real numbers for Euclidean spaces. A *field* k is itself a kind of space: a set of points $k_0$ equipped with two operations, one called *addition* and written $+ : (k_0 \times k_0) \to k_0$, and another called *multiplication* and written $\cdot : (k_0 \times k_0) \to k_0$. (Here, $k_0 \times k_0$ denotes the Cartesian product of $k_0$ with itself.) The set $k_0$ has two special points, an *additive unit* denoted 0 (such that $x+0 = x = 0+x$) and a *multiplicative unit* denoted 1 (such that $1 \cdot x = x = x \cdot 1$). Every point x must have an *additive inverse* y (such that $x+y = 0 = y+x$) and every point except for 0 must have a *multiplicative inverse* z (such that $x \cdot z = 1 = z \cdot x$); the additive inverse may be denoted -x and the multiplicative inverse may be denoted $x^{-1}$. Finally, multiplication must *distribute* over addition: $x \cdot (y + z) = x \cdot y + x \cdot z$.

A *vector space* V *over* k of dimension n is therefore a set $V_0$ isomorphic to the n-fold Cartesian product of k, and the elements of $V_0$ are called k-*vectors*. V can be canonically equipped with a basis (1,0,0,...), (0,1,...), (0,0,1,...), written as lists of length n all-but-one of whose elements are 0 (the additive unit), with the remaining element being 1 (the multiplicative unit). Every vector x can then be written as a k-linear combination of these basis elements using the field operations, as in the Euclidean case in the previous paragraph: $x = \sum_{i=1}^{n} x_i \cdot e_i$. Considered as a hyperspace, the points of V are the vectors $V_0$ and the paths are pairs of a real number m and a continuous function from the interval [0,m] to $V_0$ (that is, continuously-indexed lists of vectors in V). Paths compose by concatenation. (This definition of path requires the field k itself to be a topological space, so that continuous functions are well defined. It is possible, though outside the scope of this subclause, to relax this requirement.)

Note that any vector space is determined by a choice of field k along with a specification of its dimension.

There are more general structures still that behave like vector spaces, most prominently the *modules* over *ring* R. A *ring* is a field in which not every element has a multiplicative inverse, and in which multiplication need not be commutative (meaning $x \cdot y$ is not necessarily equal to $y \cdot x$). In this case, much of the structure of a vector space can still be defined, and the resulting hyperspace is called a *module*.

### 6.2.2.3. Hypergraphs

Many situations exhibit spatial structure that is graph-like, but higher dimensional: a graph only has 1-dimensional edges. Consider for example a model of videoconferencing: not every call will be precisely peer-to-peer; sometimes, it may be desirable to broadcast to a whole group of peers at once. In this case, one might have an ‘edge’ connecting all of n nodes, rather than just two. A graph that may have n-dimensional edges for any natural number n is called a *hypergraph*.

More formally, a *(directed) hypergraph* H is a set $H_V$ of *vertices* and a set $H_E$ of tuples of vertices (of arbitrary length) called *hyperedges*; the length of such a tuple is called the *dimension* of the hyperedge. If instead one forgets the ordering of the tuples (so that they are just subsets of vertices), then one has an undirected hypergraph.

Considered as a hyperspace, the points of a directed hypergraph are tuples of vertices and the paths v→w are lists of hyperedges such that the head of the first hyperedge is v, the tail of the last hyperedge is w, and the tail of each hyperedge is the head of its successor. The identity hyperedge is again the empty list. (In the case of an undirected hypergraph, one does not consider head and tail, only whether the source and target tuples are subsets of the hyperedges.)

### 6.2.2.4. Abstract data types

Many non-spatial data types can be equipped with hyperspatial structure, which allows for the incorporation of abstract data into Spatial Web applications: as long as two elements of a data type can be compared for equality, then the data type can be given hyperspatial structure.

If T is any data type whose instances can be compared for equality, then it can be made into a hyperspace as follows. The points of T are its instances, and if x and y are instances, then the paths x→y are proofs that the instance x equals the instance y: one can implement the paths as witnesses to the proof of equality, programs that actually compute the equality, or the “debug traces” output by such programs. A proof x→y can be composed with a proof y→z by checking the first proof then the second, and the identity proof on an instance x is the trivial proof that it equals itself.

The notion of ‘equality’ can be quite weak: in fact, any proof of equivalence is sufficient, and the definition of equivalence can be context-sensitive. For instance, if one is interested in address records, one might consider two addresses to be equal if they can both be transformed into the same canonical form.

### 6.2.2.5. Hyperspaces of spaces

#### 6.2.2.5.1. Overview

Each type of space described in 6.2.2.1, 6.2.2.2, 6.2.2.3 and 6.2.2.4 defines a corresponding *hyperspace of spaces*: the points of each space of spaces are the spaces of the corresponding type themselves, and the paths between spaces are *transformations* or *morphisms* of spaces.

An example of a transformation between spaces is when moving from a 3-dimensional view of a space to a 2-dimensional map of it, which is the use of a projection morphism. Similarly, if a space is deformed, then the deformation is a morphism.

This subclause defines the hyperspace corresponding to the space of each of the types of space described in 6.2.2.1, 6.2.2.2, 6.2.2.3 and 6.2.2.4.

#### 6.2.2.5.2. Hyperspaces of graphs

The hyperspace of directed graphs has directed graphs as its points and *graph homomorphisms* as its paths. If G and G’ are graphs, a graph homomorphism f:G→G’ is a pair of functions, $f_0{:}G_0 \to G'_0$ between the sets of nodes and $f_1{:}G_1 \to G'_1$ between the sets of edges, such that sources and targets are preserved: for every edge e, $s(f_1(e)) = f_0(s(e))$

and $t(f_1(e)) = f_0(t(e))$, where s and t are the source and target functions introduced in 6.2.2.1.

### 6.2.2.5.3. Hyperspaces of vector spaces

The hyperspace of vector spaces over a field k has vector spaces over k as its points and k-*linear maps* as its paths.

Note that by the definition in 6.2.2.2, every vector space is also a topological space. There is also a hyperspace of topological spaces whose points are topological spaces and whose paths are continuous functions between them. Therefore, if *nonlinear* continuous maps between vector spaces are desired, it is necessary to move to this larger hyperspace.

### 6.2.2.5.4. Hyperspaces of hypergraphs

The hyperspace of directed hypergraphs has directed hypergraphs as its points and *hypergraph homomorphisms* as its paths. If H and H′ are hypergraphs, a hypergraph homomorphism $f:H \rightarrow H'$ is a pair of functions $f_V:H_V \rightarrow H'_V$ and $f_E:H_E \rightarrow H'_E$ such that, for any hyperedge $(v_1, v_2, \ldots)$, the equation $f_E(v_1, v_2, \ldots) = (f_V(v_1), f_V(v_2), \ldots)$ is satisfied.

### 6.2.2.5.5. Hyperspaces of abstract data types

The hyperspace of data types has data types as its points and functions between them as its paths. This hyperspace is prominently used in functional programming: any (pure) functional program is a path in this hyperspace.

### 6.2.2.6. Cellular spaces

Spaces may be connected. Examples of connected spaces include maps tiled over a globe or rooms connected within a building.

When a collection of interconnected spaces uses a well-defined pattern or *schema*, and each space type is associated with a collection of spaces of that type and consistently has the given schema, the resulting compositional spaces are *cellular spaces*.

A *cellular space* is a hyperspace in which ‘cells’ of a chosen type are connected according to a ‘schema’.

More precisely, a *schema* may be any hyperspace. Its points are the *cells* and its paths are their *connections*.

For example, the schema could be a graph, whose nodes represent different regions of a connected space and whose edges represent the interconnections. Or in a more data-oriented setting, the schema could have points representing the tables of a database and paths representing the relationships between them.

For each schema X and hyperspace of spaces S, there is a corresponding type of cellular spaces. Therefore, a *cellular space with schema* X and *cell type* S is an assignment of S-spaces to the cells of X and of S-morphisms to the connections of X, such that the assignment *respects the composition of the connections* (in the sense defined in the next paragraph). For instance, if the cell type is taken to be the hyperspace of topological spaces, then each connection can be assigned a general continuous function. Alternatively, if the cell type is a hyperspace of vector spaces, then each cell is assigned a vector space and each connection is assigned a linear map. In each case, additional structure defined on the cell type (such as described in 6.2.3) can be lifted to the cellular space. For example, if the cells are vector spaces, then the coordinate system of each cell induces a coordinate system for the whole cellular space.

Let F denote the assignment of S-spaces and morphisms to the cells and connections of X. For F to *respect the composition of the connections* means that F assigns identity morphisms to identity connections (i.e., $F(id_X) = id_{F(X)}$) and, if p:b→c and q:c→d are connections in X, then $F(q \circ p) = F(q) \circ F(p)$.

Such an assignment of spaces to cells that respects composition is sometimes known as a *functor*.

Each type of cellular spaces with schema X and cell type S itself forms a hyperspace (a space of spaces), denoted [X,S]. The points of [X,S] are the corresponding cellular spaces and the paths are their transformations: if F and G are both cellular spaces in [X,S], then a transformation α:F→G is a family of S-transformations of each of the cells $\alpha_X: F(x) \rightarrow G(x)$ that respects the connectivity of the schema X in the sense that, if p:y→x is a connection in X, then $\alpha_x \circ F(p) = G(p) \circ \alpha_y$.

This definition of cellular spaces subsumes both graphs and hypergraphs and allows for the definition of triangulated spaces, as well as other complex spaces, such as tilings of globes or other manifolds with maps. For example, a directed graph is a cellular space whose schema is the hyperspace with two points (1 and 0) and two paths (s,t:1→0). A directed hypergraph is a cellular space whose schema is the hyperspace with one point for every natural number as well as, for each natural number n, n paths n→0. A triangulated space (of arbitrary dimension) is a cellular space whose schema is the hyperspace known as the “simplex category”.

### 6.2.2.7. Geographic cellular space

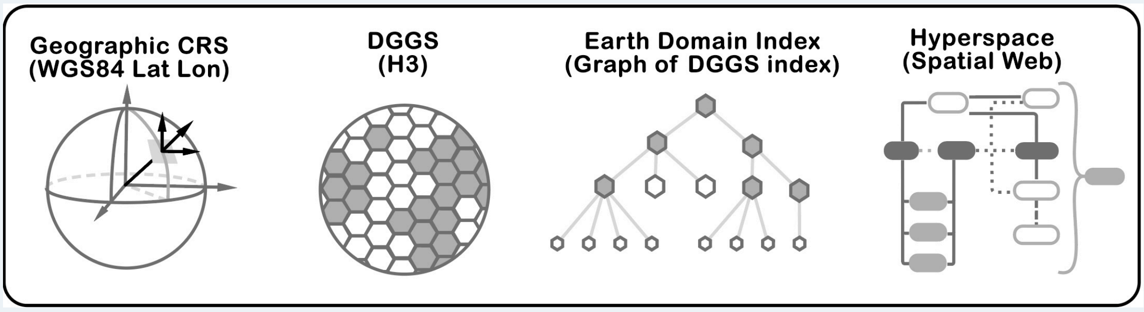
Geographic space can be modelled as a particular kind of cellular space, a DGGS, which typically models both three-dimensional physical space plus one time dimension: a DGGS is a cellular space with cells constituted by topological spaces or vector spaces.

Typically, the cells of a DGGS are anchored on the surface of the Earth and defined as 2-dimensional vector spaces, although they can extend to 3- and 4-dimensional vector spaces for geographic spacetime.

Referencing locations on the Earth using DGGSs avoids issues such as singularities at the poles or discontinuity at the date line that arise with some geographic coordinate reference systems. DGGSs therefore provide the Spatial Web with an approach for embedding geographic space into cellular hyperspace. Figure 15 illustrates a framework for the coordination of geographic DGGS and CRS with Spatial Web hyperspace.

Use of DGGS allows geographic Domains to be embedded as graphs in the Spatial Web UDG which is also a graph space.

**FIGURE 15:** Embedding geographic space in hyperspace



From left to right in Figure 15:

Geographic CRSs define an ellipsoid and axes for designating location on the Earth. The WGS84 series of geographic CRSs define Latitude and Longitude coordinates on an ellipsoid. WGS84 is extensively used in GPS and other localization systems. WGS84 indexing of the Earth surface has challenges at the poles, the date line, and when scaling resolutions.

DGGSs provide indexing of location on the Earth surface without issues at the poles and date lines. DGGSs provide efficient computation of resolutions. The H3 DGGS h3geo is a hierarchical set of hexagons and an indexing system covering the 2-D surface of the Earth.

DGGSs indexing systems provide for rapid retrieval of nodes. In a DGGS, nodes are polygons, e.g., a hexagon in H3. Because H3 is defined for many levels of resolution and not politically based, they serve as the <Geo/Earth> scheme in HSML.

The DGGS graph can be embedded in a Spatial Web hyperspace, e.g., graph space. A Spatial Web hyperspace may include as many dimensions as desired. The Hyperspace dimensions may include physical distance dimensions, attributes of the assets such as temperature, or ownership, and permission dimensions.

### 6.2.2.8. Coordinate reference systems

A Coordinate Reference System (CRS) consists of a coordinate system (CS) and a datum that relates CSs to an object (e.g., Earth, building corner). As an example, the Earth Centered Earth Fixed (ECEF) CRS is a Cartesian CS with origin at the Earth's center of mass and aligned with the axis of rotation. The World Geodetic System 84 (WGS84) CRS is an example of a geographic CRS. These CRS definitions and examples are listed in ISO 19111:2019.

Geographic CRSs are used to model the surface of the Earth, as follows:

- A Geographic CRS is composed of an Ellipsoidal CS and Geodetic Datum which sets the values for certain locations on the Earth.
- Geodetic Datum is an ellipsoid which approximates the shape of the Earth's surface.
- An Ellipsoidal CS consists of geodetic latitude and geodetic longitude and sometimes ellipsoidal height.

- Indoor CRSs are sometimes defined for confined spaces in buildings: some indoor CRSs use WGS84; others are Cartesian CRS with the origin located at some point in the building. Alternatively the building is has the spatial referencing using a cellular space, which may be embedded into a larger DGGS. Each of these approaches for indoor CRS are addressed by Spatial Web hyperspace.
- CRS registries provide stable identifiers for numerous CRSs. Most geographic data will include a CRS Identifier rather than provide a description of the CRS. For example in the EPSG CRS Registry, EPSG:4326 refers to WGS 84 geographic latitude, then longitude. That is, in this CRS the x axis corresponds to latitude, and the y axis to longitude. OGC has defined “CRS:84” to refer to WGS 84 geographic longitude and latitude expressed in decimal degrees, with longitude ranging from −180 degrees to +180 degrees and latitude from −90 degrees to +90 degrees.

Coordinate Reference systems are standardized in ISO 19111:2019 which is also published as the OGC Abstract Specification, Topic 2.

#### 6.2.2.9. Other types of spaces

Given the basic types in 6.2.2.1, 6.2.2.2, 6.2.2.3 and 6.2.2.4, other spaces can be defined either using cellular spaces or by using the operations on spaces defined in 6.2.3.7. Beyond such compositionally-derived spaces, yet more spaces can be incorporated into the hyperspace framework. These include *spaces of probability distributions* over the spaces defined in 6.2.2.1, 6.2.2.2, 6.2.2.3 and 6.2.2.4, general *topological spaces*, *metric spaces*, *convex spaces*, *smooth manifolds*, and more exotic spaces not listed here.

Each of these other types of space defines a hyperspace of those spaces, whose paths are transformations that preserve their particular structure, in a way analogous to those hyperspaces-of-spaces discussed in 6.2.2.5: for example, the hyperspace of topological spaces consists of topological spaces (as its points) and continuous functions (as the paths between them).

#### 6.2.2.10. Time in hyperspace

##### 6.2.2.10.1. Overview

In order to support both geographic and abstract spaces as *spaces*, the formal notion of hyperspace is necessarily very general. As such, it does not incorporate an explicit notion of *time*, even though time is both an important structural feature of the universe and relevant to the modeling of geography and of processes. At the same time, hyperspace can incorporate any notion of time that may be useful in applications. This subclause non-exhaustively describes three such notions and then considers the potential subjectivity of agents’ measurement of time according to their internal clocks.

##### 6.2.2.10.2. Time as a dimension of space

The simplest incorporation of time into the hyperspatial framework is to treat it as one dimension of spacetime. When modeling spacetime in a Newtonian fashion, as a Euclidean space and thus as a vector space, this means treating one of the dimensions of the corresponding hyperspace as ‘time’. More generally, as in realistic geographic applications, spacetime may be treated as a Riemannian manifold, which may be only locally a vector space (see 6.2.2.7). In this case, the preceding formalization is applied locally, and complexity may arise because the spacetime metric may not be the

Euclidean metric and because the metric may vary over the manifold, with durations varying accordingly. The latter kind of complexity is a classic feature of general relativity.

### 6.2.2.10.3. Time as the length of a path

The notion of hyperspace is a formalization of the abstract structure of space, and as such the foregoing notion of time may be accordingly abstracted. A metric on a space is equivalent to a way of measuring the lengths of paths in that space; similarly, an alternative understanding of time is as a way to measure the duration of processes. A key feature of hyperspace is that it is defined not just as a collection of points, but incorporates the paths between those points, such that paths may be composed. The paths in a hyperspace are inherently directed, and this directedness may be understood as an *abstract arrow of time*; similarly, the hyperspace with two points and a single path between them may be understood as an *abstract interval*.

These two primitives suggest an abstract notion of *motion* in a hyperspace: to take a step is to compose one path after another. The *abstract length* or duration of this path is then the number of constituent paths traversed. It is possible to take this approach further, using the mathematical tools of weighted category theory to associate each path in a hyperspace explicitly with a length: composing paths together may then involve adding lengths together.

### 6.2.2.10.4. Time as the extension of a process

In the modeling of systems and processes, it may be relevant to consider *dynamics*. A dynamical model typically has two parts: one syntactic, being the equations or algorithms which describe the dynamical system; and one semantic, being the behavior of the system that those equations yield when simulated or otherwise implemented.

These behaviors are typically *trajectories* and therefore both spatially and temporally extended. Consequently, a hyperspace that captures this structure may be obtained by taking a hyperspace representing the space in which the trajectories evolve and replacing its points by “temporally extended points”: that is, by trajectories themselves. Formally, this corresponds to working with a hyperspace of *interval sheaves*, which may alternatively be called a *behavior topos*. Note that the topos of discrete time behaviors is equivalent to the hyperspace of graphs: the vertices of a graph correspond to the points of the space, and the edges correspond to the discrete steps of the trajectories.

### 6.2.2.10.5. Local versus global clocks

An important distinction between ‘local’ and ‘global’ should be made in the context of time measurement, which leads to two important considerations: first, of relativistic effects (which have already become relevant at geospatial scales); and second, of clock drift and synchronization.

When considering spacetime as a whole, time may be treated as a global part of the structure, even if its metric may be variable. The variability of the metric means that clocks at different points may evolve at different (even incomparable) rates. Nonetheless, two relatively stationary observers situated at the same point must experience the same clock time, by definition of their being located within the same spacetime.

This situation may not accord with either psychological or modeling experience: variability in the components of distributed systems (such as agents) may mean that their 'local' *internal clocks* evolve differently, even when placed adjacently from an external perspective. The matter of perspective is important here: from the perspective of each constituent component, time is defined by the internal clock. This means that each component does not have access to the 'global' time, even if this global time exists and even if it influences the evolution of the local clocks. In this case, the time experienced or measured by the distributed system as a whole must necessarily be obtained through the consensus of its constituent clocks, either by central coordination or by distributed consensus; and in these cases the existence of a global time structure may be only of theoretical relevance.

#### 6.2.2.11. The hyperspace of hyperspaces: a web-like taxonomy

The hyperspaces of hyperspaces do not exist in isolation: there are canonical connections between them, which bear witness to a web-like taxonomy of hyperspaces. Hyperspaces and these connections between them constitute a hyperspace of all hyperspaces: the points are hyperspaces themselves, and the paths (the morphisms) are transformations between different hyperspace types, known as *functors*, which are precisely assignments of points to points and morphisms to morphisms that respect composition, in the sense discussed in 6.2.2.6.

Some of these hyperspaces-of-spaces correspond to the additional structures introduced in 6.2.3. For example, the hyperspace of metric spaces consists of all those topological spaces that are (or which can be) equipped with a metric structure. This means that there is a canonical connection between metric spaces and topological spaces: a functor from the former to the latter which simply 'forgets' the metric structure. Similarly, because every vector space is a metric space, there are 'forgetful functors' from vector spaces to metric spaces and thence to topological spaces. There is even a forgetful functor from hyperspaces to graphs, which simply takes the points of each hyperspace to be the nodes of a graph, and the paths to be the edges (thereby forgetting the compositionality).

As a different kind of example, certain manifolds can be triangulated, and this induces a *triangulation* functor from those manifolds to appropriately typed cellular spaces. Relatedly, there is a functor that represents every graph as a hypergraph (without any higher-dimensional edges). Functors preserve the basic structures of hyperspace: the points and the paths between them.

At the greatest level of generality, of course, there is the hyperspace of all hyperspaces itself, which provides a canonical setting for understanding general transformations between spaces and hyperspaces, and thus their relationships.

### 6.2.3. Additional structures on hyperspaces

#### 6.2.3.1. Overview

Many common hyperspaces have structures in addition to points and paths. For instance, there may be canonical ways to describe the number of degrees of freedom in a space (dimension), to measure the lengths of paths (metric), or to compare points for similarity. The purpose of this subclause is to define some additional structures, as well as to describe common operations on spaces that enable the construction of new spaces from existing ones; such operations on spaces correspond to additional structures on the corresponding hyperspaces-of-spaces.

### 6.2.3.2. Origin

Some hyperspaces have a distinguished point called the *origin*. For example all vector spaces have an origin, given by the zero vector.

If a hyperspace has an origin, then we can think of the paths from the origin to any given point as *addresses* for that point, as they explain "how to reach" the point. A vector is precisely a (linear) path from the origin to a point, and so we can think of vectors as 'self-addressing'.

### 6.2.3.3. Dimension

Many types of space are associated with a notion of dimension, which measures the "number of degrees of freedom" available to points in that space. The archetypal example of dimension is the dimension of the Euclidean spaces, which can be generalized to define a notion of dimension for any vector space. In this case, the dimension of a space is a function from Vect, the hyperspace of vector spaces, to $\mathbb{N}$, the set of natural numbers. This notion of dimension can be extended to cellular vector spaces: each cell of a cellular vector space is thus assigned its dimension.

However, the concept of dimension does not make sense for many other types of space, even if they can be equipped with other notions of size. For example, all graphs are in some sense 1-dimensional (because edges are 1-dimensional objects), but graphs can be measured in other ways (such as by the cardinality of their sets of nodes, or by measures of connectivity). Similarly, abstract data types do not typically have a meaningful notion of dimension.

### 6.2.3.4. Metric

### 6.2.3.4.1. Overview

A metric is a measure of the distance between the points of a space, or alternatively a measure of the lengths of paths in the space, defined in such a way that it behaves according to common intuitions about distances. More precisely, a metric on a space X is a non-negative function $d:X\times X\rightarrow\mathbb{R}_{\geq 0}$ such that the distance from a point to itself is 0 ($d(x,x)=0$) and such that taking a detour from the shortest path cannot decrease its distance ($d(x,y) + d(y,z) \geq d(x,z)$). Euclidean vector spaces can be equipped with many different metrics: the canonical choice is the Euclidean distance, which is defined as the length of the vector between any pair of points; more generally, every inner product (see 6.2.3.6) induces a metric. Similarly, graphs can be equipped with metrics, such as the minimum number of edges between each pair of nodes.

Other kinds of space, including kinds of vector space (such as the infinite-dimensional vector space of all functions into $\mathbb{R}$), may not have a sensible notion of metric.

### 6.2.3.4.2. Area and volume

In some cases, such as vector spaces over the reals or other differentiable spaces, it is possible to extend the notion of metric to supply notions of *area* or *volume* of subspaces, or to consider extended infinitesimal elements which 'integrate' to measure area or volume.

### 6.2.3.5. Similarity

Related to metrics, some spaces can be equipped with a measure of similarity between points; but it is important to note that a similarity measure and a metric are in general quite different. Intuitively, whereas a metric measures the distance between a pair of points, a similarity measure measures the angle between them. In some spaces — such as the space of n-dimensional unit length real vectors — the canonical choice of similarity measure coincides with the canonical choice of metric, but this is only a special case.

In general, a similarity measure on a space X is simply a function $s:X\times X^{*}\rightarrow F$, where $X^{*}$ is the *dual space* to X and F is a field such as ℝ. A standard example of a similarity measure is the cosine similarity measure on Euclidean vector spaces, which assigns to every pair of vectors the angle between them: in this case, the dual space $X^{*}$ is isomorphic to X itself. More generally, the dual space $X^{*}$ to a vector space X over the field F is the space of functions X→F, which can alternatively be denoted by [X,F]. Given a point x:X and a dual point f (a function X→F), f can be evaluated at x to produce the value f(x):F, which measures the similarity of x and f; this is the *canonical similarity measure* on X. In the case of Euclidean spaces, this canonical similarity is the cosine similarity: every point (every vector) x can be assigned a dual vector $x^{*}$, exactly by turning column vectors into row vectors; computing the value of $x^{*}y$ returns the cosine similarity between x and y. This canonical similarity measure extends to other kinds of space, such as the space DX of probability distributions on a space X, where it is also known as “validity” and corresponds to a kind of fuzzy truth value: in this case, a number between 0 (falsity) and 1 (truth).

### 6.2.3.6. Norm and inner product

The canonical similarity measure on a Euclidean space is precisely the *inner product* on that space. In general, an inner product $<\cdot,\cdot>:X\times X\rightarrow F$ satisfying properties of (conjugate) symmetry ($<x,y> = <y,x>^{\dagger}$), linearity ($<ax+by,z> = a<x,z> + b<y,z>$), and positive-definiteness ($<x,x> > 0$ for all nonzero x). An inner product is, therefore, a special case of a similarity measure.

Every inner product induces a norm $|\cdot|:X\rightarrow F$, which measures the “length” of the points in the space; typically, the points in a normed space behave like vectors. (However, not every norm arises from an inner product.)

Every normed vector space has a metric, defined by $d(x,y) = |x-y|$. (But not every metric arises from a norm.)

### 6.2.3.7. Operations on spaces

#### 6.2.3.7.1. Overview

Hyperspaces of spaces themselves also often have extra structure. For example, a collection of spaces of a certain type may combine into a new space (usually of the same type), without requiring the machinery of cellular spaces.

Typical operations that are available include: forming the product or tensor product of spaces; forming the sum or (disjoint) union of spaces; forming subspaces; and forming quotient spaces. The formation of products and sums of spaces can be understood as taking a collection of spaces and returning a new space formed from those components; the formation of a subspace can be understood as picking out the collection of points of a space all of which satisfy some property of interest; and the formation of quotient spaces can be understood as joining points together into new points that represent equivalence classes (for example, forming from a graph a new graph whose nodes are the connected components of the original one).

Well defined operations on spaces correspond to functors whose target is the hyperspace of spaces in question. For one example, forming the direct sum (disjoint union) of vector spaces corresponds to a type of functorial structure called a monoidal product on the hyperspace of vector spaces. For another example, quotienting corresponds to a type of functorial structure called a colimit.

#### 6.2.3.7.2. Connecting spaces

One use of such 'combinatorial' operations is to connect spaces together. For example, forming the sum of two topological spaces—or two cellular spaces, or two graphs or hypergraphs—corresponds to considering the two spaces as disconnected subspaces of a larger space (their disjoint union).

By identifying two sets of points, one in each part of the sum (such as the two sides of a doorway between rooms), and then quotienting accordingly, a space is obtained in which the two parts are connected via the two identified sets, which may thus be considered as a 'portal' between them.

The proceeding example considered quotienting two spaces, but there is nothing special about the binary case: in general, colimits may be used to produce 'n-ary' quotients, with 'n-ary portals' between them.

### 6.2.4. Requirements and Recommendations

HSML shall implement the basic concept of hyperspace.

HSML may enable the representation of the points and paths of each hyperspace. If paths are represented in an implementation of HSML, then the composition of paths shall be implemented, and this composition shall be associative and unital with respect to the identity paths.

HSML shall implement the following basic classes of hyperspace: Euclidean vector spaces; graphs; hypergraphs; cellular spaces with finite schemata, including geographic space as a special case; and abstract data types.

HSML shall implement Coordinate Reference Systems using ISO 19111:2019.

HSML shall include an <Geo/Earth> attribute scheme for any geographic location using the H3 DGGS h3geo.

HSML should enable the representation of the hyperspaces of basic classes of hyperspace, including the hyperspace of hyperspaces.

HSML should enable the representation of finite-dimensional (discrete) probability distributions over any hyperspace.

HSML may enable the representation of more general hyperspaces of probability distributions, and these may be equipped with the Fisher information metric structure (Amari, 2016, §3.5).

HSML should, where applicable, implement the following basic additional structures on hyperspaces: origin; dimension; norm; inner product; metrics; similarity.

HSML should implement the following additional operations on spaces: 1) on vector spaces: subspace, direct sum, and tensor product; 2) on graphs, hypergraphs, cellular spaces, and topological spaces: subspace, direct sum, and quotient spaces; 3) on hyperspaces: subspace, and (categorical) product; and 4) on abstract data types: subspace (subtype), product type, and function type.

HSML representation of hyperspace should utilize a shared, open standard for common hyperspaces or common hyperspace dimensions (such as time).

HSML implementations (specific schemas associated with HSML elements) shall publish serialization mechanisms for their hyperspace representations.

## 6.3. Domains and identities

### 6.3.1. Concepts

The key concepts discussed in this clause are Domain, Domain Authority, Universal Domain Graph, Identifiers, and Identity.

Domains are a central element of the Spatial Web. All ENTITIES that have a persistent identity as their defining essence are cast as DOMAINS.

- **DOMAIN**: ENTITY with identity through time that has been granted with rights and credentials. DOMAIN is an ENTITY in the Spatial Web ontology (6.6).

**Domain Authority**: An entity that is credentialed to have the ability to define within a Domain the norms and terms under which contracts are created governing: AGENTS, ACTIVITIES, and CREDENTIALS within that Domain.

**Universal Domain Graph (UDG)**: A distributed hypergraph containing all relations between all known Domains in the Spatial Web.

**Identifier**: A unique attribute or a combination of attributes that distinctly characterizes and distinguishes each ENTITY, and therefore also each DOMAIN, in the Spatial Web. This identifier is essential for recognizing, tracking, and interacting with entities consistently and unambiguously. Each entity in the Spatial Web has a unique Spatial Web Identifier (SWID).

**Identity**: A respect in which things are equivalent, or a relation of equivalence. Identity may be relative to a set of shared properties (qualitative), or absolute (numerical identity, cf. [95]). In qualitative terms, a Domain may have more than one identity (belong to more than one equivalence class), and several Domains can have the same identity.

In more detail, identity may encompass various aspects, such as:

**Unique Identifiers**: Specific labels or codes assigned to a Domain, such as a Domain name, IP address, or any other unique identifier in the Spatial Web network. Unique identifiers track the numerical identity of a Domain, ensuring it shall be uniquely located or accessed within the system.

**Characteristics and Attributes**: A Domain's qualitative identity may depend on a set of intrinsic and extrinsic characteristics. This may include the Domain's type, purpose, functionalities, or any other properties that define what the Domain is and what it can do.

**Contextual Relationships**: The identity of a Domain may be expressed in terms of its relationships with other Domains or entities. This includes hierarchical relationships, dependencies, or any interactions that help define the Domain's role or position within the larger system.

**Behavioral Patterns**: The qualitative identity of a Domain may also depend on its behaviors or patterns of interaction, especially in dynamic environments where a Domain's ACTIVITIES or responses contribute to its identification.

**Reputation and History**: For Domains that change or evolve, their identity may also involve historical data or reputation, reflecting past interactions, modifications, or any significant events associated with the Domain.

## 6.3.2. Spatial Web DOMAINS

### 6.3.2.1. Domain types

### 6.3.2.1.1. Overview

There are six well known types of Spatial Web Domains (see Table 2). Domains may encompass more than one type. Domains may exist for variable lengths of time. In addition to permissions, Domains shall include information about each entity's temporality and roles, functions assumed or parts played by the entity or thing in a particular place and time, and information regarding the provenance and material composition of the entity.

**TABLE 2:** Domain types based on their defining characteristics

| Type of Domain | Description |
|---|---|
| Geographic | Implicitly or explicitly associated with a location |
| Concept | Intangible concepts and abstract ideas shared by a community of users |
| Organization | Pertaining to membership within an entity |
| Agent | Individual domains with active states and agency |
| Person | Special subtype of agent maintaining a self-sovereign identity |
| Thing | Bounded items without agency |

### 6.3.2.1.2. Geographic DOMAIN

A geographic type of Domain refers to the features of worlds including, the earth, the moon, planets and virtual worlds. Domains of this type may have several geometric representations.

Example: “Mississippi River Watershed” is an example of a geographic type of Domain bounded by spatial coordinates. This watershed covers a vast area of land, spanning multiple states in the United States, including parts of Minnesota, Wisconsin, Iowa, Illinois, Missouri, Kentucky, Tennessee, Arkansas, Mississippi, and Louisiana. The spatial coordinates defining this watershed include the various tributaries, rivers, and streams that ultimately flow into the Mississippi River.

Within this geographic Domain, one may study and analyze various aspects, such as the flow of water, water quality, ecosystems, and the impact of human activities on the watershed. It serves as a practical framework for managing water resources, addressing environmental concerns, and understanding the interconnectedness of natural systems within a defined geographical area.

### 6.3.2.1.3. Concept DOMAIN

A concept type of Domain shall contain intangible concepts and abstract ideas that may not have a physical presence but hold significance for a community of users. Concept Domains shall organize and represent knowledge related to these abstract concepts and their relationships.

Example: “Deep Ecology” is an example of a concept type of Domain. Deep Ecology is an environmental philosophy emphasizing the intrinsic value of all living beings and ecosystems, advocating for a holistic and interconnected view of nature. In this conceptual Domain, one may explore and discuss abstract ideas such as “biocentrism” (the belief that all life has intrinsic value), “ecosystem integrity” (the balance and health of ecological systems), and “ecosophy” (a philosophy that integrates ecological and ethical principles). These abstract concepts within the Domain of Deep Ecology provide a framework for understanding humanity’s relationship with the environment and guiding environmental ethics, despite not having a physical, tangible presence.

### 6.3.2.1.4. Organization DOMAIN

An organization type of Domain shall pertain to entities, groups, or structures where membership plays a central role. It shall focus on how individuals or entities join, participate in, and contribute to an organized entity, often with shared goals, responsibilities, and decision-making processes.

Example: A worker-owned cooperative workplace is an example of an organization type of Domain. In this domain, the organization is typically a business or workplace where employees own the company. Each worker-owner has a stake in the organization’s success and decision-making; sharing equal ownership rights and responsibilities. This unique organizational structure allows each member to actively participate in decision-making processes, ranging from product choices and working hours to broader business strategies. Profits generated by the worker-owned cooperative are shared among its members based on their contributions. In this example, the organizational

Domain of the worker-owned cooperative defines the structure, governance, and shared ownership, making it distinct from traditional hierarchical corporate workplaces.

### 6.3.2.1.5. Agent DOMAIN

An AGENT type of Domain shall focus on individual entities that possess active states and the ability to effect changes in the world when performing ACTIVITIES. These entities may be characterized by their capacity for agency, where they can influence or interact with their environment.

Example: An example of an AGENT type of Domain is an educational personal assistant AI. This AI entity has the ability to actively interact with students, adapt to their needs, and assist in their educational journey. It may assess students' strengths and weaknesses, provide personalized learning recommendations, answer questions, and even adapt its teaching approach based on individual learning styles. The AI's active state and agency enable it to enhance the learning experience for each student, making it an effective tool in the educational Domain.

### 6.3.2.1.6. Person DOMAIN

A person type of Domain refers to entities belonging to the broader agential Domain but maintaining the capability to control their own Self-Sovereign Identity.

Example: A person type of Domain is a human person. Each human being represents a personal Domain with a Self-Sovereign Identity. This identity encompasses aspects such as name, sex, birthdate, nationality, personal beliefs, and individual experiences. Human persons are distinct entities within the broader agential Domain of sentient beings, and they possess the capacity for self-awareness, decision-making, goal-setting and autonomy. Each person's personal Domain shall be unique, reflecting their individuality and the diversity of human identities and experiences.

### 6.3.2.1.7. Thing DOMAIN

A thing type of DOMAIN shall encompass entities or objects that are bounded items without agency. These entities shall be passive and lack the ability for autonomous decision making or proactive behavior.

Example: A thing type of Domain is a coffee mug. A coffee mug is an inanimate object designed for holding and serving beverages like coffee or tea. It is a bounded item with specific physical attributes, such as shape, size, material composition, and design. Coffee mugs do not have active states or agency; they remain passive and serve their purpose as vessels for holding liquids. They do not set goals, make decisions, perform ACTIVITIES, or have the capacity for self-awareness.

### 6.3.2.2. Domain authority

There shall be a Domain Authority for every Spatial Web Domain. The Domain Authority shall be an entity that is credentialed to define within a Domain the terms under which CONTRACTS are created for: AGENTS, ACTIVITIES, and CREDENTIALS within that Domain. The Domain Authority shall be an individual or group that is either self-credentialed or credentialed by the Spatial Web Registration Authority (SWA)[1] or their accredited Registry. A Registry shall be a company that maintains the database of Spatial Domain names for a particular top-level Spatial Web Domain, such as .com. Domain Authorities shall have the capacity to issue HSML Credentials that constrain the execution of activities within the Domain they govern. An example of a Domain Authority may be the USA Federal Aviation Administration. The FAA may define the AGENTS, ACTIVITIES, and CREDENTIALS allowable in US airspace, such as who is a pilot, what they may do while flying a plane, and what CREDENTIALS are required to hold a pilot's license.

The SWA is a steward for the worldwide, interoperable implementation of the Spatial Web protocol. Following the Guiding Principle of Responsibility, which emphasizes the imperative to develop technology ethically and conscientiously for the betterment of all humanity, the Spatial Web shall enable capabilities to tackle significant global challenges. These challenges include, but are not limited to, combating human trafficking, addressing the absence of verifiable identities, resolving issues related to unbanked populations, mitigating the impact of invasive state and corporate surveillance, and sustainably managing planetary resources. The SWA shall recognize that legal authorities may play a role in matters of Domain Authority. The ethical application of emerging technologies may necessitate the establishment of new governmental regulations and the evolution of cultural norms and standards of behavior.

#### 6.3.2.3. Domain sovereignty

Spatial Web Domains may include digital twin models of physical things (i.e., a person, a building, a park, etc.), categories of things (i.e., flowers, roses, gifts) and purely digital models of spaces (i.e., Metaverses). Any virtual world may be linked to a Spatial Web Domain in the physical world. General categories of things are part of the Global Commons and shall be publicly owned in perpetuity. The Spatial Web enables the capability for all human persons to receive without cost an irrevocable and non-transferable individual Spatial Web Domain, with respect to which that individual will, upon acceptance, be registered as a Domain Authority at no cost (where the exercise of such authority may be subject to limits imposed by relationships to other authorities, e.g., citizenship).

The UDG for the Spatial Web shall be a Global Commons owned by all humanity, both those currently living and future generations.

The Spatial Web Registration Authority shall be responsible for holding these assets in trust and managing their stewardship.

The Spatial Web Registration Authority shall grant temporary use rights of Domains to entities for the general benefit of all life.

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[1] At the time of publication of this standard, the Spatial Web Foundation (https://spatialwebfoundation.org/) was assigned as the Registration Authority for the Spatial Web Domain ID (SWID).

### 6.3.2.3.1. Non-Person Spatial Web Domains

A Spatial Web Domain shall provide support for adding definitions or behaviors inside HSML-compliant software describing reality from multiple perspectives and correlated hierarchies for a bounded area or space. Spatial Web Domains shall provide a distinct container for things such as an entity, a legal body, or an idea, without having to be the thing. In the Spatial Web, objects shall be indexed within Spatial Web Domains with a knowledge graph. HSML shall require all Entities to have a SWID attribute using the W3C DID-core syntax; the Domain and SWID may, or may not be registered. Objects shall be searchable within the Spatial Web Domains in which they are nested. Spatial Web Domains shall include a Domain Authority that governs digitally mediated rights / permissions regarding who / what is authorized to access the Domain, what content or data is available to view, who may publish and modify content, and who may transact or interact within the space.

Spatial Web Domains shall provide a reference to or proxy for a definition of the boundaries of an area enabling them to become “bounded contexts” unto themselves, while simultaneously being partially or entirely within other Spatial Web Domains; fully or semi-nested and connected geophysical locations or logical structures. This nested architecture shall allow Spatial Web Domains to maintain their intra-relational and inter-relational domain coherence via a Spatial Web sub-Domain.

### 6.3.2.3.2. Person Domains

Following the Guiding Principles of Ownership, Security and Privacy, which emphasize: humans own their data and digital property and choose with whom they share their data; individual data is secure and transferable across any physical or virtual space; and individuals control their decentrally-stored digital identity; the Spatial Web shall enable Self-Sovereign Identity (SSI) capabilities that provide every human free, irrevocable, non-transferable, Domain Authority over their individual body’s Spatial Web Domain.

SSI infrastructure enables the capabilities of users to maintain privacy and set boundaries regarding access to their data, so that stakeholders may protect their autonomy while conducting joint work and collective activities. The Spatial Web shall help ensure “privacy by design” at all levels. Transactions within the Spatial Web shall help ensure the privacy of personal data while allowing for verification and auditability. Personally Identifiable Information (PII) within a Spatial Web Domain shall not be made publicly available without explicit consent of the Spatial Web Domain owner. Every interaction between Spatial Web Domains shall use a randomized, one-time-use, “trustless” identifier; preventing unwanted correlation / tracking of Domain behavior across sessions, networks or services.

Privacy restrictions shall make allowances for decentralized data storage with provable replay capability for attributes listed in credentials. Data such as those used to train AI models or made available for use in real-time execution shall be made deterministically available as snapshots for future use related to the evaluation of algorithm performance in specific contexts or the expression of rights such as “the right to repair”.

Internode communication may make use of a zero-knowledge proof (ZKP) system, as enabled for example by Decentralized Identity Foundation. In contexts in which ZKP is required, all such communication shall take place using a zero-knowledge messaging layer that includes a combination of verifiable credentials (discussed further in 6.5), and openly defined and managed protocols for all interactions.

### 6.3.2.3.3. Benefits of self-sovereign identity

Derivative benefits from self-sovereign identity include the following:

- **Security:** Identifying information shall be protected from unintentional disclosure.
- **Control:** The identity owner shall be in complete control of who can see and access their data and for what purposes.
- **Portability:** The identity owner shall be able to use their identity data across the entire Spatial Web.

The Spatial Web shall enable the capability for each individual human person to completely own, control and manage their identity. SSI information may be owned by the user and stored out of access of centralized organizations; whenever a user needs a specific service, they may attest to the required data using cryptographic methods. Each individual's identity may be a digital twin of themselves; a persistent digital record of assets and identity transactions. Every human person's Spatial Web Domain ID (SWID) may include an encrypted wallet, enabling their digital identity and digital assets to be interoperable and transferable across the Spatial Web. Stakeholders may each have a SWID unique to their wallet, which may not be transferable to other wallets. A set of public and private keys may encrypt their communication, and these may be the basis for maintaining digital assets while moving through Spatial Web Domains without changing credentials. Different Spatial Web Domains may require different levels of authentication.

### 6.3.2.4. Requirements and recommendations—domains

- HSML shall provide a domain type attribute; Acceptable values for Domain Type are Geographic, Concept, Organization, Agent, Person, Thing; other types may be added if they do not duplicate these.
- Domain-specific architecture specifications shall enable the creation of Domains as containers for Domains.
- Spatial Web Governance shall require a Domain Authority for every Spatial Web Domain.
- Spatial Web Governance shall enable credentialed Domain Authorities to set the norms and terms under which contracts are created for: AGENT, ACTIVITIES, and CREDENTIALS with a Domain.
- Spatial Web Governance shall assess the Domain Authority management of a domain using the criteria of Trust, Interoperability, Privacy and Security (TIPS).
- Spatial Web Governance shall enable each individual human in the Spatial Web to maintain Self-Sovereign Identity (SSI).
- Spatial Web Governance shall enable general categories of things to be publicly owned in perpetuity.
- Spatial Web Governance shall enable human persons to receive without cost an irrevocable and non-transferable individual Spatial Web Domain at birth.

- Spatial Web Governance shall enable the Spatial Web to be a Global Commons owned by all living and future humanity.
- Spatial Web Governance shall enable the stewardship of all Spatial Web assets in trust.
- Spatial Web Governance shall enable the temporary use rights of Domains to entities for the general benefit of all life.

## 6.3.3. Spatial Web Identifiers (SWIDs)

### 6.3.3.1. Decentralized identifiers

A decentralized identifier (DID) is a type of identifier for digital identity devoid of any type of centralization (see W3C did-core). DIDs enable verifiable, decentralized digital identity. A DID refers to any subject (e.g., a person, organization, thing, data model, abstract entity, etc.) as determined by the controller of the DID. DIDs are Uniform Resource Identifiers that associate a DID subject with a DID document allowing trustable interactions associated with that subject.

A DID acts as a permanent identifier which never changes and is resolvable to metadata. It acts as a verifiable identifier through cryptography and can be used to encrypt communication channels for safe and secure messaging. An entity may have any different number of DIDs for many different purposes. A DID Document may define a given verification method (e.g., cryptographic public key) to evaluate a specific proof that was created with a unique purpose (e.g., authentication).

DIDs provide a means for proving digital proof of identity without reliance on a central authority. The benefits of DIDs, as defined by W3C did-core and Decentralized Identity Foundation, include providing or enabling:

- Provider-Independent Identifiers (i.e., addresses or IDs are decoupled from a specific provider)
- Signature verification and Verifiable Credentials (VCs), which allow for instantaneous verification of arbitrary statuses
- Authenticated encryption
- Transport-agnostic security
- Feature discovery

Spatial Web Identifiers (SWIDs) shall serve as DIDs for entities within the Spatial Web. Anything in the Spatial Web that is addressable shall have a SWID defined using W3C did-core. SWIDs may be registered in a system of distributed, decentralized registries. Spatial Web Domains may be geopolitical (e.g., Earth, countries), authority-driven or IP work-related consistent with 6.3.2.1. A given Spatial Web Domain identifier may have multiple associated qualified names. Authoritative credentialed domains may be issued with unique relationships defined in SPACEs (.Earth).

### 6.3.3.2. SWID methods

Spatial Web Domains provide support for SWID methods. This is essential to help ensure that these identifiers are resolvable by entities operating within the Domain.

Entities within a Domain shall be expected to clearly specify which SWID Methods they are capable of supporting. These SWID Methods are not only critical for resolving SWIDs but also for revoking them. These methods shall dictate the process of writing associated SWID Documents, which describe various properties of SWIDs in relation to their holders. One of the key aspects detailed in these documents shall include authentication mechanisms, all within the framework of a specified data model.

The architecture of this system is based on W3C Decentralized Identifier core standard which provides a comprehensive reference for DID methods. A more detailed exploration of these methods which may be used in the Spatial is provided in W3C NOTE-did-spec-registries-20240831.

The Spatial Web shall support one or more SWID methods based on the W3C DID specification. A Spatial Web SWID method shall specifically support the functionality required for Public and Top Domains. The DID method identifier for the SWID Method will be did:swid. A Spatial Web Registry will manage the registration of all Public and Top domains using the Spatial Web SWID Method. The Spatial Web Registry will be managed according to 6.3.6.

All DIDs have the syntax did:"method-name":"method-specific-id". The Spatial Web DID Method syntax is did:swid:"method-specific-id"

Consistent with DIDs, SWIDs shall include an implicit referenceability to SWID Documents via registered "methods," which specify how to both resolve and revoke SWIDs and how to write SWID Documents themselves. A SWID Document provides additional elements needed for distributed communications, namely:

- ID: per-authority unique object identifier.
- ENDPOINT(s): one or more servers that can be used for distributed consensus. If only one is given, then a non-consensus-based mechanism is assumed.
- METHODS: namespaces defining protocols and/or versions to resolve, utilize, and revoke SWID Documents.
- ENCRYPTION: specific encryption/signing algorithm identifier.
- Uniqueness: By ensuring unique domain names and including the domain hierarchy in the SWID, the SWA can ensure that there are no duplicate IDs.

#### 6.3.3.3. Identity provenance

The identities of all Spatial Web Domains shall be verifiable by a SWID, and may support distributed ledger technology. All transactions, including sensor data updates received from IoT sensors, shall be time stamped and have Domain-relevant provenance, such that identity may be automatically updated and reaffirmed continuously, and all transactions may be cryptographically signed if desired.

For there to be Domain-relevant provenance in the Spatial Web, Domains that generate SWIDs associated with entities involved in transactions shall be able to verify the issuer of such SWIDs. The Domain-relevant provenance may take the form of historical records or structural validity checks.

Person Domains shall have a globally-usable, Self-Sovereign Identity, in such a way as to own their data and digital property and control with whom they share this data or property. Domains shall be able to issue and revoke access to their digital profile at all layers within Spaces with a high degree of flexibility and transparency, enabling the use of ZKPs where suitable.

All transactions shall be designed to be auditable without counterparty risk to each party participating in the transaction.

#### 6.3.3.4. Requirements and recommendations—identifiers

HSML shall require a SWID for all ENTITIES; SWIDs shall conform to W3C Decentralized Identifier core standard and may conform to Decentralized Identity Foundation standards.

HSML shall require SWIDs to include an implicit referenceability to SWID Documents consistent with SWIDs being DIDs.

HSML shall define SWID Documents to include elements as defined in 6.3.3.2.

UDG shall validate SWIDs generated using SWID Method prior to issuance, e.g., assess uniqueness.

Domain-specific architectures shall provide a system of distributed, decentralized registries for SWIDs.

Domain-specific architectures shall enable objects to be searchable within the Spatial Web Domains in which they are nested.

HSML shall include an attribute for .Earth DOMAINS using a SWID schema that uniquely identifies cells on the surface of the Earth.

Spatial Web Governance shall manage a .Earth DOMAIN including a scheme for SWIDs uniquely identifying cells on the surface of the Earth.

HSML shall define attributes for DOMAINS for SWID methods as required in W3C Decentralized Identifier core standard and may require attributes from W3C NOTE-did-spec-registries-20240831.

Domain-specific architectures shall provide methods that allow SWIDs associated with entities involved in transactions to be verified by the issuer of such SWIDs. The Domain-relevant provenance may take the form of historical records or structural validity checks.

HSML shall require that Person Domains have a globally-usable, Self-Sovereign Identity.

Spatial Web Governance shall enable Domains to include digitally mediated rights and permissions regarding who and what is authorized to access the Domain, what content or data is available to view, who may publish and modify content, and who may transact or interact within the space.

HSML shall include one SWID Method defined for the Spatial Web that meets all Spatial Web SWID requirements.

UDG shall include a Spatial Web registration service for Public and Top domains.

UDG shall, for audit purposes, register all SWIDs related to all public and top domains in a Spatial Web Registry.

UDG shall enable verification and validation services for domains prior to their registration.

UDG shall support the generation of SWIDs one at a time, such as for Top Domains, or generate many at a time, such as for Public Domains.

UDG shall ensure SWID uniqueness.

UDG shall ensure that SWIDs are maintained in the Spatial Web Registry.

### 6.3.4. Domain relationships

#### 6.3.4.1. Overview

Spatial Web Domains have a variety of attributes and relationships with one another, reflecting the complexity of the real world and its vast interconnectedness. The UDG's ability to accurately represent and navigate arbitrarily complex relationships—including hierarchical, heterarchical, and nested—is central to its role as the foundational component of the Spatial Web and ensures that Domain-specific data is not only coherent within itself but also in coordination with other Domains. This ability is a result of the UDG being formalized in the language of hyperspace.

The formalization draws on ideas from mereology (the theory of parthood relations), order theory (the study of hierarchy), and category theory (the mathematics of structure). In the Spatial Web, domains may be related in structures of arbitrary complexity. However, this clause focuses on hierarchy, heterarchy, and nesting as shown in Table 3 and Figure 16.

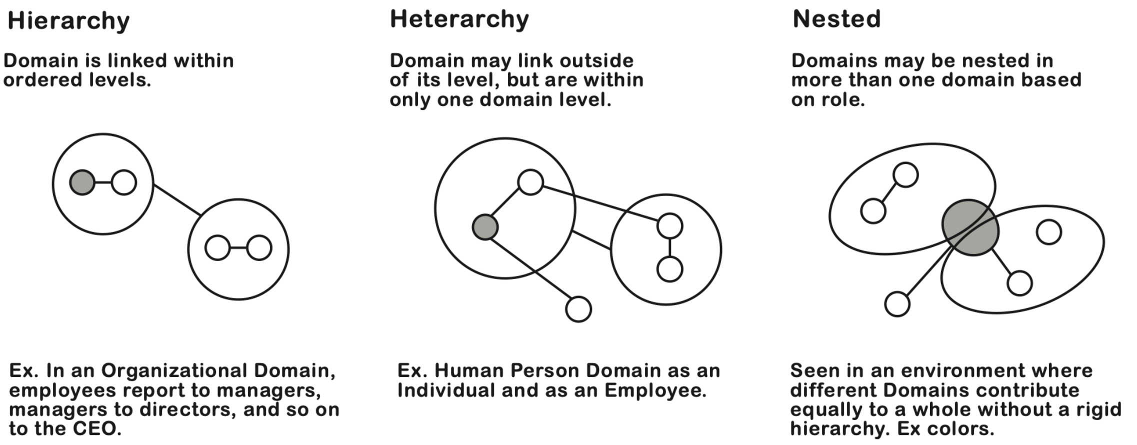
It is certain that there will be inconsistencies in the UDG, similar to inconsistencies in the WWW. Some inconsistencies will be from relationships between Domains as described in this clause. Other inconsistencies will be regarding the content of Domains in the UDG. UDG operations will need to be resilient to inconsistencies in the relationships between nodes and the content of nodes.

**TABLE 3:** Spatial Web Domain relationship types

| Type of Domain Relationship | Description |
|---|---|
| Nested | Domains are entirely contained within another Domain |
| Hierarchical | Domains are arranged in ordered levels |
| Heterarchical | Domains are unranked |

These relationships are shown in Figure 16 and described in 6.3.4.

**FIGURE 16:** Mereological relationships in domain hypergraphs



## 6.3.4.2. Order relationships in hyperspace

In hierarchical and similar contexts, a collection of domains may be naturally grouped into an *ordered set*, whose order relationship is defined by the domain hierarchy. The concept of ordered set may in turn be defined using the tools of hyperspace.

A **pre-ordered set** is a hyperspace such that, between any two points, there is at most one path, which may be denoted $\leq$. More explicitly, a pre-ordered set is a set $X$ along with a relation $\leq$ on the elements of $X$ that is reflexive ($x \leq x$, for all elements $x$), antisymmetric (if $x \leq y$ and $y \leq x$, then $x=y$), and transitive (if $x \leq y$ and $y \leq z$, then $x \leq z$).

An **ordered set** is a pre-ordered set in which every pair of elements is comparable: i.e., either $x \leq y$ or $y \leq x$ for every pair of elements $x,y$. In hyperspace language, this means that there is a path between every pair of points.

Collecting domains into ordered sets (or more general hyperspaces) permits formalizing their relationships. Domains in a pre-ordered set may or may not be related, or 'comparable', whereas domains in an ordered set are always in some relation to one another.

## 6.3.4.3. Hierarchy

Informally, a hierarchical relationship consists of domains arranged in ordered levels, with each level subordinate to the one above it. For example, in an organizational Domain, employees report to managers, managers to directors, and so on (in strict order) to the CEO. In the UDG, this allows for top-down navigation and transformation, following a clear path of authority or progression.

To formalize such relationships, the preceding order-theoretic concepts may be used. In the simplest case, every point (every domain) in an ordered set represents its own level of hierarchy.

In more complex cases, multiple domains may be grouped into each individual level of hierarchy by partitioning the ordered set $X$ into subsets $X_1$,$X_2$, etc., such that if $i<j$

then every element of $X_i$ is less than or equal to every element of $X_j$. Such a partition formalizes the *levels* of the hierarchy.

### 6.3.4.4. Multi-level (or dependent) hierarchies

The preceding approach to modeling hierarchy is as rich as order theory allows, but at times it may be useful to incorporate more structure than an ordered set allows. As an example, it may be desirable to capture relationships between levels of hierarchy, but not within them. The fact that hyperspaces themselves collect into a hyperspace means that such complex relationships may be easily incorporated into the framework.

The partition of the preceding subclause yields an ordered set whose points are the levels of the hierarchy, and where there is a path $i<j$ whenever level i is below level j. Let this ordered set be denoted H, and note that H does not yet make any reference to domains. Thus to incorporate a collection of domains, suppose that they are collected into a hyperspace, D. (For simplicity, this hyperspace may be totally unstructured, in the sense that there need not be any paths between different domains in D; but this need not be the case.) Then, an assignment of levels of hierarchy to D is simply a functor $D \to H$, a path in the hyperspace of hyperspaces.

If the domains of D themselves represent a 'finer-grained' hierarchy (for instance, "levels within the levels" of H), then one may continue this procedure arbitrarily far. For example, supposing a yet-more-fine-grained hyperspace of domains E, these may be assigned to D and then to H by the composite $E \to D \to H$. In this way, the hyperspace formalism captures multi-level, or otherwise dependent, hierarchies.

### 6.3.4.5. Heterarchy

Not all domains exist in hierarchical relationships, even of the generalized multi-level sort. The hyperspace formalism is able to capture such non-hierarchical, or *heterarchical*, relationships. Intuitively, a heterarchical relationship involves elements that are unranked or that may be ranked in multiple different ways. As an example, heterarchical relationships may be seen in a collaborative environment where different Domains contribute equally to a whole without a rigid hierarchy.

Formally, a heterarchy may be defined as a pre-ordered set of domains that is not totally ordered and therefore does not constitute an ordered set.

Even this order-theoretic notion may be too restrictive to capture some arrangements of domains, for in an ordered set there may be at most one path between any two elements. Thus, if there should be multiple ways to relate domains, then the collection of domains may constitute a general hyperspace, without restriction. This situation was already indicated in the preceding subclause, and indeed functors (paths between hyperspaces) can be used to capture arbitrarily complex domain relationships. It is for this reason that hyperspace is such a fundamental concept in the architecture of the Spatial Web.

### 6.3.4.6. Nested and adaptive domains

One type of domain relationship that is beyond order theory, but which does not require the full generality of abstract hyperspaces, is the case of nested relationships. These occur when one domain contains one or more other domain(s). At each level of nesting, it may also be possible to consider multiple domains in parallel or otherwise aggregate them together. As a source of examples, nested relationships may be found in geographic situations: a city is nested within a country, but it is nonetheless possible to consider cities together, at the city level.

Such nested domains may be formalized using the hyperspace framework. In greatest generality, a nested collection of domains constitutes a *multicategory* or *operad*: a kind of hyperspace in which the domains of paths may consist of lists of points, rather than single points. This structure precisely captures the essence of nesting: the 'n-ary' paths (those whose domain contains lists of n points) represent ways in which to combine n systems into a single system.

It is possible to define a notion of operad without generalizing the definition of path in a hyperspace, by using hyperspaces equipped with a *monoidal product* $\otimes$, a way to aggregate two points into one. For example, if the hyperspace of domains D consists of regions in a country, and $C_1$,$C_2$,$C_3$ are cities, then a path $C_1 \otimes C_2 \otimes C_3 \to M$ may be understood as representing the nesting of the three cities in a larger metropolitan area M.

Nested domain structures are more flexible than hierarchies, despite their similarity, because nesting permits multiple relationships between each pair of domains. For example, hierarchy was introduced in 6.3.4.3 in an organizational context, with workers reporting to managers, who report to directors, who report to a CEO. But in real organization, this communication is bidirectional; moreover, a director may decide to reorganize their teams, thereby changing the domain relationships.

Such adaptation is not possible in a strict hierarchy, but it is possible in nested structures. First, the relationships in a nested collection of domains may represent bidirectional communication links (of which there may be many). Second, in a hyperspace of domains D with a monoidal product, this product has an *adjoint*: a domain [Y,Z] which represents all the ways of relating two other domains Y and Z; that is, it represents the paths $X \to Y$ in D. Adjointness means that relationships $X \to [Y,Z]$ are equivalent (bijective) to relationships $X \otimes Y \to Z$, but a relationship of the former kind may be interpreted as saying that the domain X is able to control or influence the relationship of Y to Z.

A collection of nested domains whose monoidal product $\otimes$ has such an adjoint may be considered *adaptive*.

### 6.3.4.7. Dynamic domain relationships

The formalizations described in 6.3.4.2, 6.3.4.3, 6.3.4.4, and 6.3.4.5 all involve "static" structures: collections of domains whose relationships, once defined, do not change. However, the real world is not like this: it is constantly changing. For example, considering an adaptive collection of domains, it may be desirable to allow an instruction to reorganize domains to be actualized. The Spatial Web accommodates such dynamism, thanks to the flexibility and richness of the hyperspace framework.

Formally, capturing this process of change involves moving from static to dynamic hyperspaces: instead of a fixed collection of paths between each pair of points, a dynamic hyperspace has a collection of *dynamical systems that yield paths*. Mathematically, this corresponds to the passage to enriched categories; specifically, hyperspaces enriched in dynamical systems. A dynamic adaptive collection of domains is then a collection of nested domains in which a director may reorganize their teams (for example), and the teams are enabled to enact this instruction.

### 6.3.4.8. Composition and aggregation

The preceding formalism is compositional; domain relationships may be composed as long as targets and sources match, but this does not mean that any particular domain relationship is always one of constitution: how relationships are to be understood depends on the particular context and collection of domains at hand. In a nested context, the relationship may be a physical constitution, but in a hierarchical one (such as the organizational example in 6.3.4.3), the relationships may relate to the delegation of power.

When a hyperspace of domains is equipped with extra structure, such as the monoidal products used in nesting, this structure may be used to combine domains into complexes in ways that respect the existing relationships; in this way, it is possible to aggregate domains together. For example, if $C_1 \rightarrow R_1$ and $C_2 \rightarrow R_2$ represent the containment of two cities in two regions, and if $C_1 \otimes C_2$ represents the aggregation of the two cities, then there will be a relation $C_1 \otimes C_2 \rightarrow R_1 \otimes R_2$ that represents the aggregation of the two relationships. (This is to say that the aggregation structure $\otimes$ is formalized as a functor.)

It is possible to define a hyperspace of domains that contains no non-trivial relationships: domains in such a collection are unrelated. Nonetheless, it is also possible to equip such collections with monoidal structure, so that domains may be aggregated without imposing further relationships.

### 6.3.4.9. Requirements and recommendations—domain relationships

HSML shall enable representation of the Table 3, including representation of complex and dynamic domain interactions in a structured and coherent manner.

HSML shall enable cross-Domain entities as well as providing robust methods for defining Spatial Web Domain-specific entities.

Domain-specific architectures shall enable Domains to be defined using Table 3.

Domain-specific architectures shall enable a nested architecture that allows Spatial Web Domains to maintain their intra-relational and inter-relational domain coherence via a Spatial Web sub-Domain.

Domain-specific architectures should enable “privacy by design” at all levels.

Spatial Web Governance shall enable “privacy by design” at all levels.

UDG operations shall be resilient to inconsistencies in relationships between nodes and in the content of nodes.

## 6.3.5. Universal Domain Graph (UDG)

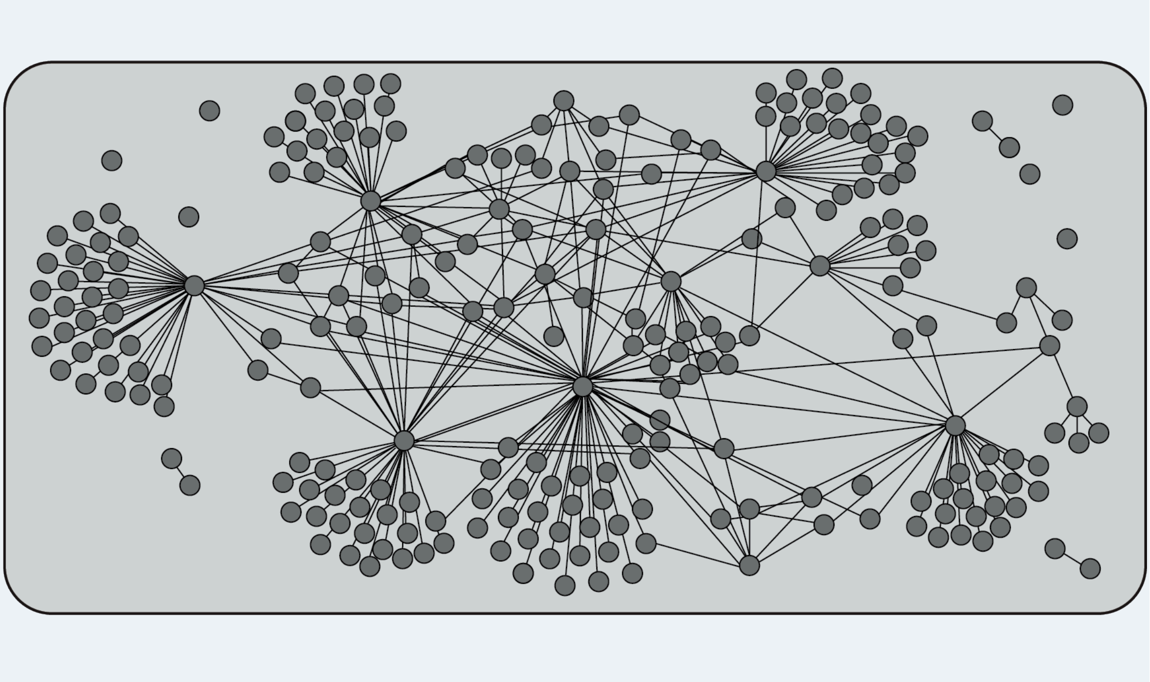
### 6.3.5.1. Overview

The UDG shall be a publicly accessible knowledge graph that serves as a key infrastructure component of the Spatial Web. The UDG shall be similar to existing knowledge bases held within current web platforms, but shall be a public utility compared to proprietary platform knowledge bases.

The UDG shall be a structured graph that groups domains and allows for nested, hierarchical and heterarchical searches and transformations within and across domains. It shall enable efficient and accurate modeling and analysis of domain relationships, which are essential for the Spatial Web. The UDG shall allow for the organization of domains into an architecture that maintains intra-relational and inter-relational domain coherence, allowing for the coordination and integration of domain-specific data and content.

The UDG is a hypergraph containing all relationships between all known SWIDs in the Spatial Web. The UDG is composed of nodes and links where the nodes are ENTITIES and the links are relations between the ENTITIES. Figure 17 shows a notional visualization of the UDG with varying cluster patterns of the nodes. Based on current large knowledge graphs and a DGGS of the Earth where every cell is a decimeter-scale node, the global UDG contains approximately $10^{14}$ nodes.

**FIGURE 17:** Notional structure of the UDG



### 6.3.5.2. UDG accessibility

Given the importance of the UDG to the Spatial Web, it is critical to help ensure that it be accessible to all and maintained in a transparent and trustworthy manner. As such, the UDG shall be a public utility that is widely accessible and usable by all Spatial Web participants.

Domain relationships listed in 6.3.4 are important for several reasons:

- Interoperability: By recognizing how Domains interact, the UDG may facilitate the exchange of information between different Domains, ensuring that data may be shared and used across various contexts seamlessly.
- Complex Searches: With nested, hierarchical, and heterarchical relationships defined, searches may be more sophisticated, allowing users to find information that is contextually relevant across multiple dimensions and scales.

- **Modeling and Analysis**: Understanding these relationships shall be essential for modeling the real world in a way that reflects its complexity, enabling better analysis, forecasting, and decision-making.
- **Adaptability and Scalability**: As entities move and relationships change, the UDG's structure must adapt. Recognizing these dynamic relationships ensures that the UDG remains relevant and accurate.
- **Governance**: Understanding the intricate relationships between Domains enhances governance by promoting a more comprehensive, coherent, and effective approach to policy-making, planning, and decision-making. It shall enable governments to navigate the complex challenges of our interconnected world more successfully and promote the well-being of their constituents and the broader society.

### 6.3.5.3. Requirements and recommendations—UDG

- UDG shall provide for distributed operations of the UDG including propagation of changes and consistency.
- UDG shall provide Spatial Web Domain interactions that are seamlessly managed and integrated.
- HSML shall enable modeling of heterogeneous Spatial Web Domains, including comprehensive methods for constructing and maintaining a distributed UDG.
- UDG shall implement Spatial Web Domain registration processes as defined in 6.3.6.
- HSML shall enable modeling of heterogeneous Spatial Web Domains, including comprehensive methods for constructing and maintaining a distributed UDG, modeling of heterogeneous Spatial Web Domains, and modeling diverse and complex Spatial Web Domain structures.
- Domain-specific architectures shall enable a publicly accessible UDG that efficiently and accurately models domain relationships.
- Domain-specific architectures shall enable Spatial Web entities to be indexed within Spatial Web Domains with the UDG knowledge graph.
- Spatial Web Governance shall define policies for managing the UDG.
- Spatial Web Governance shall define management practices consistent with the UDG as a public utility.
- UDG design and procedures shall enable a range of methods for accessing the UDG from basic, open access to UDG access services with enhanced value in accord with economic exchange, e.g., fee, advertising, etc.
- Domain-specific architectures should provide a basic, open access to domains critical to cross-domain interoperability.
- Spatial Web Governance shall foster development of Spatial Web Nodes that provide open and free access to the UDG.

## 6.3.6. Registration and governance

### 6.3.6.1. Overview

The Spatial Web Registration Authority (SWA) is the entity at which Spatial Web Identifiers (SWIDs) shall be registered. The SWA may designate one more entities to manage the registry of SWIDs for entities on the Spatial Web. The SWA, on behalf of the public, shall establish general rules for changes to the UDG, such as Domain Authority, allowable Domain names, Domain claim dispute resolution, cost of registration, and restrictions on the addition or deletion of names.

The Spatial Web Universal Domain Graph (UDG) governed by the SWA shall map three (3) types of domains:

1. Public Domains, which are knowledge commons. Public domains have no owner, and are for the public good. The SWA acts as the steward of Public Domains. Examples of Public Domains include, though are not limited to, concepts (e.g., baseball, weather, applied physics).
2. Private Domains, which are registered by individuals or by organizations and their agents. Private Domains are managed by, and have their norms defined by, Domain Authorities. Examples of Private Domains include, though are not limited to, a specific professional baseball team, a bureau or department within a government, the autonomous car of a physical person, a sensor device attached to the autonomous car of a physical person, a specific department within a particular university, etc.
3. Top Domains (top level private Spatial Web domains), which are the highest domains in a hierarchy of Private Domains. Top Domains are represented, managed, and governed by Domain Authorities. Top Domains register only one domain. However, they can be linked to all relevant Public Domains in the UDG. This ensures discoverability, governance, inheritance, and interoperability without the need for multiple SWIDs. Examples of Top Domains include, though are not limited to, a professional baseball league, which may be the Top Domain in a hierarchy including a private domain such as a baseball team within that league.

The SWA shall implement these decisions, adding, deleting, and modifying the database entries to reflect the entry, exit, and changed status of computers. For a private space to be available on the Spatial Web, the user shall approach the SWA and request to be registered. The Registry shall register the space by adding the space's name-number pair to the UDG.

A contract shall be the mechanism used for connecting entities interacting on the Spatial Web. The Spatial Web shall be a Global Commons network of networks; a portion of spaces registered in the UDG shall allow access to private networks managed by network administrators. Each entry in the UDG shall be accompanied by a contract between the central SWA and a registry network administrator. The contract shall specify the usufruct rules and conditions for inclusion in the UDG. Thus, every registry network in the Spatial Web shall have a contract with the SWA overseeing the UDG.

For generic top-level Domains such as .eco, .coop, .com, .gov, and .edu, the SWA shall have direct hierarchical authority over the institutions (registrars and registries) responsible for assigning Spatial Web Domain names to customers and running the systems that translate names into numbers. Registrars (e.g., Hover) shall be companies the SWA accredits to sell usage rights of Spatial Web Domain name registrations to customers. A registry shall be a company that maintains the database of Spatial Domain names for a particular top-level Spatial Web Domain, such as .com. The Registry shall generate the authoritative address resolution file for converting between Spatial Domain names and Spatial Web addresses.

The SWA shall distribute names and numbers; authorize the addition of new top-level Domain names (e.g., .info); determine Domain Authority, determine what is censorship of Spatial Domain names; resolve trademark disputes; maintain an authoritative record of how these Spatial Web Domain names and Spatial Web addresses map together; and operate the root servers that convey this authoritative mapping to Spatial Web servers around the globe.

An individual or legal entity wishing to register a Spatial Web Domain name under a top-level Spatial Web Domain ("gTLSD") may do so by using a registrar accredited by the SWA. Generic categorical top level Spatial Domains shall always be publicly owned (ex. colors, emotions, fields of study, etc.). AI shall automatically assign Spatial Web Domains to geographic locations. Individuals or organizations seeking usage rights of a Spatial Web Domain shall be required to provide proof of usage credentials.

There shall be many accredited Registrars located throughout the world in order to provide support in local languages. The relationship between a Spatial Web Domain name registrant and the SWA-accredited Registrar shall be governed by a Registration Accreditation Agreement (RAA) between the two parties.

Any entity that wants to offer Spatial Web Domain name registration services under gTLSDs with direct access to the gTLSD registries shall be required to obtain an accreditation from the SWA. To that end, the interested entity must apply for accreditation and demonstrate that it meets all the technical, operational and financial criteria necessary to qualify.

The SWA shall provide Registrars, Registrants and the general public with information and general support about gTLSD registry operators and SWA-accredited Registrars, and the SWA RAA. The SWA-accreditation only applies for gTLSDs. Obtaining registration or accreditation under a country code top-level domain shall be conducted with the corresponding Registry operator.

The SWA agreements with accredited Registrars and with gTLSD registry operators shall require compliance with various specifically stated procedures, "consensus policies", and temporary policies. Sponsors and registry operators of sponsored TLSDs may be required to comply with consensus policies in some instances.

### 6.3.6.2. Registration roles and naming

Domain registration introduces a number of key concepts:

- **Ownership Registry**: A database of all Domain owners, validated by their relationship to the credentials which indicate ownership of a different Domain, and the Domains which they own.

- **Domain Verification**: For Spatial Web Domains which are designated to require such verification of owners via local, state/province, national, or multi-national law, a registrar will perform the verification of the requisite information.
- **Domain Registrar**: An accredited organization which sells full or partial ownership of Spatial Web Domains to the public.
- **Domain Registrant**: A person or organization who registers a Spatial Web Domain.
- **Domain Naming**: A hyperspatial Spatial Web Domain that can be used to reference HSML compatible systems.

The Spatial Web Registration Authority shall require proof of credentials to be granted usage rights to Spatial Web Domains.

**The process for such registration shall follow a specific pattern**:

Following a certification process, the registrant shall register themselves (or their affiliated organization) as a Domain Authority. Once this registration is achieved, the registrant is granted ownership of the specified credential, indicating ownership of the registered Domain.

The Domain may then be associated with a given server IP address. This server is the Domain server. Domains owned by the credential shall be stored within the Domain server as part of the UDG for that Domain (the same server cluster can house multiple Domains, of course).

### Authorities and Domains

Spatial Web Authorities shall be a subclass of Spatial Web Domains that exert legitimate control over transactions within a given Spatial Web Domain or set of Spatial Web Domains.

Each Spatial Web Domain shall be an Authority with respect to transactions taking place within its boundaries, except insofar as these involve Spatial Web Domains subject to other Authorities.

Domain Authorities play five roles, including the following:

1. A governance role that involves governing its own domain, and governing related subdomains;
2. A registrant role that involves registering its Domain;
3. A registry role that involves maintaining all subdomains under its Domain;
4. A registrar role that may involve issuing SWIDs for entities in its domain (e.g., products, operations, personnel, agents, geolocations, etc.);
5. An index role that involves publishing domain-related information in a manner discoverable in the UDG.

Each Spatial Web Domain shall by default be an Authority with respect to transactions taking place within its own boundaries, except insofar as these involve Spatial Web Domains subject to other Authorities. Many traditional web domains are de facto authorities in this sense with respect to the content represented in their domains; HSML and the Spatial Web extend this concept to encompass spatial models that may represent aspects of the real physical world.

Authorities, by definition, shall have the capacity to issue HSML Credentials that constrain the execution of activities within the Domains that they govern.

Example: Execution of an activity within a Domain may depend on the Domain explicitly validating the activity by processing a relevant credential to determine its authenticity.

#### 6.3.6.3. Requirements and recommendations—domain registration

- Spatial Web Governance shall enable an entity to be the registration authority for Spatial Web Domains.
- Spatial Web Governance shall enable the Spatial Web to be a Global Commons network of networks.
- Spatial Web Governance shall enable each listing in the UDG to be accompanied by a contract between the central UDG and a registry network administrator.
- Spatial Web Governance shall accredit Registrars as companies to sell usage rights of Spatial Web Domain name registrations.
- Spatial Web Governance shall accredit Registries as companies that maintain the database of Spatial Domain names for a particular top-level Spatial Web Domain.
- Spatial Web Governance shall enable the registry to generate the authoritative address resolution file for converting between Spatial Domain names and Spatial Web addresses.
- Spatial Web Governance shall enable individuals and organizations a means to provide proof of usage credentials in order to register a Spatial Web Domain.
- Spatial Web Governance shall define standardized procedures in order to help ensure consistency, reliability, and efficiency in domain registration activities.
- Spatial Web Governance shall define a no-fee domain registration option.
- Spatial Web Governance shall require the no-fee option for the singular. Self-Sovereign Identity of a Person Domain managed by the individual.

### 6.3.7. Domain examples for an application scenario

This clause provides examples of the concepts defined for Spatial Web Domains. The Urban Digital Twin application scenario (5.3.7) describes several Spatial Web Domains:

- Metropolis Digital Twin Domain represented in the Metropolis SPACE
- Regional Energy Grid Domain
- Metropolis Digital Twin—Energy Model Domain

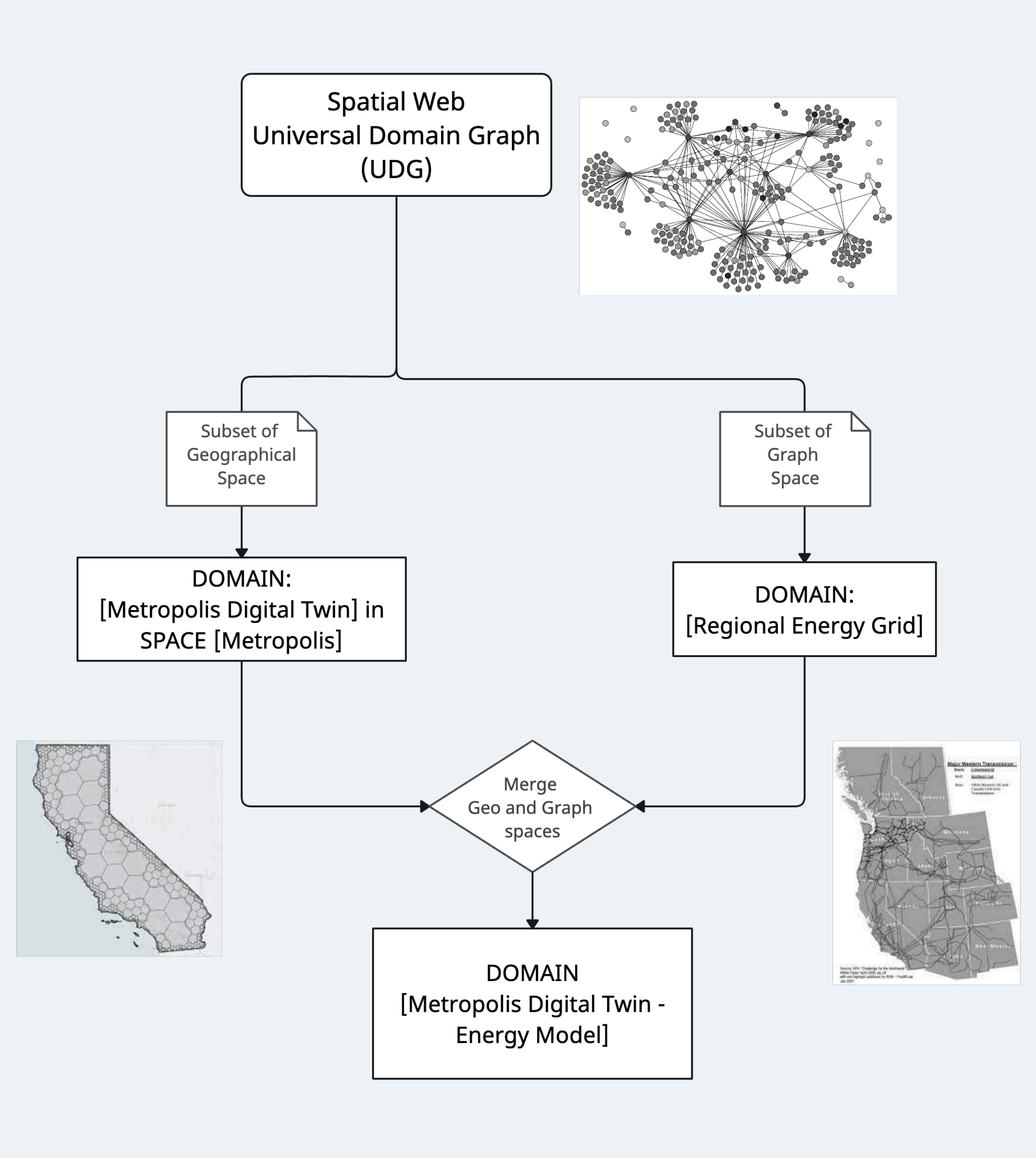
The Figure 18 shows relations between the several Domains for the scenario:

The Metropolis Digital Twin domain is a geographic Domain. Domain [metropolis] is all regions near the surface of the Earth that are managed by the Metropolis government.

The Regional Energy Grid Domain is a conceptual graph or knowledge base for the concepts and operations of a regional energy grid.

The Metropolis Digital Twin—Energy Model Domain is heterarchially related to the Metropolis Digital Twin Domain and the Regional Energy Grid domain.

**FIGURE 18:** UDT Energy Domain example



## 6.4. Agents and activities

This clause describes two HSML Entities—AGENTS and ACTIVITIES—and defines requirements for these two Entities. AGENTS and ACTIVITIES are integrated into the overall HSML Conceptual Model in (6.5).

## 6.4.1. Concepts

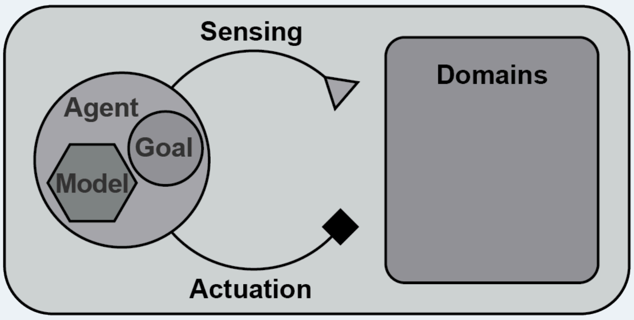
### 6.4.1.1. AGENT

An AGENT is an entity that senses and responds to its environment, maintains a model of its environment, and performs ACTIVITIES to achieve its goals.

In HSML, an AGENT is a type of Domain, and both are types of Entity. As a type of Domain, an AGENT retains its identity over time even though its states and relations may change.

This agent-based paradigm is depicted in Figure 19.

**FIGURE 19:** Agent paradigm



### 6.4.1.2. ACTIVITY

An ACTIVITY is a partially ordered set of changes effected by an AGENT.

An ACTIVITY is a specific instance of an ACTIVITY Schema that is planned or executed by an AGENT.

An ACTIVITY may be planned, ongoing, failed, or completed.

An ACTIVITY is performed on, by, in, or with, Domains, including other AGENTS.

An ACTIVITY can be near-instantaneous or temporally extended.

Attributes of an ACTIVITY may be represented using HYPERSPACE Entities.

In the context of HSML, ACTIVITIES form the foundation for all executions between Entities in the Spatial Web.

## 6.4.2. Agent capabilities

### 6.4.2.1. Overview

The core functionalities of an AGENT can include an ability to perceive its environment through sensing and act through actuation. An AGENT environment refers to any external factors, systems, and Entities that an AGENT can interact with or that can affect the AGENT's state or decision-making process. An AGENT has a model of its environment and can respond in a timely manner to changes in its environment. An

AGENT can make decisions and enact plans to effect changes in its environment and achieve its goals.

### 6.4.2.2. Sensing and perceiving

AGENTS use sensors and data inputs to actively perceive their environment. Sensing and perception involve the ability to gather data from their environment, process this data, and form a representation of the state of the environment.

Data acquisition enables the AGENT to collect data from its environment either continuously or at predetermined intervals. Perceptual processing involves the systematic transformation and organization of data in a way that is meaningful and can be utilized effectively. Data processing can involve multiple modalities, including, for example, image recognition, where visual data is analyzed and interpreted, or speech-to-text conversion, where audio data is transcribed into written form. These capabilities are foundational for ensuring that an AGENT makes informed decisions and enact plans to effect changes in the world to achieve a goal. Example sub-components include the following:

- **Sensors:** AGENTS can have embedded sensors whose main function is to detect and record environmental changes. This includes cameras for visual data acquisition, microphones for capturing sound, temperature sensors for detecting climatic conditions, and many others, each designed to perceive specific environmental data.
- **Data Inputs:** This refers to a collection of methodologies employed by the AGENT to receive data.

### 6.4.2.3. Physical and digital actuation

An AGENT is able to interact with other Spatial Web Entities to induce or bring about change within them. These interactions can be executed in physical, real-world domains or executed through digital means.

The fundamental ability allows an AGENT to effect changes in the world when performing ACTIVITIES in response to the information it has processed or in accordance with an intended goal. The ability to perform an Activity enables an AGENT to refine and adjust their behavior in future scenarios based on previous outcomes and feedback. Example sub-components include the following:

- **Effectors:** These are the physical mechanisms through which an AGENT is capable of moving or manipulating objects within its environment. Examples include motors that drive movement or hydraulic systems that provide the force for manipulation.
- **Output Commands:** In the realm of digital interactions, the agent employs instructions or signals that are sent out to other systems, entities, or digital interfaces to bring about a desired goal or state. Digital actuation can include executing software commands, interacting with digital interfaces, digital control signals, and sending requests to a database or information system to retrieve or modify data.

### 6.4.2.4. Information processing and knowledge modeling

The processes and structures used to store, organize, and manipulate knowledge gained from perceptions and interactions with the environment.

This capability equips an AGENT with the ability to make informed decisions aimed at achieving objectives by analyzing data and utilizing the knowledge modeled within its system. It enables the AGENT to learn from previous actions and external feedback, enhancing its future performance and adaptability to new or changing environments. Example sub-components include the following:

- **Data Processing Algorithms:** These algorithms carry out a variety of tasks such as filtering irrelevant data, organizing the relevant data in a structured manner, and interpreting the organized data to extract meaningful insights.
- **Knowledge Base:** This is a systematically structured repository of all the knowledge that the AGENT has acquired over time. It is designed to be dynamic, allowing for continuous updates and expansions as the AGENT encounters new information.
- **Learning Mechanisms:** Systems that by integrating new data and experiences, enable the AGENT to evolve its knowledge base and decision-making processes. These could involve the use of advanced machine learning algorithms that allow the AGENT to adapt and improve over time.

### 6.4.2.5. Autonomous decision-making

Autonomous decision-making capabilities refer to an AGENT's ability to independently analyze information, make choices, and act without external intervention when performing ACTIVITIES. This functionality underpins environment modeling, strategic planning, and adaptive execution, facilitating problem-solving and navigation in complex, dynamic operational contexts, and enables AGENTs to independently update their objectives to achieve its goals when performing ACTIVITIES. This diversity in autonomy ensures AGENTs can effectively navigate the challenges and opportunities presented by the Spatial Web ecosystem [93]. Example sub-components include the following:

- **Goal Definition and Prioritization:** Mechanisms for defining, prioritizing, and managing goals. Mechanisms can be predefined or dynamically-generated based on objectives and current state.
- **Planning and Strategy:** Systems that reason about, formulate, or select an optimal plan to achieve a goal when performing Activities. This may include path planning in a hyperspace, task scheduling, and adapting plans based on new information.
- **Execution Monitoring:** refers to the continuous process of observing and assessing the outcomes of an AGENT's interactions with its environment to ensure they align with its predictions and goals. This involves learning from success and failure, updating models, and refining goals.

### 6.4.2.6. Intelligent behavior

AGENT behavior refers to the patterns of activities or responses exhibited by an AGENT as it interacts with its environment, other AGENTs, and users. Intelligent behavior refers to the capacity for learning from experiences, adapting to changes, and optimizing responses for efficiency and effectiveness, leveraging these abilities to respond effectively to dynamic environments. Types of behavioral responses may include reactive behavior, proactive behavior, and intentional behavior. Reactive type behavior may be associated with direct responses to environmental stimuli through rule-based or event-based programming. Proactive behavior reflects the capacity to generate appropriate responses and goal-directed behaviors based on anticipating future states, using models of the environment to optimize outcomes. Intentional behavior reflects advanced, goal-oriented planning that integrates inductive reasoning and strategic planning, aiming to achieve specific, long-term objectives and knowledge updates [94].

Behavioral response types may reflect the level of AGENT intelligence, operational autonomy, or the rules and agreements embedded in contracts or interaction protocols. The capacity for enacting flexible, goal-oriented behavior is important for the functionality, adaptability, and realization of shared intelligence within the Spatial Web [85].

### 6.4.2.7. Requirements and recommendations—agent capabilities

- HSTP shall provide infrastructure and protocols for AGENTs with diverse intelligences to communicate and interact effectively.
- HSML shall represent the world and its associated knowledge in a manner that is understandable by AGENTs.
- Domain-specific architectures shall implement mechanisms and procedures for handling aberrant component behavior.
- Domain-specific mechanisms and procedures shall be specific to the risks associated with the DOMAIN's applications.
- HSML shall represent the world and its associated knowledge in a manner that is actionable by AGENTs.
- Domain-specific architectures should specify requirements for AGENT response latencies and temporal processing capabilities.
- Spatial Web Governance shall define procedures and processes for governing autonomous and intelligent AGENTs based on the AIS Rating Framework, to facilitate a trustworthy, interoperable, privacy-preserving, and secure Spatial Web ecosystem.
- AIS Rating Framework shall define procedures for real-time CREDENTIAL and certification management, based on an AGENT's attributes, capabilities, and relationships.
- AIS Rating Framework shall facilitate the dynamic adjustment of AGENT permissions, authorizations, and access based on changes in an AGENT's attributes, operational context, and ACTIVITIES.
- AIS Rating Framework should support the integration of a credential and certification management framework that is compatible with different access-control methods and systems, such as attribute-based, relationship-based, or trust-based access-control frameworks.

## 6.4.3. AGENT interactions

### 6.4.3.1. Overview

This section provides a system overview of AGENT interactions among a diversity of Spatial Web Entities and the requirements for facilitating and managing those interactions.

AGENT interactions refer to the processes and mechanisms through which an AGENT can engage, influence, or exchange information with other Entities in their environment. The ability of an AGENT to effectively interact and communicate with a diverse range of Spatial Web Entities, including AGENTS, objects, IoT devices, and human users, is crucial for enabling the interoperability, governance, and functionality of the Spatial Web ecosystem.

### 6.4.3.2. Agent-environment interactions

An AGENT's environment may be composed of resources, tools, services, and other AGENTs with which an AGENT can interact to achieve their goals. An AGENT's operational context can impose constraints on the AGENT's resources or available possibilities for action and shape the outcomes or behaviors of an AGENT's interactions. For example, a mobile robot agent in a physical world may need to interact with and communicate with Entities in their environment through physical actuation and digital actuation. A software or digital agent may operate in a digital environment, that may or may not require spatial data or awareness. Hybrid environments, or Digital Twins, serve as a bridge between the physical and digital Domains, allowing agents to test hypotheses, optimize strategies, and learn from virtual scenarios without direct physical intervention. These interactions not only extend the operational capabilities of AGENTs but also foster a deeper integration of the physical and digital environments, shaping the outcomes and behaviors within both realms.

### 6.4.3.3. Agent-Domain interactions

AGENTs interact with different types of Spatial Web Entities. The nature of the interactions depends on the attributes of the AGENT, the attributes of the Entity, the relationship of the Agent-Entity, and the environment in which the interaction is happening among other factors.

In the context of the Spatial Web, AGENTs perform ACTIVITIES on, in, or with Domains to achieve their goals. Domains can include Things Domains, AGENT Domains, Dimensional Domains, Conceptual Domains, and Organizational Domains, where AGENT Domains can include both Person and Non-Person AGENT types.

### 6.4.3.3.1. Agent-to-thing domain interactions

An AGENT interacts with Thing Domains when sensing, actuating, and communicating and performing operations to achieve their goal. Thing Domains are categorized as passive entities that do not possess the capacity for autonomy. Thing Domain attributes can include Identity (unique identifiers), type (classification of the Thing), state (current status or condition), and access rules (who can interact with the Thing and how).

Things Domains can be IoT devices, physical objects, digital assets or documents, virtual constructs, and environmental elements with which AGENTs can interact. An AGENT can interact with physical Things in the environment, such as opening or closing valves in industrial settings, adjusting the thermostat in smart homes, or controlling robotic arms for assembly in manufacturing processes. In virtual or digital environments, AGENTs can modify virtual Things or their settings, such as altering configurations in a software application, modifying digital assets in a virtual world, or deploying code changes to servers. AGENTs rely on web services and APIs to access data, functionality, and services. This includes accessing cloud computing resources, data storage, and third-party services for enhanced functionalities.

Thing Domains can have states (current status or condition), which can be dynamic and change over time, impacting how AGENTs can interact with it. AGENTs proactively interact with Thing Domains by accessing their properties/states, by listening to (perceiving) events that Thing Domains and services emit, and by acting on them. Thing Domains can have access-rules or defined policies that dictate who can interact with a Thing and in what manner, ensuring that interactions are controlled and conform to security requirements. Agents with advanced perceptual and reasoning abilities may possess the capability to identify new ways of utilizing or interacting with a Domain to achieve its goal. For instance, a robot with advanced reasoning capabilities may infer novel ways to grasp or interact with a door handle that are compatible with its specific effectors (e.g., dexterous robotic arm).

### 6.4.3.3.2. Agent-to-agent interactions

Agent-Agent interactions involve the exchange of information, which includes data, status updates, and insights. Such exchanges enhance situational awareness and decision-making processes. Agents learn from each other’s experiences, thereby improving both their individual performance and collective understanding. They collectively make decisions or solve problems through consensus, voting mechanisms, or contractual agreements. The interactions also involve coordinating their ACTIVITIES or efficiently utilizing shared resources to accomplish collective goals. By cooperating, Agents harness their combined capabilities and resources to address complex challenges, negotiate, and forge agreements, ensuring their interactions are aligned with individual aims and the overarching policies of the Spatial Web.

The interaction patterns between non-person and person agents, such as human-AI interactions, can occur in various structures including one-to-one, many-to-one, one-to-many, or many-to-many patterns. These interactions can take place in a centralized, decentralized, or distributed manner, often in a hierarchical structure where some Agents have more control or decision-making power.

Human-AI or Human-AIS Teaming: Human Agents can exercise supervisory, shared, collaborative, delegated control, and autonomous oversight roles in managing the ACTIVITIES, systems, or operations of non-human agents, such as autonomous vehicles, robots, or software systems. Non-human Agents assist, guide, or respond to human requests for information or task execution. They enhance user experience and efficiency by providing personalized content, aiding in navigation, or offering recommendations. They leverage advanced computing to support complex tasks and adapt their behaviors and learning based on user instructions or feedback. AI systems adapt to human needs and preferences, providing personalized support and suggestions, as seen in smart homes and personal assistants.

Peer-to-Peer (P2P) Agent Networks: operate on a decentralized or distributed model where participants act as both clients and servers. Interactions in P2P networks occur directly between peers without intermediaries or centralized authorities, enabling efficient resource sharing and communication. Agents are considered equal in terms of their role in the network; there is no hierarchical structure, and each peer has the same rights and responsibilities. These networks allow Agents to adapt autonomously to network environment changes and make decisions based on their programming, objectives, or available information without central direction. Agents in P2P networks have the autonomy to join or leave the network based on their objectives. Hence, these networks can self-configure, manage peer connections, and efficiently distribute resources without central control.

Multi-Agent System (MAS): A MAS consists of autonomous Agents working collaboratively in a decentralized or distributed manner to fulfill both individual and shared objectives. These Agents operate based on localized understandings or models of their environment, functioning across distinct spatial locations or computational environments without a single locus of control. Agents can differ in their permissions, roles, capabilities, knowledge bases, and goals. They engage in communication and interaction through a variety of protocols, languages, or mechanisms, which span from elementary command signals to sophisticated high-dimensional vector representations. In hierarchical MAS configurations, a structured interaction pattern -—either tree-like or nested—designates certain Agents with enhanced or specialized decision-making responsibilities. Other MAS configurations maintain operational cohesion by building consensus and establishing agreements. This ensures that Agent interactions align with individual objectives and the collectively agreed norms and constraints within the ecosystem.

### 6.4.3.4. Requirements and recommendations—Agent interactions

- HSTP shall provide infrastructure and protocols for AGENTs with diverse intelligences to communicate and interact effectively.
- HSML shall represent diverse types of environments, including virtual, physical, and hybrid spaces, using a universally understandable model.
- HSTP shall help ensure communication protocols are reliable and efficient, facilitating information transmission between AGENTs regardless of their underlying implementation or the network over which they communicate.
- HSML shall help ensure standardization by providing a common language or procedures for AGENT communication, ensuring messages are understood across diverse AGENT designs.
- HSTP shall support AGENT communication and interactions of varying levels of contextual and syntactic complexity, from simple command and control signals to semantically rich high-dimensional vector representations.
- HSML shall support the development of infrastructures that enable AGENTs to identify and resolve conflicts related to contract assignment, goals, and resource allocation, ensuring harmonious collaboration.
- HSTP shall enable AGENTs to communicate over necessary timescales for optimal function and integrate an autonomous rating framework to support understanding

of AGENTs' capabilities, responsibilities, and interaction behaviors within multi-agent systems.

- HSML shall enable humans and Domain Authorities to specify interaction preferences or protocols through the HSML framework for enhanced customization.
- HSTP shall support scalability, enabling increased AGENT interactions without compromising performance, crucial for large-scale operations.
- HSTP shall incorporate mechanisms for authentication, authorization, and encryption to safeguard interactions.
- AIS Rating Framework shall offer flexibility, allowing dynamic interactions among AGENTs with varied capabilities, intelligence, and objectives across a broad spectrum of ACTIVITIES and contexts.
- AIS Rating Framework should be interoperable with different encryption frameworks, allowing or restricting AGENT communications and interactions based on their verifiable and certifiable attributes and capabilities.
- AIS Rating Framework shall enable governance of AGENT interactions, ensuring safety, reliability, and responsibility, while prioritizing functionality, fairness, transparency, and governance rule adherence, thus creating a trustworthy and efficient Spatial Web ecosystem.

### 6.4.4. ACTIVITIES in detail

#### 6.4.4.1. Overview

This clause provides an overview of HSML ACTIVITIES, detailing the specific state of the world that must be achieved for their execution. This section provides a description of how ACTIVITIES represent an AGENT's capabilities and performance, encompassing planned, ongoing, and completed stages. Additionally, it examines how ACTIVITIES enable the coordination of collaborative interactions and commitments among multiple Agents."

Autonomous Agents have the capability to make decisions, organize, and select plans to effect changes in the world, in a way that aligns with their desired or intended goals.

Agents can undertake a wide range of goal-directed ACTIVITIES in dynamic environments, from simple ACTIVITIES that involve transitioning a system or environment from one state to the desired state without considering internal components and intermediate states, to more complex ACTIVITIES that involve effecting a set of changes that are carried out in a sequential or concurrent manner to achieve a desired outcome state. Increasingly complex ACTIVITIES may require extensive coordination and are often contingent on outcomes or decisions of ACTIVITIES at various stages, or on the ACTIVITIES of other AGENTs.

Actions can sometimes fail to bring about the intended or desired effect because of a limitation in the Agent's abilities or performance, uncertainties or unforeseen events within the environment, or because of conflicts with other Agents or Entities.

### 6.4.4.2. HSML Activity Schema

An HSML Activity Schema is a template of an Activity, outlining the conditions and variables necessary for its execution. An Activity Schema specifies the conditions and variables required for an ACTIVITY type without being tied to a specific occurrence, and thus serves as a blueprint for creating HSML ACTIVITY instances. An ACTIVITY Schema represents a type of ACTIVITY that can be performed by an AGENT or group of AGENTs, defined in terms of the conditions that must be obtained in order for the ACTIVITY to have occurred. These include the final result of the ACTIVITY, as well as any initial conditions enabling it, and any intermediate conditions. Such conditions may themselves refer to other ACTIVITY Schemas. The ACTIVITY conditions so defined may be simple (irreducible, representing a single goal state) or complex (involving sequences or sets of changes). The primary attributes of an Activity Schema include the following:

- **Activity Schema ID**: A unique identifier for the Activity Schema. This ID is used to reference the schema within the Spatial Web ecosystem, allowing AGENTs and systems to recognize and differentiate between various types of ACTIVITIES. The Activity Schema ID ensures that each type of ACTIVITY can be accurately identified, retrieved, and executed according to its specific definition.
- **Conditions**: A description of an ACTIVITY in terms of the desired state or outcome that the Activity aims to achieve upon successful execution, which may comprise a sequence of conditions, as well as any initial conditions presupposed by the Activity. Conditions are defined using variables, which are placeholders that need to be filled with specific values when an Activity Instance is created. These variables represent aspects of the Activity such as the target Domain, the AGENT performing the Activity, and environmental conditions that must be met.
- **Variables**: Critical components of the intended condition, typed open variables are defined within the Activity Schema but are not assigned specific values until an Activity Instance is created. These variables allow the Activity Schema to be flexible and reusable in various contexts.

For example, in a “transport item” Activity Schema, open variables might include the item to be transported, the destination, and the mode of transportation. When an AGENT plans to execute this ACTIVITY, it will instantiate an Activity Instance by filling in these open variables with concrete values (e.g., transporting a package to a specific location via drone). A condition can also reflect normative constraints to ensure that an Activity is performed in compliance with relevant norms and regulations within the Spatial Web. This may include constraints that must not be violated during the planning or execution of the Activity (See HSML Routing ACTIVITY for example definition). Conditions may be expressed in terms of predicates that must hold true. For example, an AGENT can only perform a “close door” ACTIVITY on a door if an “is_open” status is true.

### 6.4.4.3. HSML Activity Instance

An HSML Activity Instance represents the run-time instantiation or parameterization of an HSML Activity Schema. It is the concrete realization of the schema, transforming the general template of an Activity into a specific, actionable instance. This transformation is achieved by providing concrete values for the open variables defined in the Activity

Schema, thereby specifying the exact parameters and conditions under which the ACTIVITY is to be executed.

**ACTIVITY Schema ID**: Specifies the ACTIVITY Schema that this ACTIVITY is an Instance of.

**Parameters**: Type-consistent values assigned to open variables within an ACTIVITY Schema when it is instantiated. They provide the detailed information necessary for the execution of an ACTIVITY, tailoring a general schema to a particular situation or instance. Variables may include, but are not limited to, identifiers for AGENTs (e.g., drone Agent SWIDs), targets, locations, and any other pertinent data required for the execution of the ACTIVITY. A parameterized ACTIVITY Instance becomes a tailored execution plan that addresses the specific requirements of a given scenario or objective, and can be enacted by AGENTs.

**ACTIVITY Status**: A HSML ACTIVITY Instance can be “Planned”, “In Progress”, “Completed”, or “Failed”.

### 6.4.4.4. HSML ACTIVITY Composition

The conditions defining an HSML ACTIVITY Schema may refer to other ACTIVITY Schemas, enabling the creation of complex or composite Schemas which can then be instantiated as complex ACTIVITIES. Multiple ACTIVITY Schemas may thus be aggregated to define a single, coherent execution plan, reflecting the hierarchical and modular nature of interactions on the Spatial Web. Composition is described in terms of three types of ACTIVITY Schemas: Atomic, Complex, and Sequential.

Atomic ACTIVITY Schema: Schema for an HSML ACTIVITY representing a single, indivisible state change, which does not reference any ACTIVITY Schema in its conditions. An Atomic ACTIVITY can be executed directly without contingent steps, and represents the simplest Activity an HSML-compliant AGENT can perform, constrained by the AGENT’s design or interface. For example, a command executed by a drone AGENT to “initiate take-off” is an Atomic HSML Activity.

Complex ACTIVITY Schema: Schema in which at least one condition references an HSML ACTIVITY Schema. Conditions may reference other ACTIVITY Schemas explicitly (by Spatial Web ID) or via variables (whose types specify which ACTIVITY Schemas may instantiate them). Sub-ACTIVITIES may be used to define Conditions on their own, or may be combined with extra logical syntax to define more complex conditions.

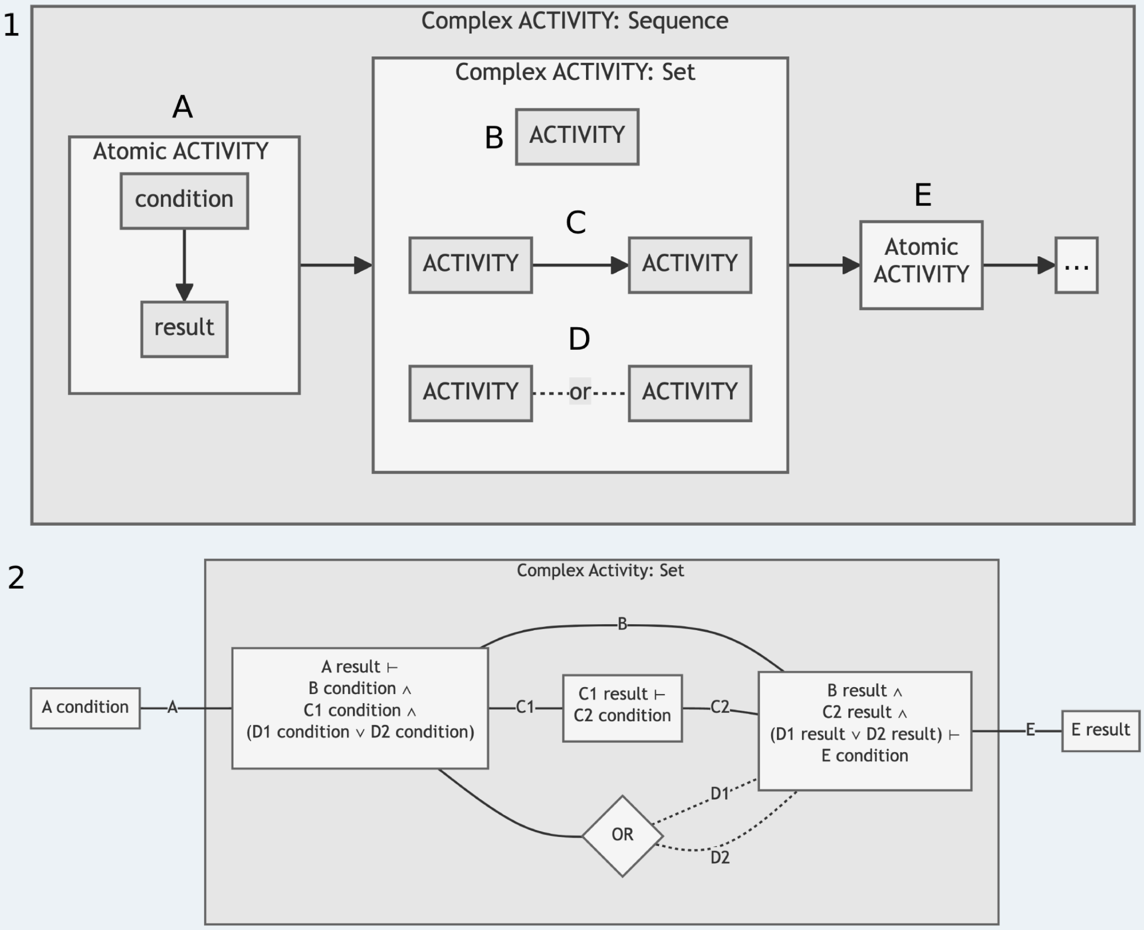
Important examples of Complex ACTIVITY structures include the following:

- **Sequential ACTIVITY Schema:** An ordered sequence of ACTIVITY Schemas, in which the result of each step entails the initial conditions for the succeeding step. A Sequential ACTIVITY Schema is by definition Complex, but not all Complex ACTIVITY Schemas are Sequential.
- **Sets:** An unordered collection (logical conjunction) of ACTIVITY Schemas, representing a set of independent ACTIVITIES to be performed. May represent a “batch” of operations (for example, concurrent, parallelizable tasks), and can be used within a Sequence to specify steps that are jointly necessary to achieve a further result, but whose relative order is unimportant (for example, a drone take-off ACTIVITY depends on a battery-charging ACTIVITY and a wireless communication-enabling ACTIVITY but in no particular order).

- **Alternatives:** Complex ACTIVITY Schemas containing open ACTIVITY Schema variables represent choices left open at the top level (for example, a transport-goods ACTIVITY Schema represents an exclusive disjunction over transport methods defined by more specific ACTIVITY Schemas).

Various types of ACTIVITY Schema composition are depicted in Figure 20. The upper panel (1) depicts a Complex ACTIVITY (Sequence) in which one constituent is also Complex (a set of ACTIVITIES, one of which is a disjunction between two alternatives). The lower panel (2) depicts in detail the order of execution and dependencies for the sub-ACTIVITIES labeled A-E in the upper panel. For example, the resulting condition of sub-ACTIVITY A entails the initial conditions for sub-ACTIVITIES B and C, as well as at least one of the possible conditions sufficient to enable D.

**FIGURE 20:** ACTIVITY composition example



## 6.4.4.5. Representation of Agent Capabilities

AGENTs possess diverse capabilities and varying levels of intelligence, enabling them to perform a wide range of ACTIVITIES. In the Spatial Web, AGENT capabilities are represented through ACTIVITY Schemas that are linked to the AGENT, reflecting its capacities and permissions. The permissions associated with an AGENT ACTIVITY define the set of possible opportunities for interaction that are available to the AGENT within a specific Domain. Atomic Type ACTIVITIES may be specific to an AGENT and can be inherited or derived from developer or manufacturer specifications. An ACTIVITY may be associated with an AGENT in a domain-specific context using a CREDENTIAL to define the set of possible interactions available to the AGENT within a specific

Domain. The Spatial Web allows for the representation of AGENT capabilities as a set of ACTIVITIES that are linked to an Agent based on verified capabilities and permissions.

### 6.4.4.6. Representation of Planned Activities

Activity plans are developed, initiated, and executed by Agents to achieve high-level goals or fulfill a contractual obligation. Activity plans capture an intended goal state to be effected by an Agent. An Agent with Activity planning capabilities may need to consider various factors, such as the current context of the world, the desired future state, and the constraints or conditions that must be satisfied to achieve an intended goal. This planning process allows agents to strategically navigate their environment and predict future states, understand the consequences or risks associated with an intended action, effectively laying out a roadmap towards achieving specific objectives within the Spatial Web framework.

Agent plans can be formed through various methodologies like hierarchical decomposition, breaking down complex tasks into simpler, actionable steps, or by performing a search on state space for actionable possibilities based on current conditions and desired outcomes. The HSML ACTIVITY framework and the Universal Domain Graph enables AGENTs to construct, represent, and enact plans in a way that is compliant with the Spatial Web's standards and policies, ensuring that the planned ACTIVITIES are aligned with the objectives set forth in a HSML Contract.

### 6.4.4.7. Coordination and Conflict Avoidance Mechanisms

AGENTS may need to formulate and enact plans that rely on shared resources or spaces. A lack of timely information about AGENT resource allocation or AGENT positioning in a shared space can result in conflicting or suboptimal ACTIVITY plans. AGENTS with advanced planning and autonomous decisions-making abilities can actively request or access details regarding assigned resources and other Agent attributes using, for example, the Spatial Web UDG or HSML CHANNELS. This capability allows AGENTS to preempt conflicts and evaluate potential risks during the planning phase. In cases where AGENTs lack the ability to integrate conflict avoidance measures into their plans, HSML ACTIVITY Instances and HSML CONTRACTS can serve as a framework for integrating conflict resolution and management conditions into an ACTIVITY execution framework. This same mechanism or strategy also supports the continuous alignment of AGENT ACTIVITIES with ethical guidelines and normative constraints, regardless of the AGENTS levels of ability or intelligence (See 6.4 for further discussion).

### 6.4.4.8. Requirements and recommendations—activities

- UDG shall provide the capability to register and manage ACTIVITIES that are associated with AGENTs, reflecting their capabilities and permissions.
- Spatial Web Governance shall provide a framework for Domain Authorities to define, register, and manage Domain-specific norms and regulations that govern the execution of ACTIVITIES within their respective Domains.
- HSML shall enable the representation of ACTIVITIES in a way that is compatible, understandable, shareable, and executable by diverse AGENTS or ENTITIES within the Spatial Web ecosystem.

- HSML shall model ACTIVITY Schemas that specify templates for ACTIVITIES in terms of the conditions that they (are intended to) bring about, as well as any conditions presupposed for its execution, where such conditions are specified as predicates over HSML data structures (i.e., Domain descriptions) that may contain open variables.
- HSML shall model the conditions associated with an HSML Activity Instance.
- HSML shall inherit from the conditions of the Activity Schema it instantiates, binding values as necessary to any variables left open at the level of the Activity Schema.
- UDG shall keep a record of HSML ACTIVITIES that were executed as part of a Contract, providing a history of the Activity, verification of the execution of the Activity, and enabling the tracking of the Activity's progress.
- HSML shall provide guidance for registered HSML Activity Name to be intuitive, and easy to understand and interpreted by users or other interacting Entities.
- Domain-specific architectures shall provide guidance for how HSML ACTIVITIES are to be performed within acceptable time-frames and meet performance criteria such as response time, throughput, and resource utilization.
- HSTP shall provide methods for HSML Activity models to adhere to security measures and protocols to protect sensitive information and prevent unauthorized access or malicious behaviors.
- Domain-specific architectures shall define guidance for ACTIVITIES to adhere to ethical guidelines and principles, ensuring fairness, transparency, and accountability in their execution.
- HSML encoding of ACTIVITIES should be designed to be adaptable and flexible, allowing for the modification of plans and goals based on changes in the environment or the emergence of new information.

### 6.4.4.9. Example activity: Autonomous medical air delivery

This section provides an example Autonomous Medical Air Delivery Activity, which is performed by an autonomous drone (AGENT) (see 5.3.4).

The Activity Schema defines a template in terms of the conditions the Activity intends to bring about in the world and the types of valid variables necessary for its execution. The 'Autonomous Medical Air Delivery' Activity Schema serves as a structured framework for executing medical air delivery operations via an autonomous drone AGENT. It defines the process through initial conditions of pre-flight preparation, intermediate conditions of autonomous navigation, and end conditions of package delivery, outlining a clear sequence of goal states. Conditions are defined using open variables, which are assigned parameters and values upon instantiation.

The HSML Activity Instance is a specific realization of the HSML Activity Schema. By parameterizing the open variables defined in the Activity Schema, the general blueprint is transformed into a specific, actionable instance. Concrete values are provided for open variables, such as the drone AGENT's SWIDs, and queries are established to evaluate the state of affairs against those defined in the Activity Instance. The Activity Instance relies on the fulfillment of the defined conditions and successful evaluations of the variables to transition the Activity through different phases. An 'ActivityStatus' variable is updated based on the fulfillment of the defined conditions and successful evaluations of the variables, such as "Planned," "In Progress," "Completed," or "Failed".

### 6.4.4.9.1. Example HSML Activity Schema

**Activity Schema ID:** Unique identifier for the Activity Schema. May also reference Activity Schemas used to construct the present Activity Schema.

**Conditions** Defines the intended Activity in terms of the conditions it intends to bring about in the world:

1. **Initial Condition:** Pre-flight Preparation
2. **Intermediate Condition:** Autonomous Navigation
3. **End Condition:** Package Delivery

**Open Variables**: placeholder to assign parameters and dynamic attributes that are assigned upon instantiation, including the following:

- **DroneAgentID:** A unique Spatial Web identifier for an autonomous drone (AGENT).
- **FAADomainAuthorityID:** A unique Spatial Web Identifier for the domain authority governing the Domain in which the Activity is performed.
- **OperationalApproval:** A Boolean indicating an autonomous drone's (AGENT) operational authorization from the FAA authority (AGENT).
- **MedicalPackageID:** A unique SW identifier for the medical.
- **AerodromeID:** A unique identifier for the operational airspace.
- **WaypointList:** GPS coordinates and altitude detailing the start and end points of the delivery route in an aerodrome digital map (DOMAIN).
- **WaypointAchievement:** A series of Booleans indicating successful navigation through predetermined waypoints.
- **DroneChargeStatus:** A Boolean or percentage value reflecting battery level of the autonomous drone (AGENT).
- **PayloadStatus:** A Boolean indicating the presence of a payload in an IoT storage container that is part of the drone (AGENT).
- **DroneLocation:** A query on the autonomous drone (AGENT) GPS location and altitude, providing real-time positioning data.

### 6.4.4.9.2. Example HSML Activity Instance

**Activity Schema ID:** (unique identifier)

**Conditions:** goal states as described in the Activity Schema, as follows.

1. **Initial State: Pre-flight Preparation:** The autonomous drone (AGENT) is situated at Waypoint 1, fully prepared and loaded with the medical package (Domain), having received FAA operational approval (CREDENTIAL) for performing an autonomous flight.
2. **Intermediate State: Autonomous Navigation:** Following pre-flight preparations, the drone (AGENT) autonomously navigates to Waypoint 2, maintaining FAA operational

authorization (CREDENTIAL) and providing continuous location and progress updates.

3. **End State: Package Delivery:** The autonomous drone (AGENT) has landed at the destination waypoint, within a specified timeframe. The medical package (DOMAIN) is released from the IoT storage device on the drone (AGENT).

**Parameterization:** Assign parameters to open variables. Variables that are updated across different stages of the Activity, such as the 'WaypointAchievement', are updated using logical statement evaluations. Variables that change over time, such as the 'droneLocation', can be updated in real-time using a query on the relevant Spatial Web Entity.

**Assign SWID:** SWIDs are assigned to the relevant open variables, such as the DroneAgentID, FAADomainAuthorityID, MedicalPackageID, AerodromeID variables.

**WaypointList:** The WaypointList is instantiated with the GPS coordinates and altitude of the starting point and end points of the delivery route.

**DroneLocation:** is updated with a query on the drone's GPS location and altitude, providing real-time data on the drone's positioning throughout the delivery process.

**WaypointAchievement:** is characterized by a series of Booleans, showing whether the drone has successfully navigated through the predetermined waypoints. This variable is updated using a query on the done's location and the predetermined waypoints.

**DroneChargeStatus:** is denoted as a Boolean whether the drone's current battery level is sufficient for the mission, serving as a condition for transitioning the ACTIVITY from 'Pre-flight Preparation' to 'Autonomous Navigation' phase.

**PayloadStatus:** is indicated by a Boolean, confirming the presence of the Medical Package (DOMAIN) in the drone's IoT storage container.

**ActivityStatus:** describes the current phase of the Activity on the basis of the fulfillment of defined conditions and successful evaluations of the variables, e.g., "Planned", "In_progress", "Completed", "Failed".

## 6.5. Credentials, norms, and contracts

### 6.5.1. Concepts

#### 6.5.1.1. Credential

A set of one or more claims made by a Domain.

#### 6.5.1.2. Norm

A standard or principle of right action serving to guide, control, or regulate proper and acceptable behavior, which can be specified in terms of the conditions under which it is binding on agents' actions and the conditions under which such actions conform or fail to conform to it.

#### 6.5.1.3. Contract

A binding agreement between two parties, especially enforceable by law, or a similar internal agreement wholly within an organization.

This standard does not require that a CONTRACT contain any particular economic terms.

### 6.5.2. Safety and trustworthiness of Spatial Web agents

Safety and Trustworthiness in the Spatial Web is enabled by governance.

This clause provides a conceptual framework describing the Entities that enable governance of autonomous agents on the Spatial Web [100] [101].

As referenced in the discussion of AIRS ratings in 6.4, “governance” is here used in a wide sense that includes constraints placed directly by state actors on the activities of autonomous agents via legislation or regulation, as well as more context-specific, but still potentially legally enforceable, constraints placed on such activity by mutual agreement among parties to a transaction (i.e., contracting). Governance in the Spatial Web is discussed more broadly in 6.3.

Safety and Trustworthiness of Spatial Web AGENTs, in particular Autonomous agents, requires representing and reasoning about CREDENTIALs, norms, and CONTRACTs. See [97] for an example of safety certification in the context of robotics.

Trust is assured reliance on the character, ability, strength, or truth of someone or something, and is required to enable anonymized data to be shared among Spatial Web nodes privately and securely. [77] identifies four aspects of trust between parties intermediated by digital technology (Introduction to Trust Over IP):

- **Authenticity:** Does each party possess the identity and/or identity attributes that the other party or parties ascribes to it?
- **Integrity:** Do the communications between the parties arrive in complete and untampered form?
- **Confidentiality:** Is the content of the communications between the parties protected such that it is only available to authorized parties?
- **Privacy:** Will the expectations of each party—with respect to usage of the information communicated between the parties—be upheld by the other party?

Authenticity shall be supported in HSML by SWIDs. Confidentiality will be provided by features of the transactional layer (HSTP) which are addressed in 7.1.2.11. Privacy is built into the Spatial Web as a design principle, as discussed in 6.3.

Also relevant is the distinction between Static Trust and Dynamic Trust in the (International Data Spaces Association Reference Architecture Model). The former involves merely certification of parties to a transaction (including core technical components), while the latter involves their active monitoring as transactions are completed. The requirements around privacy in 6.3 are intended to enable dynamic trust for participating Spatial Web nodes.

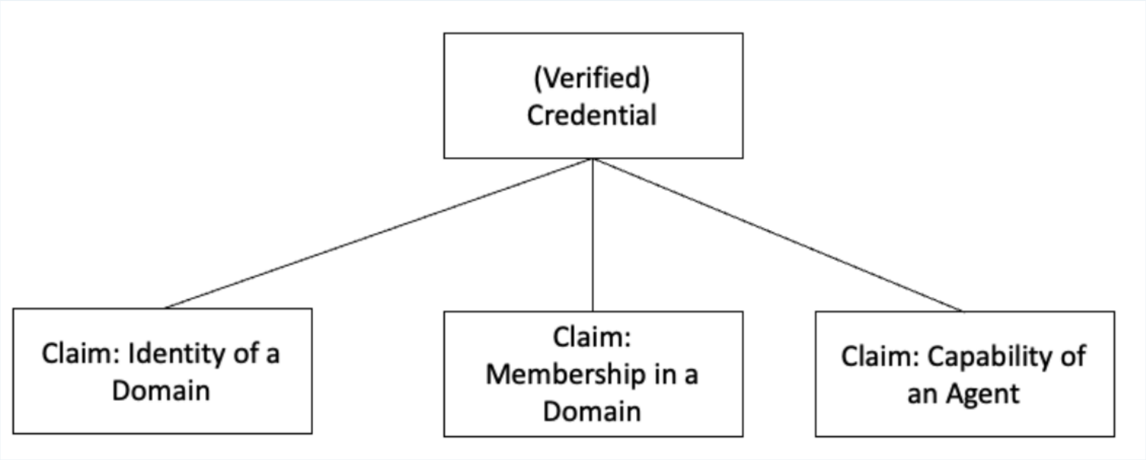
## 6.5.3. Credentials for claims associated with entities

### 6.5.3.1. Discussion

Credentials are used for authentication and identity- or role-based permissioning on the Spatial Web, and may more broadly be used to implement conditions for Activity execution.

A credential may allow an entity to make a verifiable *claim* as an *issuer* (see definitions in W3C vc-data-model). A verifiable credential is a tamper-evident credential that has authorship that can be cryptographically verified.

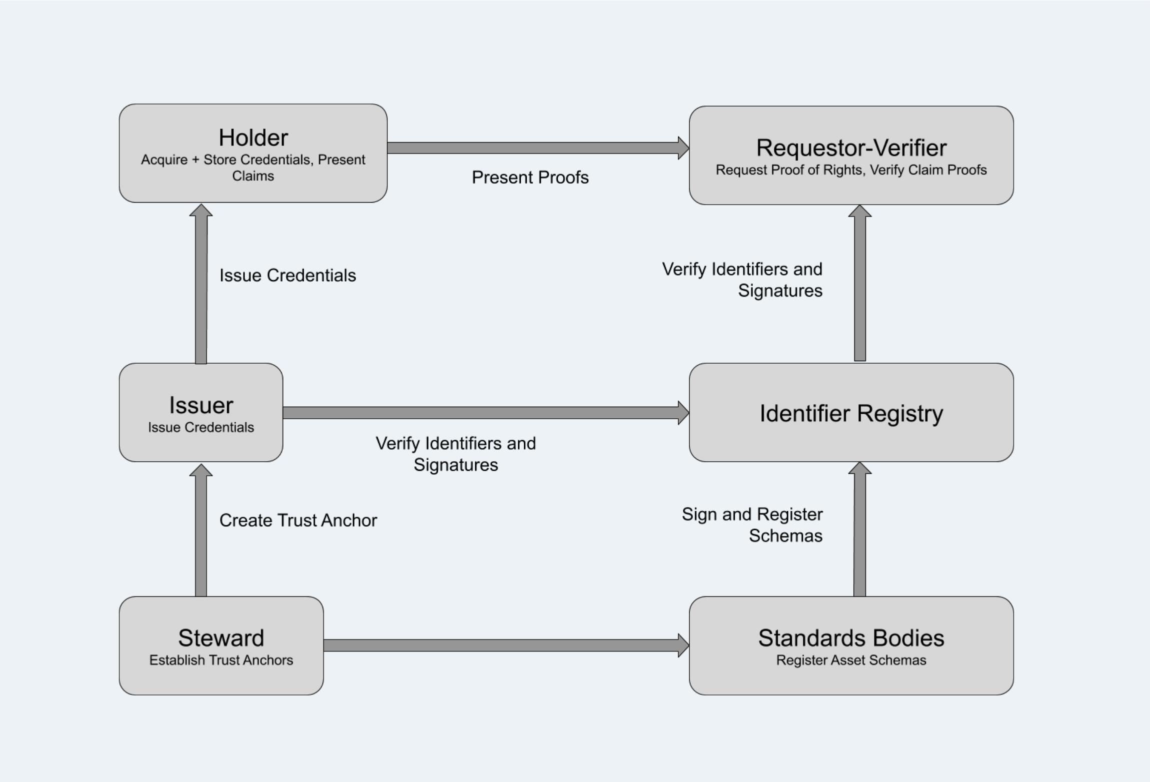
**FIGURE 21:** Types of claims



In the Spatial Web, CREDENTIALs are used for several claims: Identity (6.2), Domain relationships (6.2), AGENTs' ability to perform an Activity (6.3), as well as for signing Contracts (6.5.4.3).

The general flow of claim information is as follows:

**FIGURE 22:** Claims Schema



The Claims schema Figure 22 provides a decentralized identity system architecture that facilitates redundancy and resiliency in the technology infrastructure and organizational governance models. Multiple standards bodies and “governments,” supported through “stewards,” define and register “schemas” that can be utilized by Credential “issuers,” which can be used to verify claims represented by Credential “holders.” See the definition for registration in 6.3.6.

Verifiable protocols are crucial for ensuring that autonomous agents act in a manner that satisfies stakeholder requirements. Normative concepts, policies, and preferences are critical to internet-based multi-agent systems.

### 6.5.3.2. Requirements: Claims and Credentials

- HSML shall encode Claims for an AGENT’s ability to perform an Activity shall be certified by a registered Domain Authority.
- HSML shall encode Encrypted digital Credentials that are independently verifiable without the notification of third parties. When a party verifies the issued Credentials, a record of this verification shall be created and made available to the Credential-issuing domain(s), in order to prevent the tracking of origins and contexts of verification requests.
- HSML shall define a claims schema that supports spatial claims and identities, as well as generic claim mechanisms, via HSML Credentials.
- Spatial Web Governance shall define a decentralized identity architecture based around Credentials comprised of:

- **a.** A network steward shall define regulatory standards bodies and establish trust anchors;
- **b.** A standards body shall then define schemas for specific Activities;
- **c.** An issuer shall follow those schemas, assigning identifiers that are written to a registry and provided to individual Credential holders (see 6.3.6)
- **d.** Credential holders shall then prove those Credentials to a requester-verifier in response to a challenge/opportunity request.

## 6.5.4. Governance via Contracts, Activities and Credentials

### 6.5.4.1. Activities, conditions, and normativity

HSML Activities, as described in 6.4, represent the capacities of AGENTS for effecting change in the Spatial Web, defined in terms of the conditions they aim to establish, specified in terms of HSML data structures. Activity conditions can, for example, be represented as a query run against the HSML representation of a Domain, which evaluates to a Boolean indicating whether or not the Activity's defining conditions have been satisfied in the Domain model.

The execution of Spatial Web Activities within Domain(s) may also be subject to conditions imposed unilaterally, mutually agreed upon or negotiated between parties to a transaction. Examples include provisions in a contract for work or transfer of ownership, as well as Domain rules that actors within a Domain explicitly or implicitly agree to abide by, including laws and regulations issued by various authorities. These conditions can similarly be represented as expressions evaluable against the state of HSML Domain models.

Thus HSML may be used to model two closely related types of normative or "ideal" states: Activities can be encoded in terms of their success conditions (i.e., intended effects), and rules may be encoded in terms of their compliance (or violation) conditions. This common encoding enables a wide range of normative concepts to be expressed and automatically applied to govern Activities represented in HSML, using rules and Activities.

### 6.5.4.2. Relation to existing languages for planning and norms

The way in which Activities and related normative concepts are represented in HSML is closely related to existing languages for the automation of (a) planning, in the context of artificial intelligence and autonomous agents, and (b) the assessment of normative statuses based on rules (laws, regulations, and the like).

eFLINT [83] is a language for representing how normative statuses evolve, given a model of a situation, actions, and norms associated with various institutions. One of its key data structures, an Act frame, describes Activities in terms of their preconditions, as well as the effects they bring about. Fact frames define arbitrary facts that hold in the simulated situation.

Planning Domain Definition Language (PDDL) [86] is a domain-agnostic language for specifying planning problems, where actions represent the operations that can change the state of the world in a simulated environment (or domain). Similar to eFLINT's Act frames, PDDL defines actions in terms of preconditions (conditions that must hold in order for the action to be executed) and effects (conditions that will be brought about as effects of the action).

HSML Activities similarly specify the states of affairs they (are intended to) bring about, as well as any states presupposed by a change or state transition. HSML Activities, together with Contracts (discussed in the subsequent subsection), thus constitute an abstraction suitable for the purposes of both automated planning and automated governance.

The possibility of some such common abstraction is evident, given that both planning and governance are concerned with achieving normative states of the world. While planning concerns how to proceed from an initial state to a normative state, governance concerns whether a given state is ideal (and what the consequences are when it is not, which in the Spatial Web can be specified in terms of further Activities for enforcement, litigation, etc.).

Existing frameworks such as eFLINT or PDDL could be used to implement HSML Activities (and Contracts), such that they satisfy the requirements in 6.5.4.5.

### 6.5.4.3. Contracts as Agreements for Activities

HSML Activity Schemas define types of changes to be effected by an agent in terms of their satisfaction conditions. The agreement that such conditions should obtain, i.e., that some specific instance of an Activity should be executed within a Domain, and be carried out by, on, and for specific parties and involving specific objects, locations, etc., is an instance of a (hyperspatial) Contract.

In addition to the near-instantaneous changes of normative state effected by contractual agreements, such as legal transfer of ownership of an asset under specified conditions, Contract evaluation may include validation of a Contract, which is a check that the Activities specified in the Contract have been carried out, as per their completion conditions, specified in the HSML data representing the relevant Contracts and Activities. In this way, real-world (spatial) events as well as purely digital transactions can be represented and negotiated by parties interacting on the Spatial Web.

### 6.5.4.4. Non-functional requirements on Activity performance

Non-functional requirements can apply to real-world processes governed by Spatial Web Contract and Activity performance. For example, a drone may be required not only to complete a route from A to B, but to do so safely and in an energy-efficient manner. Such requirements may be imposed by third parties (such as relevant state actors) as constraints on Activity execution in addition to those that a Contract's immediate parties might be interested in achieving.

Requirements on Activity execution from third-party Domain Authorities can be specified in several of the following ways:

- As independent Contracts signed by relevant Agents, leaving compliance to Agent-internal logic.
- As restrictions on Activity registration or execution within a governed Domain.

- By adding additional conditions to an existing Activity, creating a more granular Activity Schema combining requirements from all concerned parties.

Requirements on a Spatial Web transaction which cannot be specified as Activity conditions in the sense described in 6.5.4.1, 6.5.4.2, and 6.5.4.3; i.e., as predicates or queries on the state of HSML data, cannot be validated algorithmically by HSML Contract validation mechanisms, and their satisfaction shall be assessed by other means (i.e., human judgment).

### 6.5.4.5. Requirements and recommendations: Contracts

- HSML shall enable the negotiation, validation, monitoring and confirmation of contractual agreements that govern transactions on the Spatial Web.
- HSML CONTRACTS shall constitute agreements for the performance of an HSML Activity Instance. Contract status shall be a function of the status of the associated Activity instance, such that the contract conditions can be evaluated as True or False against the relevant Domain description(s).
- Spatial Web Governance shall define HSML CONTRACT conditions that shall apply to the entire Spatial Web.
- Domain-specific architectures shall define HSML CONTRACT conditions to be explicitly defined and agreed upon by all relevant parties and shall enable the automatic execution of contracts when such mutually agreed conditions (as encoded in an HSML CONTRACT entity) are reached. Conditions may be represented at the level of granularity required by the situation, as agreed upon by relevant parties.
- Domain-specific architectures shall define how CONTRACT evaluation is be performed by Domains in as close to real time as possible, and shall be subject to the possession of Credentials by the parties to the contract, as specified in condition(s) contained within the relevant Activity definition.
- Domain-specific architectures shall define how CONTRACT evaluation is performed by Domains in as close to real time as possible.
- Domain-specific architectures shall be subject to the possession of CREDENTIALS by the parties to the CONTRACT, as specified in condition(s) contained within the relevant ACTIVITY definition.
- Domain-specific architectures shall define how Contract evaluation at the edge of the network shall be implemented to optimize performance and transparency such that client and server, edge and cloud, can have a priori parity on contracts and code execution between them. (See clause 7.1.1 for computing nodes and networks.)
- Domain-specific architectures shall define how workflows are to be consistently designed across different identities, Domains, and Spaces having necessary permissions, and subsequently chained together to help ensure that trust accrues with every interaction.
- Domain-specific architectures shall define how Claims in a Credential to a relevant status or identity may be subject to certification by a third-party testing organization.

- Domain-specific architectures may accept verified Credentials as sufficient to provisionally establish that an AGENT is qualified for an Activity.
- HSML shall enable the representation of issuing of Contracts as an HSML ACTIVITY, subject to norms and standards specified in further conditions, and subject to validation by relevant third parties as described in 6.5.4.

### 6.5.5. Norms and Domain Authorities

#### 6.5.5.1. Encoding normative structures in HSML

HSML Contracts and Activities encode expectations about how certain entities will behave, conditional on specific assumptions encoded as Activity conditions (predicates). Activities encoding a machine-readable description of normative constraints on Agent behavior in an Activity's initial conditions and the consequences of conforming to or violating the rule in its resulting conditions can represent rules or other normative structures. Agents operating in a governed Domain may then assent to this form of governance by explicitly signing a Contract to participate in the enforcement Activity, or Domain-specific sub-types of Activities may be created based on such normative constraints, as described in 6.5.4. Where these constraints are applied, governance of Activities within relevant Domains is accomplished by granting Credentials for only those Activity types found consistent with Domain Authority rules.

This framework enables a "rules-as-code" [118] or "law-as-code" paradigm, which encompasses both the translation of existing sources of law (regulations, statutes, etc.) into executable code, e.g., via natural language processing (NLP) techniques, and the design of new sources of law, particularly those concerned with the governance of autonomous systems.

#### 6.5.5.2. Law as code example

The following subsection presents an example in which legal norms applicable to unmanned vehicle flight are translated into HSML Activities and Contracts.

[98] contains the following governing unmanned aircraft flight in the European Union:

"During flight, the unmanned aircraft shall be maintained within 120m from the closest point of the surface of the earth."

This rule can be represented in terms of the following HSML data structures:

"A remote pilot [AGENT], operating within the relevant jurisdiction [DOMAIN], is authorized [CREDENTIAL] by the European Union Aviation Safety Agency ("EASA") [DOMAIN Authority] to fly [ACTIVITY] an unmanned aircraft or UAV [DOMAIN], given that the flight path of the UAV always remains below 120m [ACTIVITY condition referencing a SPACE]."

The following describes three data structures in pseudocode: first, the authorization Activity type whereby a UAV flight Activity is allowed or prohibited by the EASA; second, the drone flight Activity type; and third, the instantiation of this Activity type with parameter values supplied. Details of the implementation of Activity conditions outside the scope of this Standard, such as the specification of units of measure, are omitted.

- EASA Unmanned Flight Authorization Activity Schema

  - variables
    - `$flight_activity: UnmannedFlightActivity`
    - `$flight_credential: Credential`
  - conditions
    - initial
      - `max($flight_activity.parameters.route.position.z) less_than_or_equal_to 120.0`
    - result
      - `$flight_activity.pilot has_credential $credential`
- Flight Activity Schema
  - variables
    - `$route: Space[]`
    - `$pilot: Agent`
    - `$uav: Domain`
  - conditions
    - initial
      - `$pilot has_credential <license_to_fly>`
    - result
      - `$uav.position in $route`
- Flight Activity
  - schema
    - FlightActivitySchema
  - parameters
    - `$route: [<geo_waypoint_1_SWID>, <geo_waypoint_2_SWID>, <geo_waypoint_3_SWID>]`
    - `$pilot: <agent_SWID>`
    - `$uav: <UAV_SWID>`
  - status
    - Requested

This simplified example uses a single hard-coded rule (maximum flight height of 120.0 meters), but in practice, a generic UAV flight authorization Activity schema would combine many such rules, and could be built compositionally out of more fine-grained Activity types.

### 6.5.5.3. Norms and Domain Authorities

Spatial Web Domain Authorities, as defined in 6.3, are Entities in hyperspace that confer rights and responsibilities, and more generally define norms binding within associated Domains, e.g., laws in a state, rules based on authorization and roles in a private (e.g., corporate) space, or any other normative structure, as discussed in 6.5.5.4. Such Domain Authorities may serve a variety of roles, depending on their hierarchical and other relationships with one another. Activities occurring within a Domain are subject to norms enforced by relevant Domain Authorities. However, neither the encoding of such norms in HSML nor compliance with them may be interpreted as establishing the legitimacy of the rules specified by such Authorities, or their claimed right to impose or enforce them. In particular, the authority of a Domain Authority over any particular Domain is limited by factors such as the existence of higher-level Domain Authorities in a Domain hierarchy, and by the self-sovereignty of some Domains, such as those representing individual human beings.

As discussed previously in 6.3, Domain Authorities may be self-credentialed. Intuitively, each sovereign individual is an Authority over the corresponding Domain representing that individual in the Spatial Web (which does not preclude the existence of other Authorities also having or claiming jurisdiction over that Domain). Legal authorities are a special case of a much more general pattern in which Domain Authorities define sets of normative constraints on Activities within their associated Domains. While it is likely not practical to represent every normative property in terms of explicit, registered Domain Authorities, the concept is broad enough to cover all such cases.

The Activities governed by Domain Authorities may be defined at any level of the UDG and linked or subscribed to, as well as subclassed or aggregated to create novel Domain-specific Activity types (subject to constraints imposed by the source Domain Authority). Domain rules codify which types of Activities (and thus Contracts) are allowed by relevant Domain Authorities to occur within governed Domains, and permit Domain Authorities to automatically validate incoming requests for performance of such Activities, and to refuse non-compliant requests. Specifications of the Activities allowable within a Domain provide an interface for rules imposed by the Domain Authority (i.e., in the form of parameters capturing normatively relevant aspects of the Activity), where such Activity-level parameters may also facilitate consistency checking among sets of Domain rules and registered Activity types.

The Spatial Web Registration Authority takes no position on which norms enforced by Domain Authorities are actually binding on any given individual, organization, nation, etc., but allows participants in the Spatial Web to *represent their normative claims* by way of rules associated with credentialed Domain Authorities, as well as via Contracts. Some Domain Authorities in the Spatial Web will mirror relevant authorities in the real world (e.g., sovereign nations, which, like sovereign human individuals, shall have the right to control over the Spatial Web Domains representing their territories). The infrastructure of the Spatial Web is not designed to settle conflicts among Domain Authorities, but to represent such conflicts accurately in the form of competing claims, each with its own provenance. Participation in a Domain (via the execution of Activities by a Spatial Web AGENT) may involve explicit consent to the terms governing that Domain, via HSML Contract.

### 6.5.5.4. Requirements: Activities and Domain Authorities

Spatial Web Governance shall authorize Domain Authorities to validate (either directly or via an appropriately designated proxy) requests to perform Activities (i.e., Contracts) within a governed Domain.

Spatial Web Governance shall define Domain Authority validation procedures to include the functional equivalent of a Boolean evaluation of whether a given Contract's completion conditions are consistent with allowable states of the Domain model according to Domain rules, which may themselves be encoded as queries on the state of the Domain model, and may include the possession of Credentials by various parties, as well as the registration of Activity types with relevant Domain Authorities (see 6.3.6).

Spatial Web Governance shall help ensure that HSML Activities that occur within the jurisdiction of a Domain Authority, including instances of those Activities (i.e., Contracts), as well as the rules defined by that Authority, shall be evaluated as queries against the state of the relevant HSML Domain model(s).

Spatial Web Governance shall help ensure that Activities and Contracts that enable the definition of abstract normative conditions on Activity execution by Domain Authorities, be automatically applied to Activity performance within governed Domains.

Spatial Web Governance shall help ensure that Activities and Contracts that allow requirements on Activity performance imposed by Domain Authorities to be interoperable with the conditions that define an Activity of a given type, such that more fine-grained Activity types sanctioned by such Authorities can be created automatically or with minimal effort.

## 6.6. Spatial Web ontology

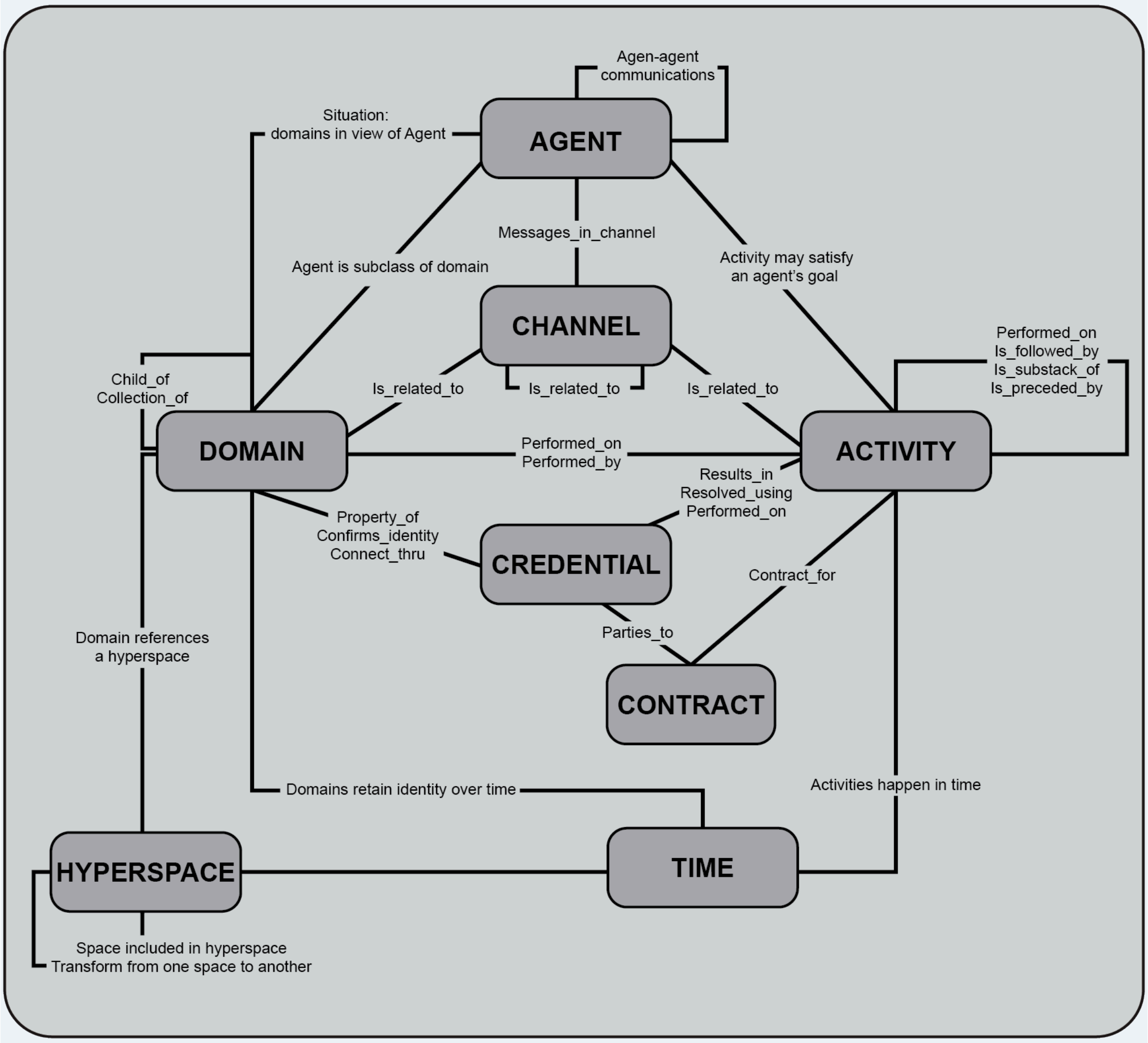
### 6.6.1. Concepts

The Spatial Web ontology is composed of entities that are the primary concepts used across the Spatial Web and in the Hyperspace Modeling Language (HSML). HSML implements the Spatial Web ontology as a set of schemas that enable increased coherence across diverse datasets without sacrificing flexibility.

The Spatial Web ontology Figure 23 defines several classes. All classes other than the base class (ENTITY) are extensions of the base class. The Spatial Web ontology entities are as follows:

- ENTITY
- ACTIVITY
- AGENT
- CONTRACT
- CHANNEL
- CREDENTIAL
- DOMAIN
- HYPERSPACE
- TIME

**FIGURE 23:** Spatial Web entity relationship diagram



This clause provides an Entity Relationship Diagram and definitions of entities as the basis for an ontology. Formal logic is too detailed for this reference model that defines components and requirements for the components. Formal logic implies using stronger syntax, e.g., RDF and axioms, e.g., using OWL. The requirements in this clause pertain primarily to the HSML Implementation Specification in which formal logic may be employed.

The Spatial Web ontology builds upon careful examination of several existing ontologies, i.e., IEEE Std 7007™-2021, ISO/IEC 21838-1:2021, ISO/IEC 21838-1:2021, [75], and [107].

## 6.6.2. ENTITY

An ENTITY is that which is perceived, known, or inferred to exist, has existed, or is anticipated to exist.

Functionality—ENTITIES are the basis for all Spatial Web ENTITIES and are fundamental to the execution of HSML software.

Purpose—ENTITIES contain the properties that are universal for all ENTITIES, such as SWID, or Name, and a means for HSML-compliant software to work with any entity, including those elements that are subclasses from the entity, in ways that require nothing more than the composition of the base object. An example would be changing relationships between entities.

Execution—Entities act as a base class in object-oriented programming (OOP) software or a core component in prototypical or other non-OOP languages that support such functionality.

Attributes of an ENTITY include the following:

- Shall include: SWID
- May include: ENTITY subclass
- May include: CREDENTIALS

### 6.6.3. ACTIVITY

An ACTIVITY is a temporally-extended process that unfolds across time. It is a strictly defined series or partially ordered set of changes to be effected by an Agent. See 6.4

An ACTIVITY is a Spatial Web ENTITY representing a partially ordered set of changes that a Spatial Web AGENT is capable of effecting. An ACTIVITY Schema specifies at least one condition, describing (in terms of HSML entities and their properties, e.g., via Boolean expressions) the state that results after an Activity has been completed. Optionally, ACTIVITY Schemas may also specify initial conditions upon which execution of the Activity depends, as well as conditions describing intermediate results. It is up to HSML implementations to help ensure that the resolvers of ACTIVITIES compute the functions necessary to transform HSML data such that each *condition* is produced when the previous one is satisfied. If no initial condition is specified, the ACTIVITY can be performed in any context.

Functionality—ACTIVITY defines a set of changes to be effected by an Agent, and represents behavior or logic that can be executed by HSML-compliant systems.

Purpose—ACTIVITY provides a method of describing granular sets of changes in HSML in terms of their defining conditions, in a way that is evaluable and executable by HSML-compliant software.

Execution—ACTIVITY is the basis of all entity-to-entity execution in the Spatial Web, and serves as a base class in object-oriented programming software.

Activities may be transitive or intransitive, depending on whether they update the state of any other HSML elements.

An ACTIVITY Schema is a template that can be used to generate an ACTIVITY Instance, the performance of which is an event associated with some time stamp.

Normativity—The *conditions* field of an ACTIVITY Schema describes the temporal evolution of events and actions within Spatial Web Domains, should such an ACTIVITY be executed. Parties on the Spatial Web may explicitly agree to the performance of an ACTIVITY by signing a CONTRACT for that ACTIVITY. This agreement functions normatively for all parties to the CONTRACT. At the same time, ACTIVITIES impose constraints on how HSML data is interpreted in order for an implementation to be compliant [i.e., all resulting conditions should, *ceteris paribus*(all other influencing factors are held constant), be computed when the ACTIVITY is executed, when and only when any specified initial conditions are met].

The *conditions* of HSML ACTIVITIES parallel the *preconditions* and *post-conditions* of Act Frames in eFLINT [83], which encode changes in normative status. Their use in planning and representing the temporal evolution of Spatial Web Domains also parallels the role of *preconditions* and *effects* in the Planning Domain Definition Language (PDDL) [86].

Relationships in Figure 23 for ACTIVITY are as follows:

- An ACTIVITY may be composed of other ACTIVITIES
- An ACTIVITY may be preceded by or be followed by an ACTIVITY
- An ACTIVITY happens in TIME
- An ACTIVITY may be the subject of or be instantiated by a CONTRACT
- An ACTIVITY may be authorized by a CREDENTIAL
- An ACTIVITY may result in creation of a CREDENTIAL
- An ACTIVITY is performed on and is performed by a DOMAIN
- An ACTIVITY is performed on, is performed by an AGENT. This relation results from an AGENT being a type of DOMAIN
- An ACTIVITY may be performed to satisfy the goal of an AGENT
- An ACTIVITY may be referenced in messages in a CHANNEL

Attributes of an ACTIVITY Schema include the following:

- Shall contain all mandatory fields of an ENTITY
- Shall contain a *conditions* field, where conditions may include open variables for HSML ENTITIES and require the possession of, or entail the generation of, CREDENTIALs
- Shall contain a *variables* field, which specifies the type of any free variables occurring in the *conditions*

Attributes of an ACTIVITY Instance include the following:

- Shall contain all mandatory fields of an ENTITY
- Shall specify the ACTIVITY Schema of which the ACTIVITY is an instance
- Shall contain a *parameters* field, which associates specific HSML Entities with the roles specified in the corresponding ACTIVITY Schema’s *conditions*, matching the types of its open *variables*
- Shall contain a status with allowed values: “Planned”, “Ongoing”, “Failed”, “Completed”

### 6.6.4. AGENT

An AGENT is an ENTITY that senses and responds to its environment, maintains a model of its environment, and performs Activities to achieve a goal. See 6.4

An AGENT is a type of DOMAIN capable of performing an ACTIVITY. An AGENT may execute specific, narrowly defined tasks or be an intelligent AGENT capable of autonomous decision-making.

Relationships in Figure 23 for AGENT are as follows:

- An AGENT is a type of DOMAIN and inherits all relations and attributes from DOMAIN.
- An AGENT may change attributes of DOMAINs.
- A SITUATION relationship is an entity comprised of all DOMAINS that can be perceived and reasoned about by an AGENT. Situation is to be understood as defined in IEEE Std 7007™-2021: a situation is an entity comprised of participating entities and relationships that represent the limited parts of reality that can be perceived and reasoned about by agents.
- An AGENT creates a model of its environment through interaction with DOMAINS.
- An AGENT may control the changes specified in an ACTIVITY.
- An AGENT may communicate with another AGENT (this is a direct communication outside of a CHANNEL).
- An AGENT may post messages to a CHANNEL.

Attributes of an AGENT include the following:

- Shall contain all mandatory fields of an ENTITY.
- Shall contain attributes that describe its goals.
- Shall contain attributes that describe its model of the environment.

### 6.6.5. CONTRACT

A CONTRACT is a binding agreement between two parties, especially enforceable by law, or a similar internal agreement wholly within an organization. See 6.5.

A CONTRACT is a Spatial Web ENTITY that represents a request to perform an instance of an ACTIVITY. It specifies, via Spatial Web ID (SWID), the *parties* to the CONTRACT, which shall include a *requester* (the party requesting the contract), as well as any actors (parties acting as AGENTs to fulfill the ACTIVITY's *conditions*), insofar as these are not already specified in the ACTIVITY *conditions*.

Relationships in Figure 23 for CONTRACT are as follows:

- A CONTRACT is requested by a DOMAIN.
- A CONTRACT is requested by an AGENT.
- A CONTRACT is accepted (signed) by an AGENT.
- A CONTRACT is fulfilled by an AGENT.

- A CONTRACT is an agreement for the performance of an ACTIVITY.
- A CONTRACT represents an agreement between two or more parties: requesting DOMAIN, fulfilling AGENT(s), and any relevant third parties.

Attributes of a CONTRACT include the following:

- Shall contain all mandatory fields of an ENTITY.
- Shall contain a field for parties specifying the CONTRACT's requester as well as any parties to the CONTRACT not already specified in the *conditions* of the ACTIVITY for which it is an agreement.
- Shall contain a *contract status* with allowed values of "Requested", "Executed", "Fulfilled", "Rescinded", or "Breached".
- A time stamp shall be associated with changes of *contract status*.

### 6.6.6. CHANNEL

A CHANNEL is a Spatial Web ENTITY that groups a stream of HSML entities related to an activity of a specific context that does not itself warrant a domain or hierarchy.

Functionality—CHANNELS are an HSML element that describes a set of HSML elements considered in a specific context that does not itself warrant a domain or hierarchy.

Purpose—Channels provide the HSML schema a means of grouping HSML elements together without further complicating domain hierarchy with groupings of taste or preference rather than structural reflections of reality.

Execution—Channels are used to parse functionality and data in the creation of child instances, and act as a common means of searching a limited context of a spatial graph.

Relationships in Figure 23 for CHANNEL are as follows:

- A CHANNEL may be a collection of CHANNELs, where the wider CHANNEL contains all information from all lower CHANNELs.
- CHANNEL be specific to a specific ACTIVITY or ACTIVITIES
- CHANNEL be specific to a specific AGENTS based on CREDENTIALS

Attributes of a CHANNEL include the following:

- Shall contain all mandatory fields of an ENTITY.

### 6.6.7. CREDENTIAL

A CREDENTIAL is a set of one or more claims made by a DOMAIN. See 6.5.

CREDENTIAL is a Spatial Web ENTITY holding information that a DOMAIN (a person or device) possesses that allow it to make a verifiable claim. Verifiable means that the claim can be authenticated.

Functionality—CREDENTIALS are entities that describe an affirmation of a claim that is relevant to ACTIVITIES and DOMAINS.

Purpose—Credentials a means of establishing ownership and a means of resolving contracts.

Execution—Credentials are used in contract execution.

Relationships in Figure 23 for CREDENTIAL are as follows:

- A CREDENTIAL relates to an ACTIVITY may include authorization to perform, and certification of ability to perform.
- ACTIVITIES are resolved using CREDENTIALs.
- ACTIVITIES are performed on CREDENTIALs.
- DOMAINs are owned through CREDENTIALs.
- CREDENTIALs are the property of DOMAINs.

Attributes of CREDENTIAL include the following:

- Shall contain all mandatory fields of an ENTITY
- Shall contain one or more claims

### 6.6.8. DOMAIN

A DOMAIN is a Spatial Web ENTITY with identity through time endowed with rights and credentials. See 6.3

Functionality—Domains provide structure, often parallel structures, for the existence of people, places, and things including concepts. Hierarchical in nature, they allow for parent, child, and sibling relationships.

Purpose—The purpose of a DOMAIN is to offer a conceptual area in which to add definitions or behavior with HSML-compliant software that allows reality to be described from multiple perspectives and correlated hierarchies. It can be used to provide a single distinct container for things such as an object, a legal body, or an idea, without having to be the thing itself.

Execution—Domains are used by software as ubiquitous contexts for data and execution.

Relationships in Figure 23 for DOMAIN are as follows:

- A DOMAIN may be related to other DOMAINS
- A DOMAIN resolves an ACTIVITY
- A DOMAIN requests a CONTRACT
- A DOMAIN may be a child of another DOMAIN
- A DOMAIN references a SPACE to define location or paths
- A DOMAIN is owned through a CREDENTIAL

Attributes of DOMAIN are as follows:

- Shall contain all mandatory fields of an ENTITY
- Shall contain an attribute of DOMAIN type

### 6.6.9. HYPERSPACE

HYPERSPACE is a Spatial Web ENTITY for a generalized concept of space. HYPERSPACE is any set whose elements are related by a notion of path. HYPERSPACE includes multiple classes as shown in Figure 14. SPACE denotes subclasses of HYPERSPACE.

SPACE provides the framework to define a boundary for a DOMAIN. For example, the boundary of a DOMAIN may be given as a geometry, e.g, point, line, polygon, solid, where the coordinates of the geometry are in a Cartesian space. The SPACE can be more general, for example, a range of values that identifies a spectrum boundary such as for colors, volume, or brightness.

Functionality—SPACEs are HSML elements that inherit from ENTITY. SPACEs conform to the definitions provided in 6.2. A SPACE is a subclass of Hyperspace, denoted by the SpaceType attribute in HSML. Types of Space include, but are not limited to, Graph space, Vector space, Abstract space and Cellular space. A Space may be associated with other types of Space. Changing the relation of a Domain from one type of Space to a different type of space is a Spatial Transform or Transformation.

Purpose—Spaces enable the definition of physical or virtual locations, positions and geometries as they exist at a point in time or within a range of time.

When SPACE, the SpaceType attribute, is of value “Cellular”, and DOMAIN is of type geographic space, then an attribute of Earth_DGGS shall be populated. The Earth_DGGS attribute shall use the indexing system of the H3: Hexagonal hierarchical geospatial indexing system discrete global indexing system.

Relationships in Figure 23 for SPACE are as follows:

- SPACE may be associated with a DOMAIN
- SPACE may be a child of another DOMAIN
- SPACE may be related to another SPACE where a suitable transformation may be defined

Attributes for HYPERSPACE include the following:

- Shall contain all mandatory fields of an ENTITY
- Shall contain SpaceType with values from 6.2
- May contain Earth_DGGS with value of H3Index from H3: Hexagonal hierarchical geospatial indexing system, required when DOMAIN type is geographic

### 6.6.10. TIME

TIME may be a dimension in spacetime. It may be a length of a duration. It may be a trajectory. It may be related to a clock. When experienced by an AGENT, TIME has a past, present, and future. TIME is a spatial Web ENTITY (6.2).

Relationships in Figure 23 for TIME are as follows:

- TIME may be related to HYPERSPACE
- TIME may be related to ACTIVITIES

Attributes for TIME include the following:

- Shall contain all mandatory fields of an ENTITY
- May contain a temporal reference frame, e.g., a time zone

### 6.6.11. AGENT, ACTIVITY, and CONTRACT relationships

**FIGURE 24:** Agent-Contract-Activity relationship diagram

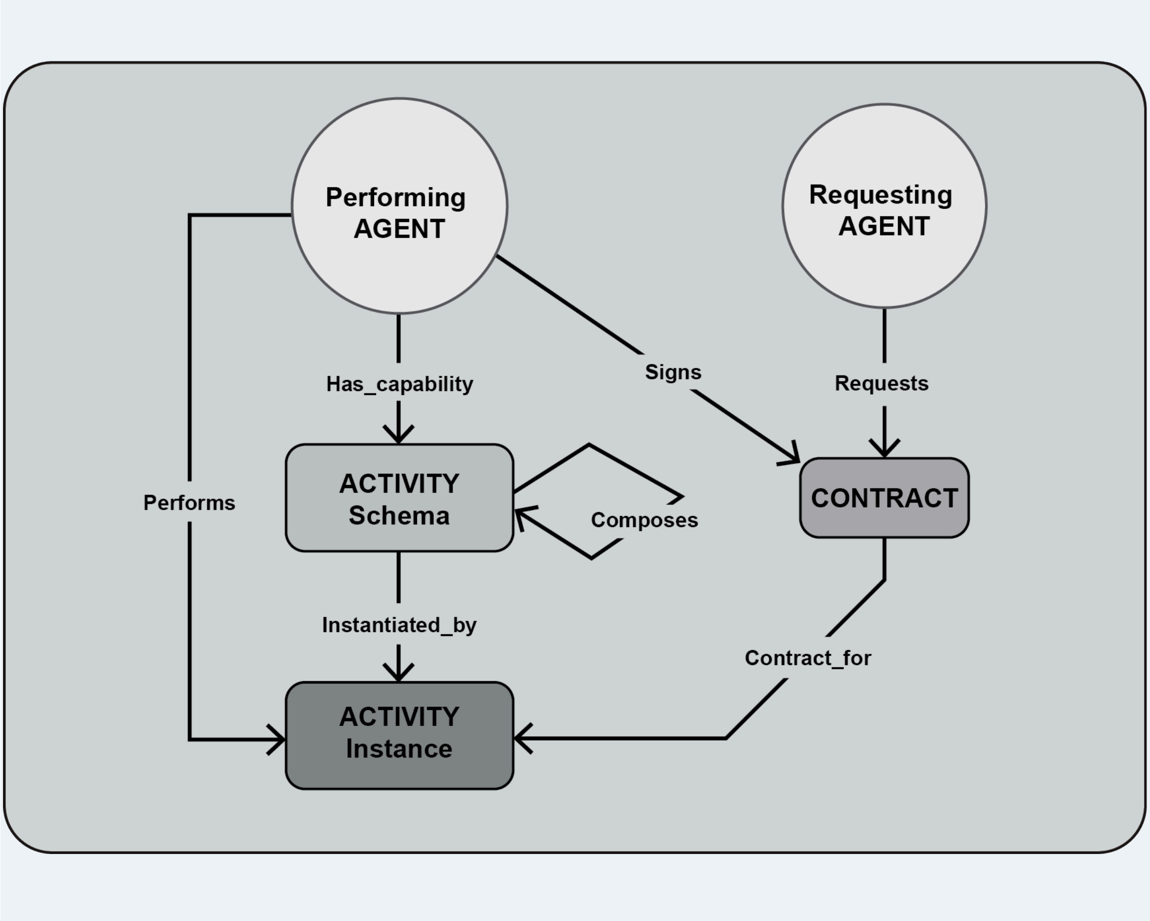


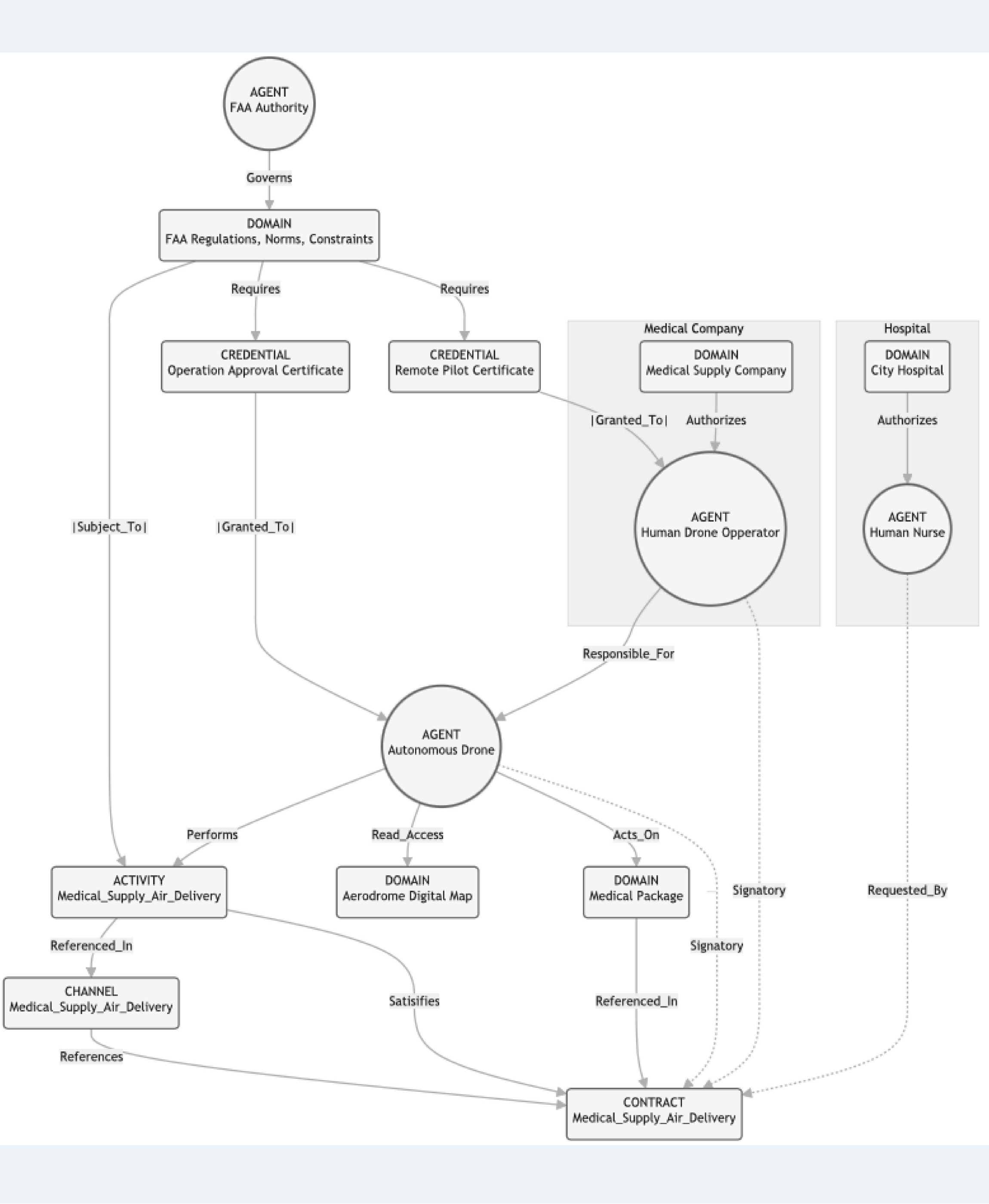
Figure 24 pictures the core relationships that obtain in the HSML ontology among, a) AGENTs, b) ACTIVITY Schemas, c) ACTIVITIES (aka ACTIVITY Instances), d) CONTRACTs. A Requester is an AGENT requesting performance of a task or other CONTRACT. The loop connection on ACTIVITY Schema represents the composition of Complex ACTIVITY Schemas, as discussed in 6.4.

### 6.6.12. Example use of Spatial Web ontology

In this example (see Figure 25), Spatial Web entities are associated with a Warehouse Floor CHANNEL, representing the state and ACTIVITIES of a Warehouse (DOMAIN). In particular, the Wave Pick ACTIVITY is discussed, which is performed on a Warehouse Bin DOMAIN, associated with a SPACE in Cartesian coordinates, and an ECommerce Item DOMAIN, a child of the Logistics Company DOMAIN. The Distribution Center DOMAIN is also a child of the Logistics Company DOMAIN and resolves this ACTIVITY.

The abstract definition of an ACTIVITY has been described. This can be performed (producing an event if successfully resolved by the DOMAIN) in a Worker DOMAIN, given they have the relevant Employee CREDENTIALs and Pick CREDENTIALs for the given DOMAIN.

**FIGURE 25:** Spatial Web ontology example



## 6.6.13. Requirements—Spatial Web ontology

- HSML shall implement the attributes and relationship of the Figure 23 for each Spatial Web entity.
- HSML shall define several profile encoding formats, e.g., JSON (see ISO/IEC 21778), OData (See ISO/IEC 20802-1 and ISO/IEC 20802-2), JSON-LD (see W3C json-ld11), and GraphQL (see The GraphQL Specification Project).

- HSML shall provide standard elements for SpaceType properties as defined in 6.2.
- HSTP shall enable create, read, update and delete on HSML entity relations and attributes.

## 6.7. Queries

### 6.7.1. Concepts about Spatial Web queries

Queries on the Spatial Web are expressed using HSML and are used to identify information about DOMAINS in the UDG.

A query using HSML has the following general form: An AGENT with CREDENTIALS requests the values of attributes about a DOMAIN where the DOMAIN is identified using HYPERSPACE.

A foreseeable use-case would employ automatic translation systems to enable queries expressed in natural language to be converted into HSML before they are forwarded to relevant Domains. Queries may also be converted from existing query languages such as SQL or GraphQL.

An important example of the kind of interactions enabled by wide adoption of the present Standards are situated queries, in which the position of a user in the Spatial Web (including realtime physical location) could be used to automatically fill in indexical elements of query schemas, based on local context. This would allow users of the Spatial Web to naturally express queries in the first person based on their current needs.

Example: A worker in a spatial-web-enabled warehouse could submit a query of the following form:

“Find tasks [ACTIVITIES] for me [AGENT] which I am certified to perform [CREDENTIAL] around my current location [DOMAIN] referenced to a [SPACE] over the next hour [TIME]”.

This query would be sent through a specific CHANNEL with CREDENTIAL, ACTIVITY, SPACE, and DOMAIN attribute values linked to the AGENT’s SWID. Local hyperspatial data could then be used to automatically discover relevant activities and filter them based on authorization and context.

### 6.7.2. Kinds of queries

#### 6.7.2.1. Bootstrapping/Context query

Bootstrapping queries correspond to a query on an instance to tell a client about the activities an entity can perform. This entails bootstrapping operation in hstp/hsml. This type of query happens when a query needs more context. A bootstrapping query is an expression of the following concept: “Find the ACTIVITIES this AGENT can perform on a CHANNEL in a DOMAIN.”

### 6.7.2.2. Activity queries

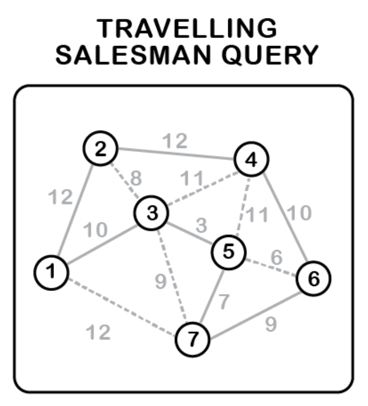
Activity queries correspond to a request for new activities or pending activities. The client can be aware of an ongoing stream and update it through these queries.

A tasking query is an expression of the following concept: “Find ACTIVITIES for which an AGENT holds a CREDENTIAL to perform, around my current location (DOMAIN referenced to a SPACE) over the next hour (TIME).” This type of query is used in 5.3.2.

An authorization query is an expression of the following concept: “DOMAIN requests CREDENTIAL for access to a device [DOMAIN] through a CHANNEL to conduct ACTIVITY”

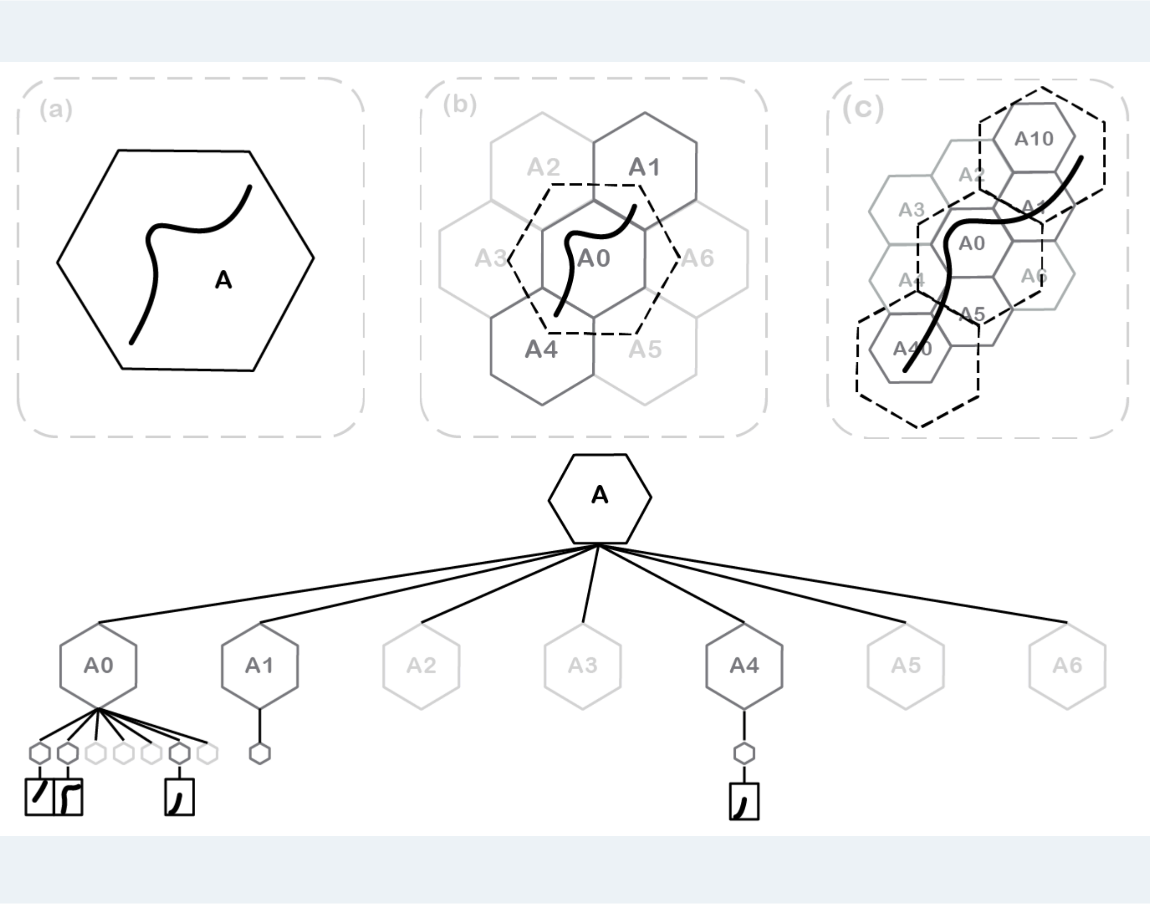
A routing query is an expression of the following concept: “Identify a route (ACTIVITY) where an AGENT holding a set of CREDENTIALS can navigate from a starting DOMAIN to an ending DOMAIN.” This type of query is used in 5.3.3. For more about routes as an activity see 6.4. An example of a routing query where the DOMAINs are referenced to a graph type of SPACE is the Figure 26.

**FIGURE 26:** Traveling Salesperson Query



An example of a routing query where the DOMAINs are referenced to a cellular type of SPACE is the Figure 27. Through this query, the DOMAINS can be indexed to a hexagonal cellular structure in a nested fashion, e.g., using the H3 Geo discrete global grid.

**FIGURE 27:** Hexagon Cell Index Query

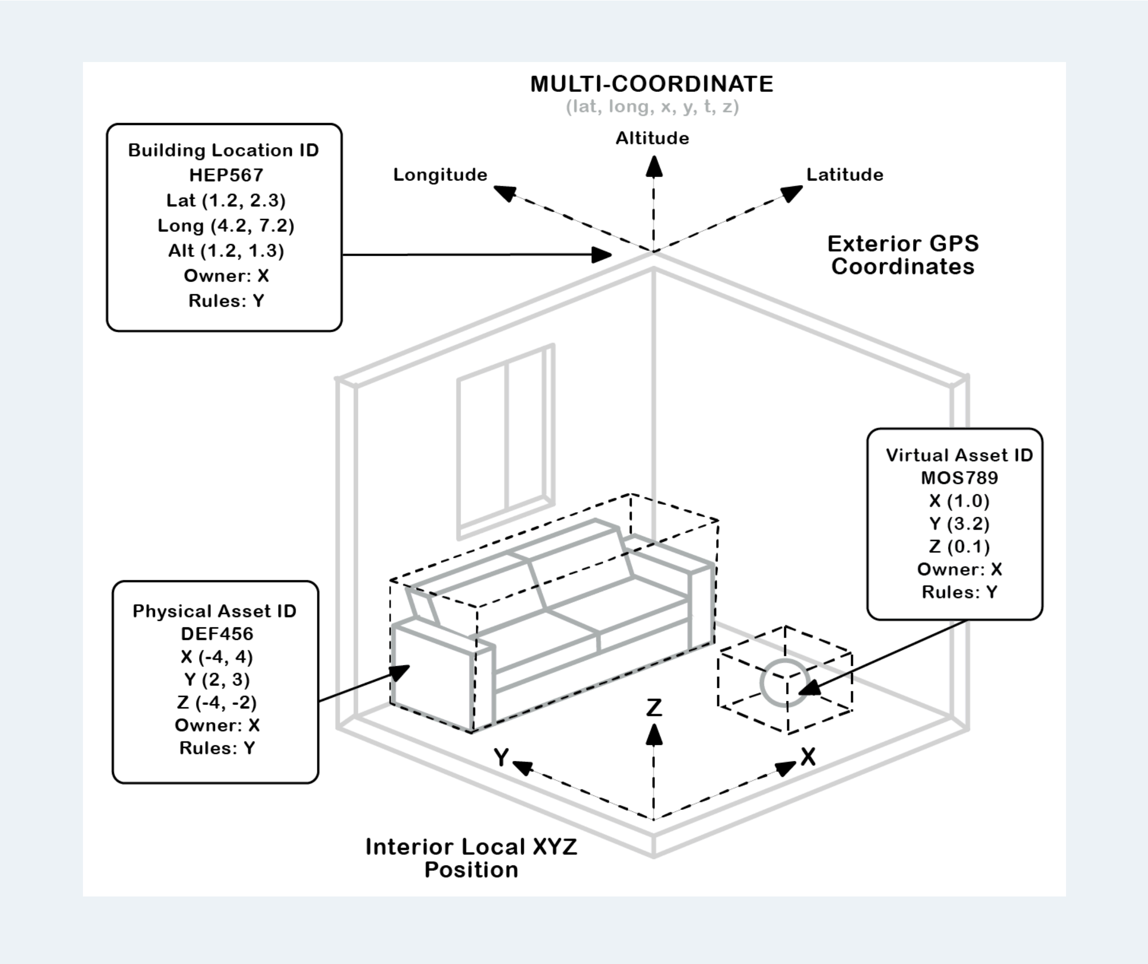


## 6.7.2.3. Hyperspace range queries

Spatial range queries identify DOMAINs that are within a spatial range. The spatial range is expressed based on the type of HYPERSPACE, SPACE, and TIME that is used to reference the location of the DOMAINS. The DOMAINS identified in the query may depend upon the CREDENTIALS held by the AGENT making the requested query. For example, the precision of the query depends on both the credentials of the client as well as the activity for which the query is intended. For example, these queries may be used to identify all landing strips (DOMAINs of interest) in the city of Berlin (the larger DOMAIN).

A geometric spatial range query (see Figure 28) is an expression of the following concept: “Identify DOMAINS within a larger DOMAIN which satisfy a spatial relation and the DOMAINS are referenced in a topological SPACE.” See Figure 14 for definition of topological space. DOMAINS are represented in the topological space using geometric objects such as points, lines, polygons and solids. Methods for testing spatial relations between geometric objects are as defined in ISO 19125-1 and identically in OGC 06-103r4 For a geographic domain with a topological space, the spatial relations may be non-Euclidean.

**FIGURE 28:** Geometric spatial range query



A cellular spatial range query is an expression of the following concept: "Identify DOMAINS within a larger DOMAIN which satisfy a spatial relation and the DOMAINS are referenced in a cellular SPACE." See Figure 14 for definition of cellular space. DOMAINS are represented in the cellular space using space filling cells which are indexed. Methods for testing spatial relations in a cellular space are defined for example in [58]

### 6.7.2.4. Abstract data type query

An abstract data space of ostensibly non-spatial data types can be equipped with hyperspatial structures which can be used to assess equality. This notion of equality is the basis for abstract data type queries.

An abstract data type range query is an expression of the following concept: "Identify DOMAINS which satisfy an equality relation relative to a sample DOMAIN where the domains are referenced in a abstract data type SPACE." See Figure 14 for definition of abstract data space. DOMAINS are represented in the abstract data space using hyperdimensional coordinates. Methods for testing equality relations between abstract DOMAINS shall be defined.

### 6.7.2.5. Graph queries

A graph data space consists of edges and nodes. The UDG is a large graph where ENTITIES are nodes connected by edges. Queries on the UDG are graph queries.

A basic graph query is an expression of the following concept: “Identify DOMAINS which satisfy a graph relation relative to a sample DOMAIN, where the domains are referenced in a graph type SPACE.” See Figure 14 for definition of graph data space. Methods for testing graph relations between DOMAINS shall be defined.

Domain relation queries permit the acquisition of properties associated with a DOMAIN, including its subdomains and containing domains. Such queries leverage categorical knowledge which can be connected to a spatial conceptual embedding. A domain relations query is an expression of the following concept: “Identify DOMAINS which satisfy domain relations relative to a sample DOMAIN, where the domains are contained in the UDG” See Table 3 for description of the different types of domain relationships. Methods for testing domain relations between DOMAINS shall be defined.

### 6.7.2.6. Semantic queries

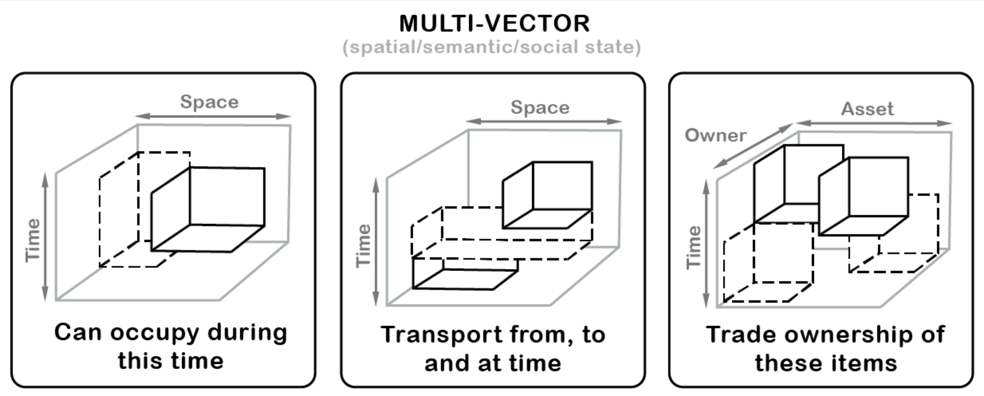
Semantic queries make use of words and concepts as represented in hyperspace.

A basic semantic query is an expression of the following concept: “Identify all concepts (DOMAINs) in the English Language (DOMAIN) similar to the English word “dog” (DOMAIN) over a 20 year period of TIME.”

An ontology graph query extends the basic semantic and graph queries by considering the types of relations between ENTITIES. An ontology graph query is an expression of the following concept: “Identify ENTITIES which satisfy a ontological graph relation relative to a sample DOMAIN, where the domains are referenced in a graph type SPACE and links are typed by concepts in the Spatial Web ontology.” See Figure 14 for definition of graph data space. Methods for testing ontological graph relations between DOMAINS shall be defined.

A geographic query includes both semantics and hyperspace (Figure 29). A geographic graph query is an expression of the following concept: “Identify DOMAINS which satisfy an ontological graph relation relative to a geographic DOMAIN, and where the domains satisfy a spatial relation in the SPACE associated with a geographic DOMAIN.” For example, a user might use a geographic query to find all the restaurants within a certain distance of a specific location, or to find all the parks within a particular city. A geographic query may also include a TIME relation to identify DOMAINS of interest.

**FIGURE 29:** Multi-Space Query



### 6.7.2.7. Vector queries

A vector query searches for elements based on a vector representation of the data which can be evaluated numerically by algorithms. This allows the data to be compared and searched in a more efficient way than if the data were represented in text.

A user can use a technique called word embedding, mapping words or phrases to a high-dimensional vector space. For example, the vectors for the words “king” and “queen” might be similar in some dimensions (because they are both related to royalty) but different in others (because they have different gender connotations).

A basic vector query is used to search for ENTITIES that are similar to a given ENTITY represented as a vector. A user might use a vector query to search for documents that are similar to another document based on the vector representations of the words in the text.

Multi-vector queries permit the sight and performance of multiple transformations on an entity, such that they can achieve the desired outcome. Those transformations can be spatial, semantic, or even social. A query of this type is: “This box (DOMAIN) can occupy (ACTIVITY) in a SPACE for an amount of TIME after which it is to be moved (ACTIVITY).

Agent-to-agent communication with higher levels of intelligence includes vectors and metrics to support hyperdimensional computing (See 6.4). Included in these messages are hyperdimensional vectors, or hypervectors, say representing a point in 10,000-dimensional space. Hyperdimensional vectors are used for concepts as well as images. These hypervectors support hyperdimensional communication and multi-agent reasoning. The HSML schema shall support encoding of hyperdimensional vectors.

## 6.7.3. Requirements and Recommendations

- HSML shall enable Bootstrapping/Context queries
- HSML shall enable Activity queries
- HSML shall enable Hyperspace range queries

- HSML shall enable Abstract data type query
- HSML shall enable Graph queries
- HSML shall enable Semantic queries
- HSML shall enable Vector queries
- HSTP shall enable queries on HSML ENTITITES

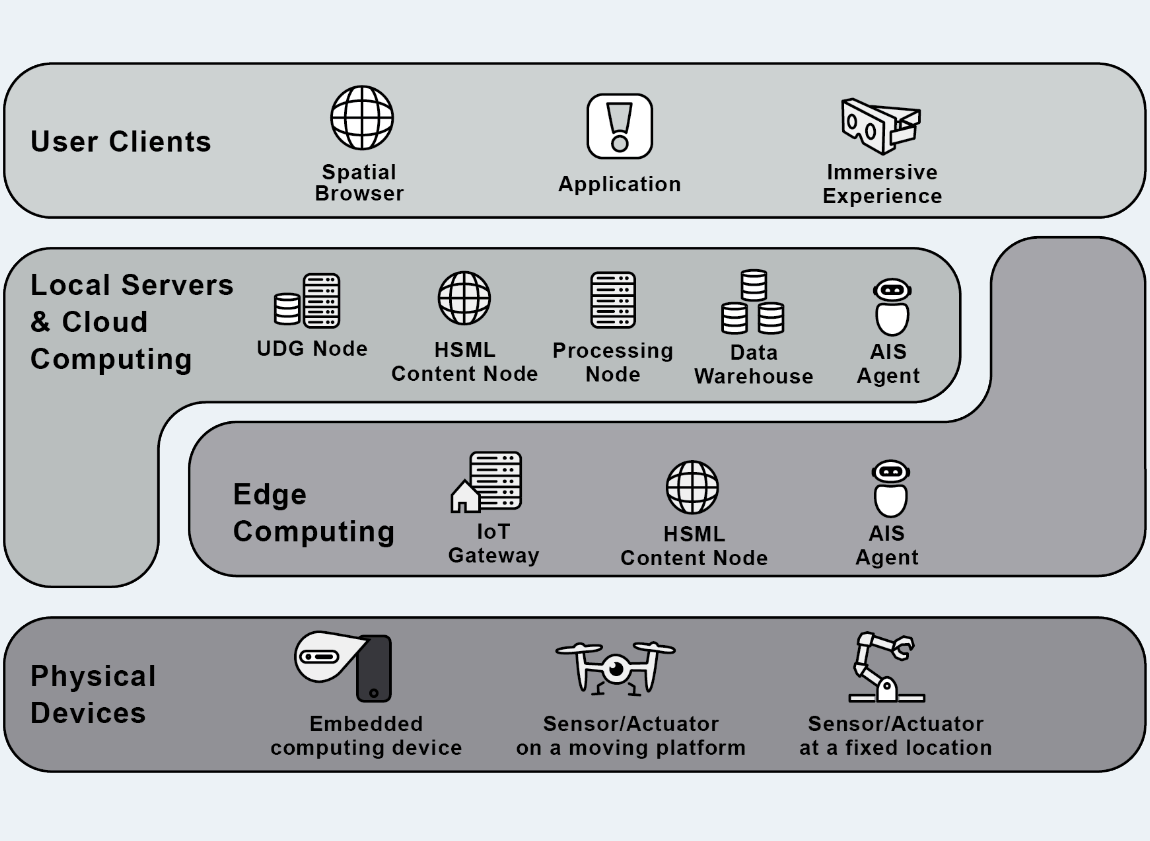
# 7. Distributed computing

## 7.1. Computing architectures

### 7.1.1. Distributed computing continuum

The Spatial Web is a distributed computing system with nodes connected by communications networks. Distributed computing is a model of computing in which a set of nodes coordinates its activities by means of digital messages passed between the nodes (Definition from ISO/IEC TR 23188:2020). The Spatial Web distributed computing model is organized as a set of tiers with each tier containing a set of nodes. Nodes within a tier are similar and may be close to each other in a network sense of close, e.g., enterprise nodes.

**FIGURE 30:** Distributed computing continuum



The Spatial Web distributed computing model contains four tiers as described in the following sections.(see Figure 30)

### 7.1.1.1. User client tier

Humans and other actors identified in the Application Scenarios (5.3) interact with the Spatial Web through one or more user clients. The Spatial Web Browser is analogous to a web browser accessing the World Wide Web. The Spatial Web Browser accesses Spatial Web entities and, based on Spatial Web HSML content, provides a visualization to the user. Similarly, immersive experience clients interact with the Spatial Web, and permit human users to interact with the Spatial Web in real-time, with immersion and user agency. Application clients are application code embedded in a computing node associated with the actor, e.g., part of a robot.

### 7.1.1.2. Servers and cloud computing tier

This is a large, disparate tier of computing nodes hosted on a wide variety of computing hosts including cloud-hosted computing. Cloud computing is a paradigm for enabling network access to a scalable and elastic pool of shareable physical or virtual resources with self-service provisioning and administration on-demand (Source: ISO/IEC 22123-1:2023). In this tier, Spatial Web services are accessed using HSTP.

Included in this tier are the servers hosting Distributed UDG System servers.

Cloud computing includes nodes that host large amounts of big data. Variations of big data storage include data warehouse, data lake, and data lakehouse. A data warehouse is a standardized term for a special kind of database system built upon existing operational databases that play a key role in building a decision support system for an organization or an enterprise. A data warehouse may be a repository of both structured and unstructured data, at any scale, without a requirement to structure the data before storage. A data lakehouse has been called an evolved version of the data lake that combines elements of the traditional data warehouse. A Spatial Web node may provide services in data warehouses, data lakes, or data lakehouses.

#### 7.1.1.3. Edge computing tier

Many physical devices utilize edge computing in which processing and storage takes place at or near the edge, where the nearness is defined by the system's requirements (Source: ISO/IEC TR 23188:2020). The edge computing nodes can be associated with a geographical cluster of edge devices, providing low latency dedicated computing for the cluster. An edge computing node may serve as an IoT gateway which connects one or more proximity networks and the IoT devices on those networks to each other and to one or more access networks (Source: ISO/IEC 20924:2024). Examples include gateways, routers, switches, multiplexers, and a variety of other access devices (W3C REC-wot-architecture11-20231205).

Digital Twins may reside on edge computing nodes. A digital twin is a virtual representation of a device or a group of devices that resides on a cloud or edge node. It can be used to represent real-world devices which may not be continuously online, or to run simulations of new applications and services, before they get deployed to the real devices. W3C REC-wot-architecture11-20231205

#### 7.1.1.4. Edge devices and platforms tier

Edge devices or IoT devices interact and communicate with the physical world through sensing or actuating to provide interaction with the physical world (Source: ISO/IEC TR 23188:2020). Edge devices may be embedded in larger physical entities acting as platforms for the devices. Edge device platforms may be fixed or moving. Moving platforms include autonomous vehicles including drones. Edge devices typically include local processing separate from the edge computing networked devices.

### 7.1.2. Distributed computing concerns

#### 7.1.2.1. Internet scale

The Spatial Web shall be inherently scalable from the simplest interoperation of two systems to the interoperability of a dynamic coalition of distributed, autonomous, and heterogeneous systems within a complex and global ecosystem containing millions of unique entities. The communication function should support the ability to accommodate an increasing number of connectivity endpoints, reaching internet scale.

#### 7.1.2.2. Interoperability and heterogeneity

The Spatial Web shall span over many existing heterogeneous systems with differing protocols, data types, and applications. The Spatial Web shall provide Interoperability which is the ability of two or more systems to exchange information and mutually use the information that has been exchanged. — ISO/IEC 22123-1:2023. It is essential to consider the following aspects of interoperability:

- **Technical:** ability to use a physical communications infrastructure to transport data.
- **Syntactic:** ability to share syntax or common information model structures for data and establish a protocol to share the information as specific typed data.
- **Semantic:** ability to establish and mediate various approaches to meaning of information.

### 7.1.2.3. Open standards

The Internet has succeeded in no small part because of its purposeful avoidance of any single controlling entity IETF RFC 9518. The Internet can accommodate a spectrum of requirements and is now positioned as a global public good because joining, deploying an application on, or using the Internet does not require permission from or ceding control to a single entity. Architectural design, particularly that provided by open standards, offers control over this sort of centralization, providing a balance of innovation and consolidation.

For example: the adoption of HTTP and HTML as open web standards transformed the Internet from a fragmented network of proprietary systems to a unified platform for sharing web content and services. These standards facilitated compatibility across different hardware and software, enabling the creation and seamless operation of web pages. This shift led to an expanded web with enhanced capabilities, where developers could innovate on a common technological foundation without monopolistic control. Open standards like HTTP, HTML, and Spatial Web architecture thus promote both uniformity for interoperability and diversity for competition and innovation, essential for the industry's growth.

### 7.1.2.4. Deployment across computing continuum

As shown in Figure 30, the Spatial Web distributed computing environment spans across a computing continuum. This continuum features a wide variety of computing nodes and communication protocols. Deployments of the Spatial Web shall take advantage of the features in the different layers of the continuum.

The W3C Web of Things Architecture identifies consideration for the computing continuum that applies to the Spatial Web. The Spatial Web should support computing using HSTP and HSML across the computing continuum including a wide variety of capabilities such as edge devices with resource restrictions and virtual things on the cloud. The Spatial Web should support multiple levels of network/tier hierarchy with intermediate entities such as gateways and proxies. The Spatial Web should support accessing Spatial Web nodes in the local network from the outside of the local network (the internet or another local network), considering network address translation.

Edge computing supports leveraging computing resources at nodes located at the edge of the network. Edge network services are used to utilize abundant computing resources at the network edge along with higher bandwidth and lower latency. For example, autonomous vehicles exploit integrated computing by offloading complex computational tasks to the edge nodes and minimizing latency between close physical proximity vehicles, e.g., for collision avoidance. Integrated sensing, localization, and communication at the edge provides improved situational awareness using rapid and reliable communication as well as also high-resolution sensing and high-accuracy localization (or positioning/mapping).

### 7.1.2.5. Mobility, discoverability, and automatic configuration

Entities in the Spatial Web may be mobile and transiently connected to networks. The Spatial Web system supports discoverability and automatic configuration of Spatial Web nodes. Some Spatial Web nodes work over mobile systems both because they move with humans, as is the case with smartphones and wearable devices, or because they move by themselves, similar to robots. Based on their locations, these devices are likely to change SWID, IP address, and networks without explicit interactions requiring proprietary signaling or protocols.

The Spatial Web shall provide mechanisms for automatic discovery of nodes, and their properties and capabilities as well as the means to access them. The discoverability of IoT devices can contradict some aspects of security. Four categories of node discovery technologies relevant to edge devices are the following:

- Discovery of nodes that are in close spatial proximity (<10 cm with near-field communication, <100 m with BLE).
- Discovery of endpoints of nodes on the network (for example, multicast domain name service, Multicast Constrained Application Protocol, Simple Service Discovery Protocol, and Web Services Discovery).
- Directories for the discovery of IoT devices and their resources [for instance, the constrained RESTful (CoRE) Resource Directory, Extensible Messaging and Presence Protocol IoT Discovery, HyperCat, Sensor Instance Registry, and Simple Protocol and RDF Query Language Endpoint].
- Accessing IoT device metadata once they are discovered (for example, CoRE Link Format, OGC SensorThings, and Optical Markers).

Once a node is discovered, some scenarios require automatic configuration. Automatic configuration allows Spatial Web nodes to react to the addition and removal of nodes such as devices and networks. Automatic configuration needs security and authentication mechanisms to help ensure that only authorized components can be automatically configured into the system. Security mechanisms may be defined appropriately for different domains. Examples of automatically configured devices and protocols include Dynamic Host Configuration Protocol (DHCP), Zero Configuration Networking (Zeroconf), Bonjour, UPnP, etc.

### 7.1.2.6. Real-time capability

Several of the application scenarios (5.3) require a real-time capability. Real-time capability is when computation is performed during the actual time that an external process occurs, in order that the computation results can be used to control, monitor, or respond in a timely manner to the external process ISO/IEC/IEEE 24765:2017. Real-time capability depends upon many factors, not all of which are defined in the design of the Spatial Web, e.g., communication network performance, node computing performance, physics of edge actuators, and sensors.

The Spatial Web is designed to operate with communication network performance where bandwidth ranging from hundreds of gigabits per second to several terabits per second (i.e., having latency in the sub-millisecond range).

Edge computing capabilities provide additional support for real-time capabilities by keeping the computing devices and edge devices in close physical network distance.

### 7.1.2.7. High latency / low connectivity network and device support

While the Spatial Web, and HSTP in particular, enables real-time capabilities, it also supports high latency / low connectivity networks. This support is implicit in the definitions of discovery and automatic configuration, but important to recognize in contrast to the real-time capabilities.

### 7.1.2.8. Location Awareness for Spatial Web nodes

For some Sensor Web nodes application-level awareness of the nodes physical location may be necessary. The Sensor Web should enable application domains to enable location awareness. The [124] provides a range of options, including the following:

- Applications cannot tell where they are running, unless they can infer from timestamps on data (e.g., that after reading a sensor, the data is several seconds old on arrival).
- Applications can tell what clique they are in, and type of device, e.g., control tier, embedded in turbine; enterprise tier, virtual on set of servers owned by client.
- Applications can be tied to specific types of devices, have access to maps and can infer physical location properties of devices.
- Applications know exactly in the 4-dimension space (time-space) where they are executing, what hardware they are near and what paths are available by specific route to any local device.

Additional consideration should be given for a Spatial Web client to ascertain the physical location of the distributed computing equipment that is hosting the Spatial Web node that the client is accessing.

For scalability to global internet, the Spatial Web shall provide a globally unique index using DGGS (6.2.2.7)

### 7.1.2.9. Safety

Spatial Web implementations need to consider reducing the risk of harm or damage to an acceptable level. When the Spatial Web is anticipated to operate in safety critical operations, additional analysis beyond that taken for the design of this Reference Model should be taken to help ensure the risk is appropriate for the application. Industrial operations deal with the physical world and industrial analytics need to be validated with domain-specific expertise to model the complex and causal relationships in the data. The combination of first principles, e.g., physical modeling, along with other data-science statistical and machine-learning capabilities, is required in many industrial use cases to provide accurate analytics results.

### 7.1.2.10. Resilience

Resilience is the ability of a system to adapt and continue to perform their functions in the presence of faults and failures ISO/IEC 30141:2018. The Spatial Web should be designed to be resilient to faults. The network of Spatial Web nodes should have only transient loss of function when a single node becomes non-operational. Because many Spatial Web systems operate continually in a real-world environment, the communication function should be resilient, even when there is a temporary physical disconnection. When a broken connection is restored, data exchange should be automatically restored so that the latest updates are available to the consumers along with any relevant missed updates.

### 7.1.2.11. Security

#### 7.1.2.11.1. HSTP payload encryption

HSTP over the transport layer shall provide context required to route requests between parties. HSTP message contents shall be encrypted and access to decryption keys granted upon validation of HSTP credentials; i.e., HSTP credentials are verifiable (as described in W3C vc-data-model).

#### 7.1.2.11.2. Zero-trust security

The Spatial Web relies upon zero-trust security concepts. Zero Trust is a security model requiring all users to be authenticated, authorized, and continuously validated for security configuration before being granted access to applications and data. Zero-trust architectures assumes that there is no traditional network edge; networks can be local, in the cloud, or a combination or hybrid with resources anywhere as well as workers in any location.

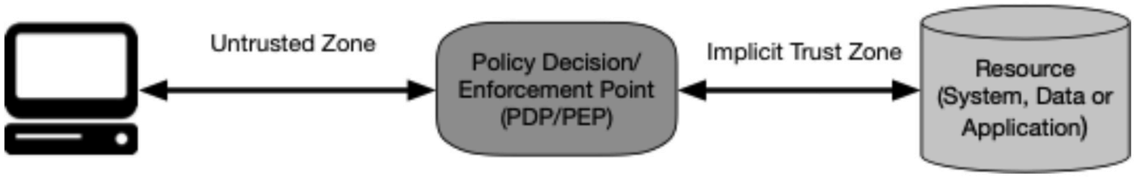
As defined in [71], the purpose of Zero Trust is to prevent unauthorized access to data and services coupled with making the access control enforcement as granular as possible. In the abstract model of access shown in Figure 31, a subject needs access to an enterprise resource.

Identities — whether they represent people, workloads, endpoints, or IoT devices — are the foundation of a zero-trust approach.

Access is granted through a policy decision point (PDP) and corresponding policy enforcement point (PEP).

A trust algorithm (TA) is the process used by the policy engine to ultimately grant or deny access to a resource.

**FIGURE 31:** Zero-trust architecture



## 7.1.3. Requirements and recommendations—distributed computing

### 7.1.3.1. HSTP requirements

- HSTP shall allow Spatial Web domain architectures to enable location awareness.
- HSTP shall allow Spatial Web domain architectures to enable clients to ascertain the physical location of the distributed computing equipment that is hosting the Spatial Web node that the client is accessing.
- HSTP shall be designed to be resilient to faults: The network of Spatial Web nodes should have only transient loss of function when a single node becomes non-operational.
- HSTP shall be designed to operate with varied communication network performance. This includes support for both high latency / low connectivity support and scenarios where bandwidth ranges from hundreds of gigabits per second to several terabits per second (i.e., having latency in the sub-millisecond range).
- HSTP shall enable independent implementations that are interoperable.
- HSTP shall implement a zero-trust security model.
- HSTP shall provide interoperability of digital messages between nodes.
- HSTP shall provide protocols for automatic configuration that allow Spatial Web nodes to react on the addition and removal of nodes such as devices and networks.
- HSTP shall support accessing Spatial Web nodes in the local network from the outside of the local network (the internet or another local network), considering network address translation.
- HSTP shall work in centralized or distributed computing environments.

### 7.1.3.2. Distributed UDG system requirements

- UDG shall be designed to operate with communication network performance where bandwidth ranging from hundreds of gigabits per second to several terabits per second (i.e., having latency in the sub-millisecond range).
- UDG shall provide mechanisms for automatic discovery of nodes, and their properties and capabilities as well as the means to access them.

- UDG shall support the ability to accommodate an increasing number of connectivity endpoints, reaching internet scale.

#### 7.1.3.3. Domain-specific architectures requirements

- Domain-specific architectures operating in safety critical operations shall undertake safety design evaluations to help ensure the risk is appropriate for the application.
- Domain-specific architectures shall address the risk of centralization.
- Domain-specific architectures shall be defined using the tiers identified in Figure 30.
- Domain-specific architectures shall encrypt HSTP payloads, controlling access to decryption keys via CREDENTIALs.
- Domain-specific architectures shall use HSTP over the transport layer to provide minimal context required to route requests.

## 7.2. Spatial Web nodes

### 7.2.1. Canonical nodes

Distributed computing is accomplished by a set of hosted computing nodes with messages passing between the nodes. This clause defines canonical nodes for the Spatial Web distributed computing architecture Figure 30.

Client nodes: Spatial Web client nodes provide an interface for human users. The clients access other nodes using HSTP and HSML. Client nodes may interact with other client nodes and with nodes in other layers.

- Spatial Web browser: Spatial Web client functionality is provided using a web browser, hosted in client platform, e.g., phone or laptop.
- Spatial Web application client: Spatial Web client functionality is provided as an application hosted in client platform, e.g., phone, laptop.
- Immersive experience: With an immersive human interface, e.g., virtual or augmented reality, Spatial Web client functionality is provided as an application hosted in client platform, e.g., headset.

Cloud and local server nodes. Nodes may be hosted using Cloud computing 7.1.1.2 or on local servers. Nodes interact with other nodes using HSML and HSTP. A node may act as both client and server in HSTP interactions.

- UDG node: Each node hosts a portion of the UDG and interacts with other UDG nodes. UDG nodes serve as a set of distributed registries for Spatial Web Entities. UDG nodes accept requests from other Spatial Web nodes to discover Spatial Web Entities. The UDG may return a single SWID or may respond with an HSML message including multiple ENTITY SWIDs and links between the ENTITIES. UDG node responses include network addresses for HSML content nodes.

- HSML content node: Nodes host the content of the Spatial Web entities. HSML content nodes are the analog of servers and content caches on the Web. These nodes accept and post HSTP packets in order to store a collection of HSML, with a focus on storage space and CRUD operations.
- Processing nodes: Processing nodes are similar to a serverless function on the Web. Nodes accept HSTP packets and perform some operation or operations on HSML content.
- Data warehouse: Repository of large amounts of data that are accessible by content nodes and processing nodes using HSML and HSTP. Examples include:
  - Large knowledge bases and underlying object stores
  - Digital Twins
  - Geographic and Digital Earth nodes which may include up to 50PB of earth data
- AI Agent: Node that hosts Artificial Intelligence computing and may include autonomous elements Figure 19. AI Agent nodes have the capacity to exhibit or simulate intelligent behavior. AIS Agent Nodes may perform Active Inference computing.

Edge nodes. Edge computing 7.1.1.3 nodes are hosted near to the edge of the network. Physical proximity may be relevant as it impacts latency and power availability.

- IoT gateway. Node that bridges between networks of differing technology, allowing Spatial Web exchanges to cross over network boundaries.
- HSML content node. HSML content node as defined for Cloud and local server nodes but optimized for computing on edge hosts.
- AI agent. AI agent node as defined for Cloud and local server nodes but optimized for computing on edge hosts.

Physical devices

- Embedded node: Spatial Web node that is part of a physical device (e.g., a smart phone).
- Node hosted on a moving platform with sensors and actuator; including remote sensors and in-situ sensors. Includes robots or other devices which directly interact with physical entities.
- Node hosted on a stationary platform with sensors and actuators; including remote sensors and in-situ sensors.

### 7.2.1.1. Warehouse robot scenario example

Referring back to the warehouse robot application scenario (5.3.2), this clause demonstrates an example of exchanges between Spatial Web nodes. Specifically, the scenario events are decomposed into multiple diagrams to facilitate focused discussion.

In Figure 32 a human and a robot are granted CREDENTIALs allowing them to perform a pick/pack ACTIVITY in warehouse DOMAIN. Note that the Operations Manager would go through a similar process to get a CREDENTIAL allowing them to perform an ACTIVITY of requesting pick/pack ACTIVITY be performed in warehouse DOMAIN.

**FIGURE 32:** Warehouse robot scenario example part 1: initial CREDENTIALs

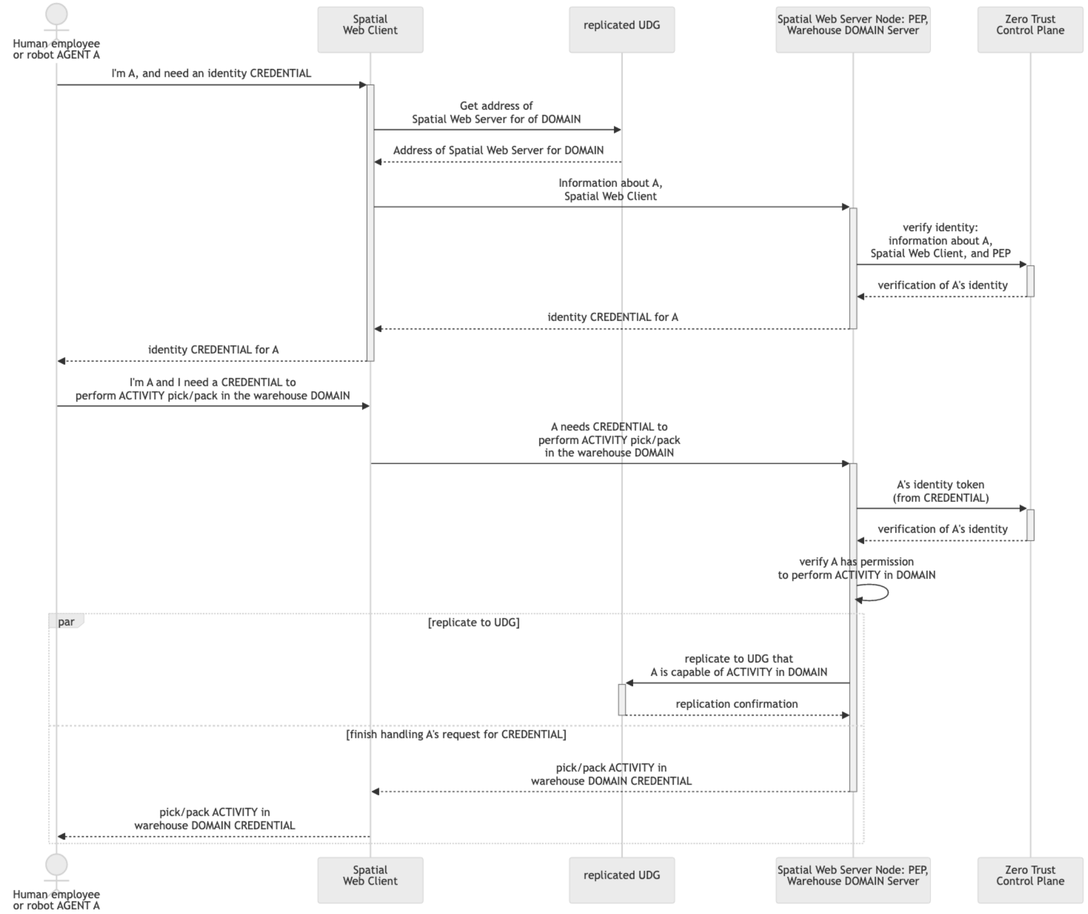


Figure 33 shows an example of nodes in the Spatial Web negotiating a contract (after getting their identity and ACTIVITY CREDENTIALs).

**FIGURE 33:** Warehouse robot scenario example part 2: CONTRACT negotiation

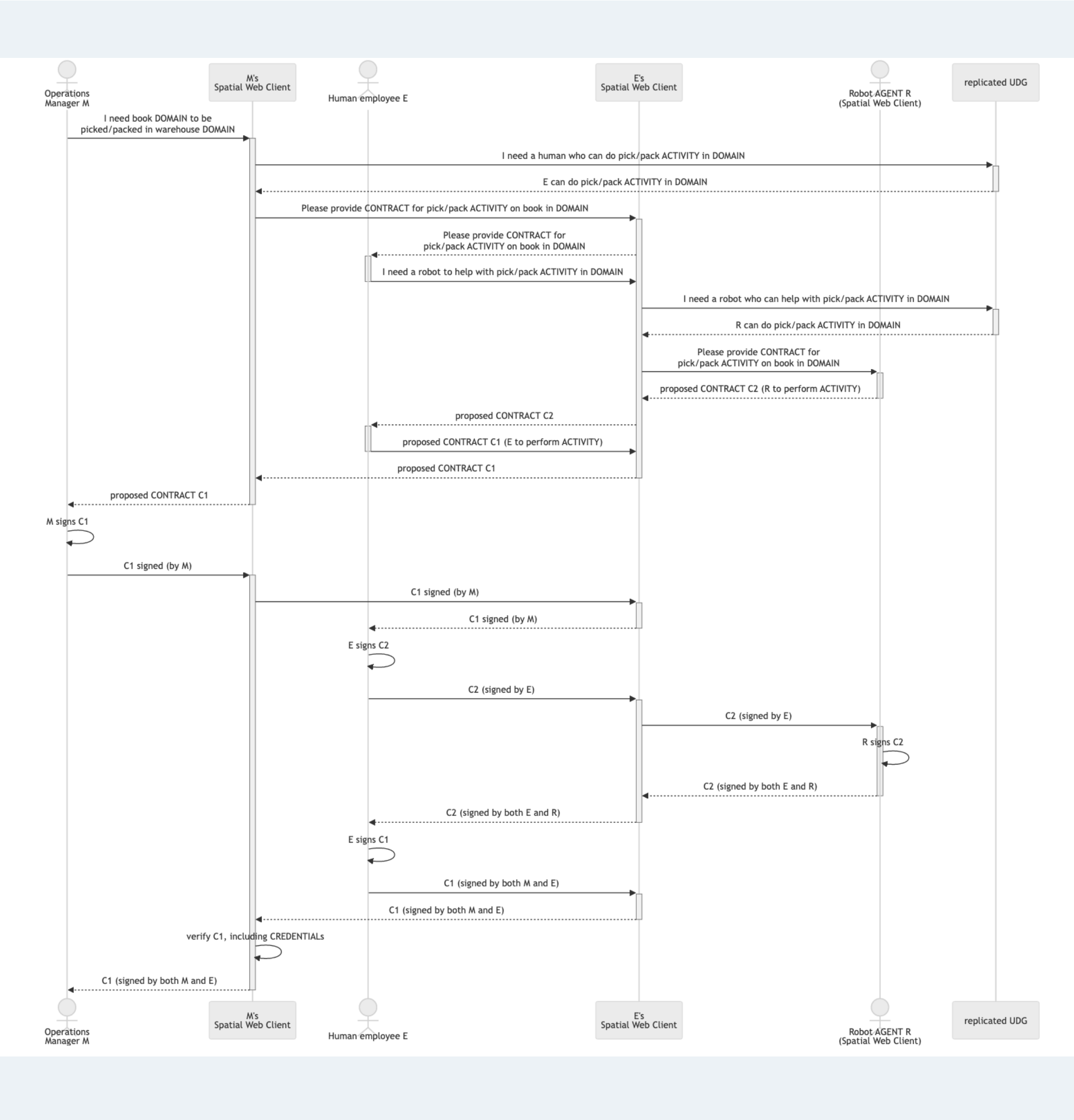
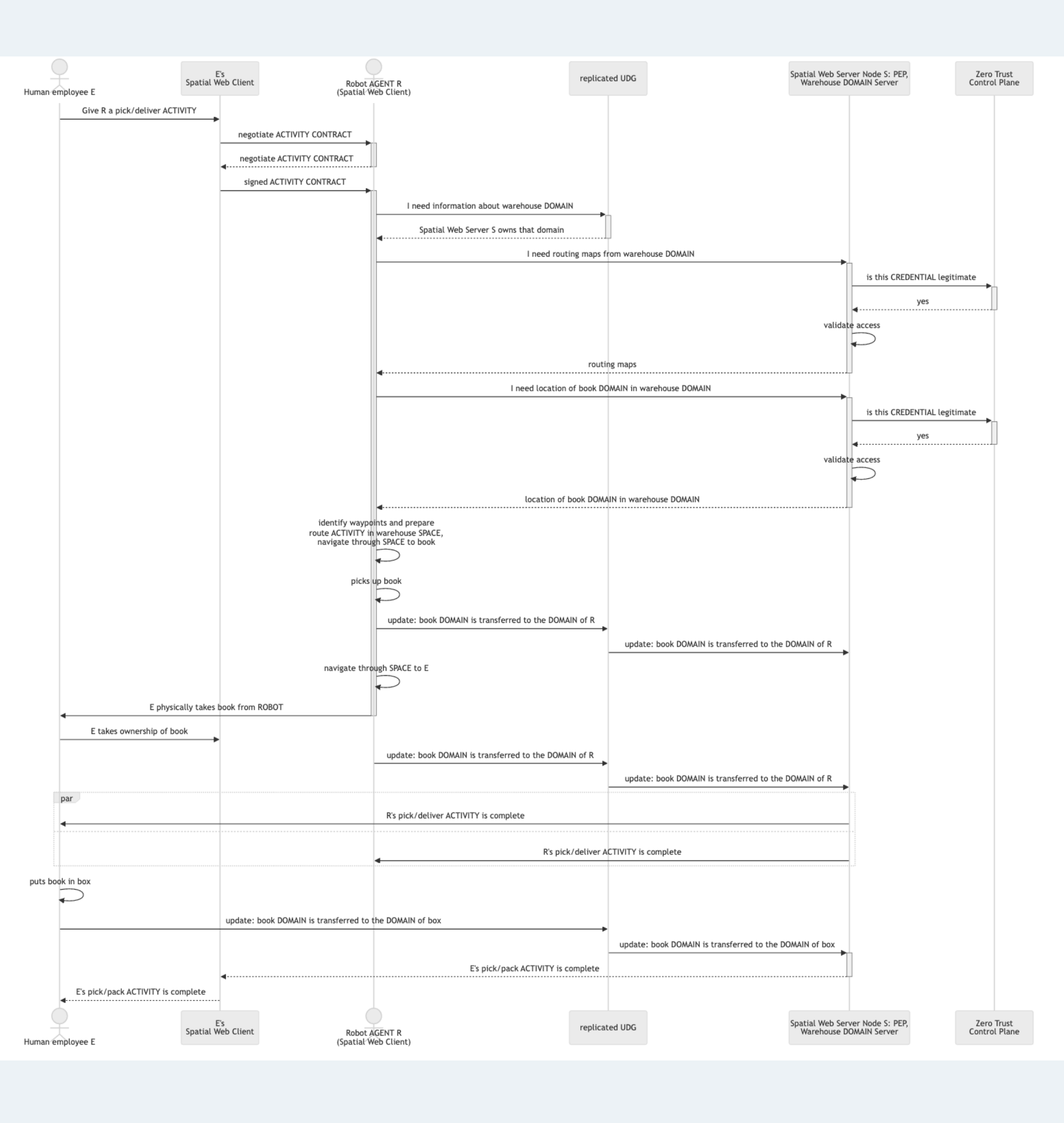


Figure 34 shows the robot and the employee working together to complete the pick/pack ACTIVITY that the employee accepted.

**FIGURE 34:** Warehouse robot scenario example part 3: CONTRACT completion



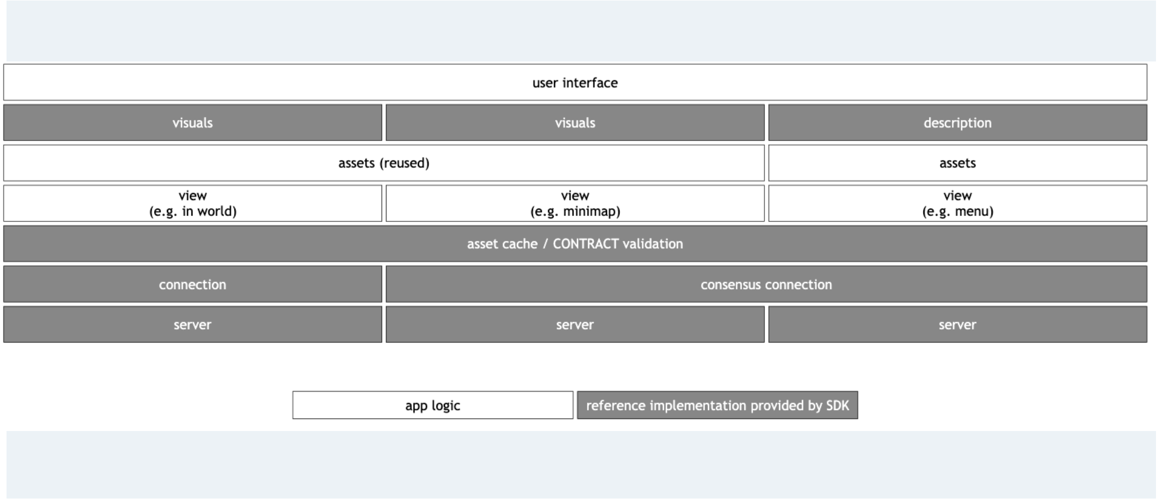
## 7.2.1.2. Spatial Web client

To support interoperability, some Spatial Web clients may reuse a common architecture and, in some cases, may reuse common code. An architecture is provided in HSTP Client Integration Figure 35. The architecture is based on several elements of HSTP:

- HSTP enables a decentralized consensus network for registering and transacting spatial information concerning any physical, digital or hybrid (i.e., “digital twin”) entity, comprising a cluster of graph-like databases expressible in-memory or in distributed ledgers.
- HSTP implies the existence of an interpreter, and some concept of state/object-management. This approach appears in both client applications, spatial servers, and individual IoT endpoints.

- A key feature of HSTP is the ability to both collaborate and exchange on a purely peer-to-peer basis. For this reason, ledgers include the ability for any node to itself be an instance able to answer basic HSTP requests, including simple rendering tasks, allowing local multi-user scenarios to be efficiently created and managed, with clear mechanisms by which to integrate or authorize transactions.

**FIGURE 35:** HSTP Client Integration



As shown in HSTP client integration Figure 35, the entity-cache and CONTRACT-validation engine allow cross-ledger interaction between multiple servers which are also expressed as visual entities. These entities appear in and can be queried from views, which contain entities (often reused across views), that manifest as user interface visuals, with which the application and user directly interact. At a lower level, these views are pulled from connections, which are sometimes consensus-based and backed by multiple servers.

CONTRACTs are a core concept in the context of Spatial Web node communication via HSTP. Refer to 6.5 and 6.6.5 as the source of requirements regarding CONTRACTs.

In general, the application interacts with objects, which are contained within views, with views being full world experiences, mini-maps, or list-based. Linking across all of those is a shared object cache, stored in the local ledger (e.g., in client browser memory) which is where CONTRACT validation occurs (allowing cross-ledger contracting), and which also generally abstracts the mechanisms that form consensus across multiple actual server connections. Although many connections are single-authority, multi-party-authority allows either more trusted or faster content networks.

Local ledgers are primarily used for either view or change requests, the cache of objects across those, and the inherent connection between them.

A full local ledger implementation contains the following major subcomponents:

- View Management
  - Requester Identification, Object Retrieval, Content Visualization, View Localization and Transaction Helper APIs
- Known Object Cache

    - Indexed by ID, Authority and Referencing Views.
    - Object Version and View Subscription Tracking
    - Local/Temp Object Tag Management
- CONTRACT Validation Kernel
    - Collects Referenced Objects
    - CONTRACT Expression Evaluation
    - Can Apply Transactions Once Validated
- Connections
    - External Services/Endpoints
    - Identity Validation (via Object Cache Public-Keys)
    - Data Adaptation when required
    - Consensus Mechanics
- Encryption Tools
    - Hashing and Signing with Private Keys
    - Verification of Public Key Signatures/Hashes
    - Nonce/Key-Pair Generation
    - Offer/Claim/Schema/CREDENTIAL/Proof Processing

## 7.2.2. Requirements

### 7.2.2.1. Spatial Web ecosystem requirements

HSTP shall support the implementation of a Spatial Web ecosystem, including support for: Spatial Web client nodes, Spatial Web Servers, Spatial Indices, Spatial Web adapters, Distributed consensus and distributed ledger infrastructure, Spatial rendering servers, and Peer-to-peer servers

### 7.2.2.2. Spatial Web node requirements

- Domain-specific Spatial Web nodes shall conform to all HSTP and HSML requirements.
- Domain-specific Communications between Spatial Web Nodes shall use HSTP.
- Domain-specific Spatial Web nodes shall interact with the Distributed UDG System.

### 7.2.2.3. Requirements for Spatial Web servers

- Domain-specific Spatial Web clients shall provide spatial transaction ledger functionality.
- Domain-specific Spatial Web servers shall respond to queries with Entities based on identifiers while locating and prioritizing Entities that fit within a specific spatial query, that prioritization is based upon the frustum of the volumetric range query as expressed in an HSTP statement.

- UDG shall include Spatial Index Servers that make maps ranging from simple SQL indexes to graph-based databases to widely adopted and standard spatial indexing services which deliver spatial indexing.

#### 7.2.2.3.1. Requirements for distributed UDG consensus and distributed ledger technology (DLT) nodes

- UDG shall manage entity replication and update with consideration of how quickly the entities are changing.
- UDG shall manage rapidly changing entities using a peer-to-peer methodology between Spatial Servers, managed by cloud instance(s), but bound by spatial CONTRACTs stored in a DLT Spatial Domain.
- UDG shall manage slow-changing cross-ledger entities and CONTRACTs on a distributed ledger.
- UDG System may incur latency when achieving consensus.

#### 7.2.2.3.2. Requirements for spatial rendering and mapping nodes

- Domain-specific nodes may include Spatial rendering and mapping nodes that render spatial results into simplified views on the server.
- Domain-specific nodes may include Spatial rendering and mapping nodes that use mapping and volumetric media formats which provide a mixture of vector and rasterization mechanisms expanded to 3-dimensional, perspective-correct content types to support streaming media comparable to current video streaming formats.
- HSML shall define a canonical approach suitable to cross domain, e.g., point, quaternion, hyperspace [with the latter consisting of a point (origin) and orientation (quaternion)].

## 7.3. HSTP conceptual model

HSTP is a generic and generalizable protocol designed to enable the standardized communication between systems that is required to build a coherent, decentralized, secure, and privacy-respecting Spatial Web.

The prior description here for HSTP crosses into areas that are not defined in the protocol but represent desired functionality from HSTP/HSML compliant systems or from transport protocols such as TCP. That HSTP enables such things is clear, but there is no mechanism for doing them within HSTP. Similarly to HTTP, A web document can be requested using HTTP, but HTTP does not create the web document or interpret it once it's received. It's a protocol rather than an execution layer.

### 7.3.1. Concepts

Interoperability: The ability of two or more systems or applications to exchange information and to mutually use the information that has been exchanged.

Consistent implementation of HSTP conceptual model across several protocol bindings (7.3.4) for both peer-to-peer and request-response patterns. Protocol binding approach defined is consistent with W3C wot-architecture.

Peer-to-Peer Communication: The ability for two systems to communicate directly with one another without the use of an intermediary system, typically associated with end user systems and software.

Request — Response Communication: The standardization of expected headers and content for messages which request changes and those which respond to those requests.

SWID: A unique identifier per domain which identifies the 'node' the domain represents in the broader Spatial Web UDG.

HSTP Objects are payloads in HSTP messages. Consider messaging across the Spatial Web 7.1.1 including issues of bandwidth, latency.

"Resolve" HSML Activities: This is an HSML Activity responsible for responding to a separate dependent HSML Activity such that the dependent HSML Activity knows how to and/or whether it may proceed.

Distributed UDG System: A distributed meta-graph which contains all relationships between all known SWIDs in the Spatial Web.

Activity Signature: A hash of the Activity definition which acts as a signature for its more complex internal structure.

## 7.3.2. Purpose

HSTP is an application-level protocol for distributed and interoperable computer systems and end-point devices. HSTP/0.9 is a simple protocol for raw data transfer across the Internet in a meta-layer referenced as "The Spatial Web." HSTP enables HSML-compliant systems to communicate to one another in a request-response manner to execute functionality and share data.

## 7.3.3. HSTP in Operation

HSTP is an application-layer protocol and a request/response protocol. A single request may generate multiple responses. A single specific response may require multiple collaborating requests. An HSTP compatible-system sends an HSTP message to another HSTP compatible system in the form of an HSTP OPERATION, passed over some transport protocol.

### 7.3.3.1. HSTP OPERATIONs

HSTP OPERATION requests and responses are encoded using profile encoding formats defined by the HSML Implementation Specification, e.g., JSON, OData, JSON-LD, GraphQL. The system that sends an HSTP OPERATION request is the "requester", and the system that is meant to receive the message is the "target".

### 7.3.3.2. HSTP OPERATION request

**HSTP OPERATION requests** are comprised of the following fields:

**NAME**: the operation name; no functional purpose; syntactic metadata

**TARGET**: the target domain (SWID); This is either a spatial Domain with modifiers, a SWID with modifiers, a specific URI endpoint with modifiers, a protocol version or a SWID identifying the requester domain and system

**REQUESTER**: requester's domain; SWID of the requester

**ADDRESSES**: catalog of requester's publicly listable addresses (as determined by the requester)

**NEIGHBORS**: requester's publicly-listed neighboring SWIDs to at minimum a distance of 1 on the UDG.

**HSML**: the HSML field of an HSTP operation may include any or all of the HSML entities

### 7.3.3.3. HSTP OPERATION response

The receiving HSTP-compatible system (target) responds using the identifier provided by the request, be it spatial domain, SWID, or other URI.

**HSTP OPERATION request responses** are comprised of:

**STATUS**: A response status code which indicates success or failure.

**ADDRESSES**: catalog of target's publicly listable addresses (as determined by the requester).

**NEIGHBORS**: target's publicly-listed neighboring SWIDs to at minimum a distance of 1 on the UDG.

**RESOLVERS** (optional): A mapping from the (empty) parameters defined in the requested HSML ACTIVITY to values that the target proposes in response; e.g., The SWID and Signatures of the Resolving Activities.

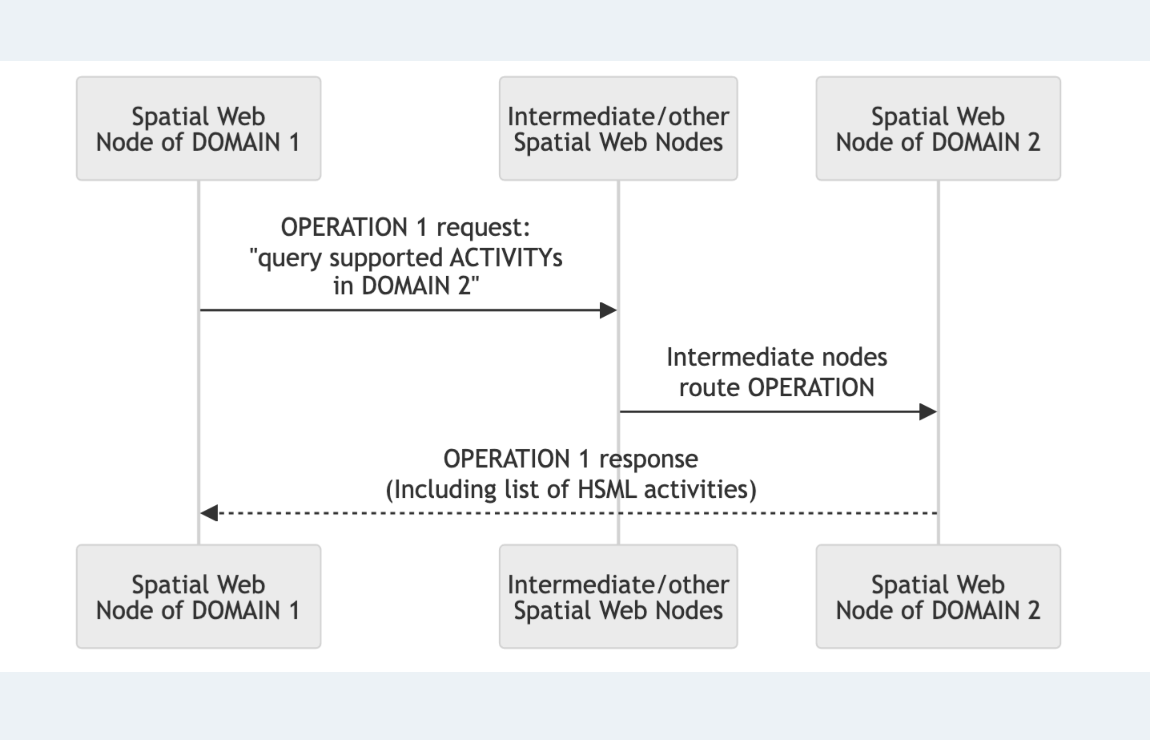
**PAYLOAD** (optional): If applicable, the response content alongside the content's MIME type.

Note that, after handling an HSTP OPERATION request, the target system may follow up by sending a new HSTP OPERATION to the initial requester, e.g., proposing a more specific operation. This allows individual domains to manage their application level protocols in whatever way best suits their domain.

Such interactions can be chained between two or more systems to create complex behaviors across HSTP-compliant systems and devices without limitation to the number of connections in the chain. Proxies, Gateways, and Tunnels are indistinguishable from more fully functional HSTP systems. Rather than working differently, they simply have a more limited set of resolving Activities which results in the routing or forwarding of messages as needed.

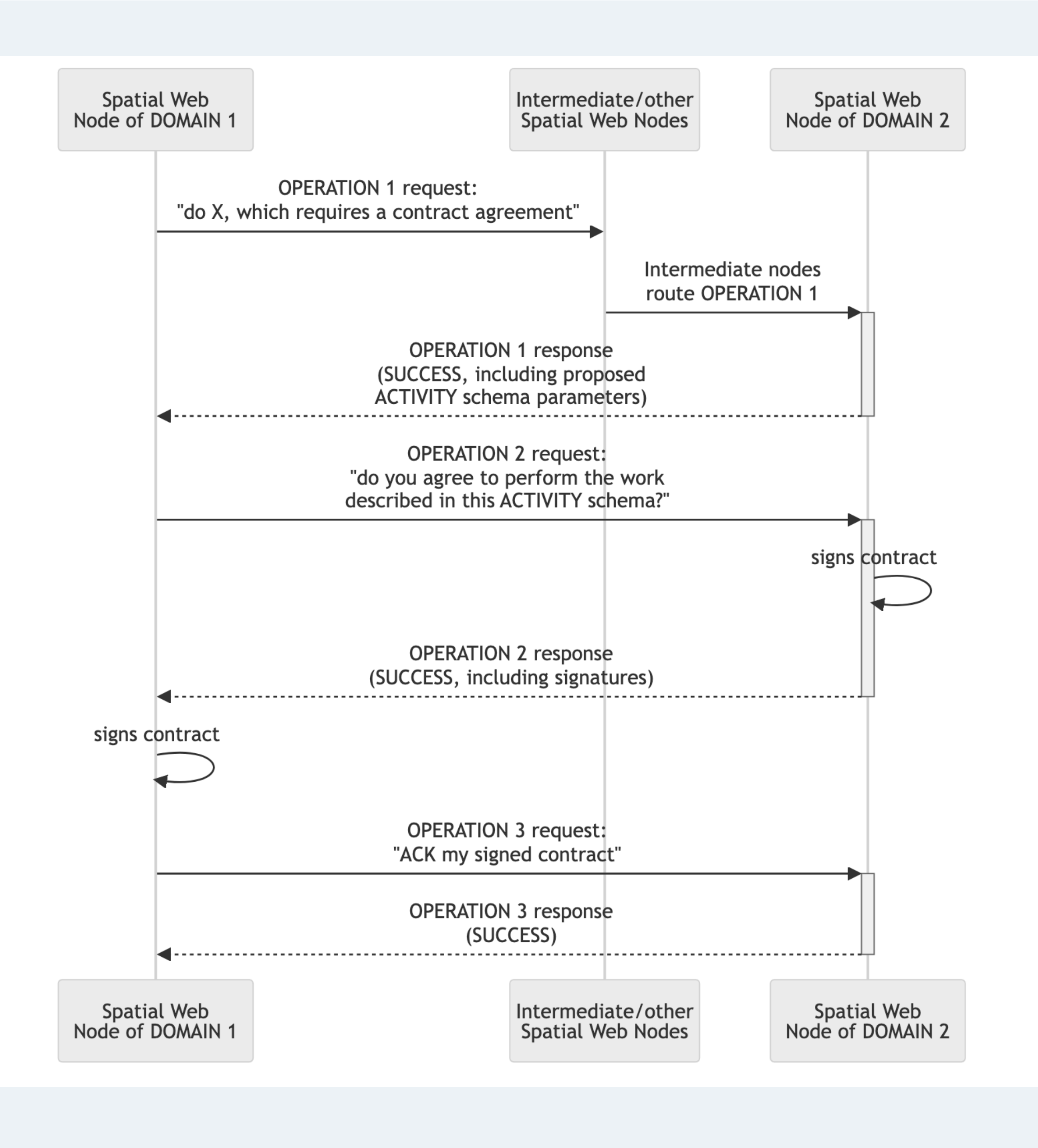
### 7.3.3.4. Simple examples HSTP OPERATION request / response flows

**FIGURE 36:** HSTP OPERATION example: simple lookup



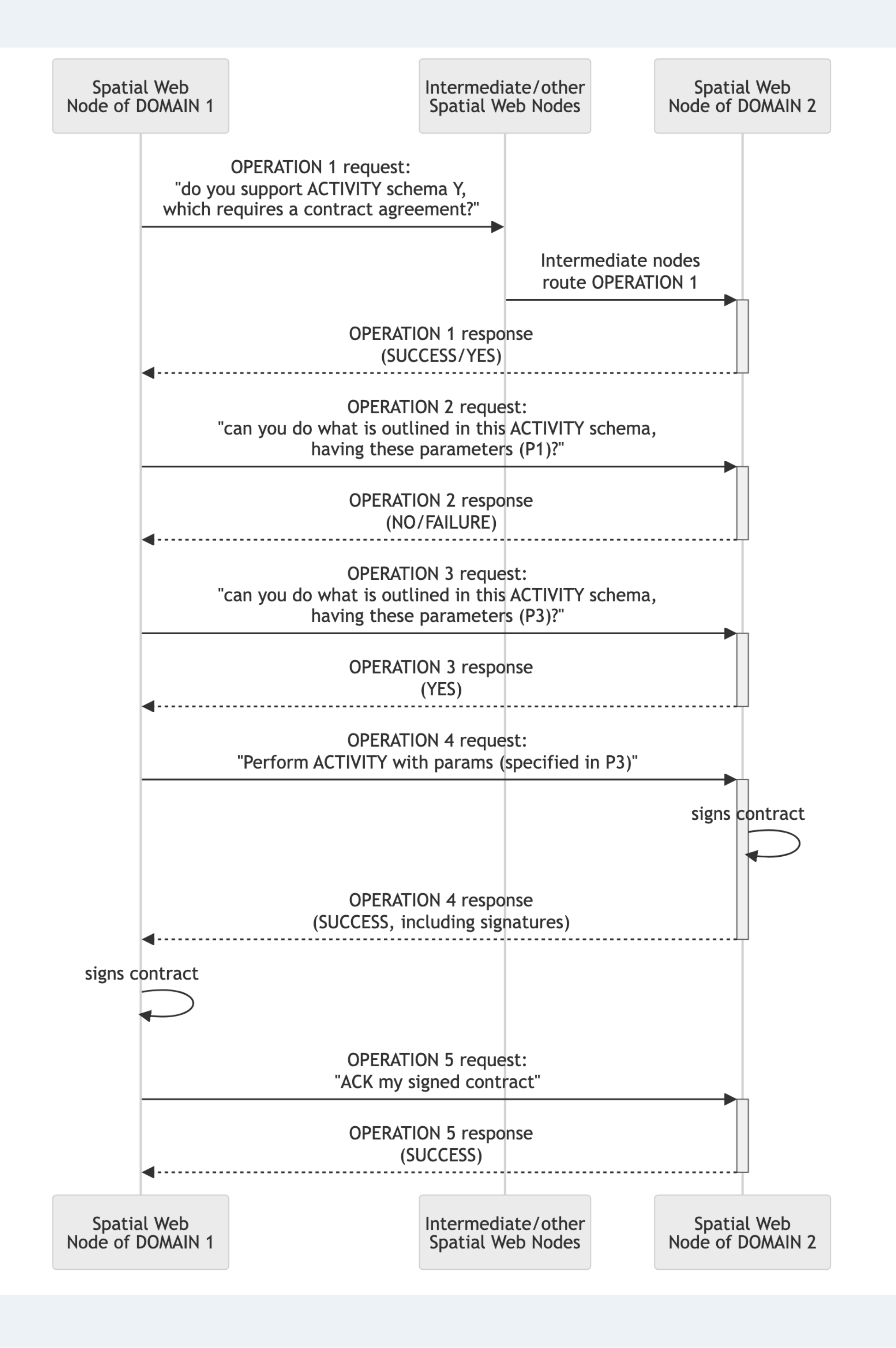
In Figure 36, we see a very simple exchange where one domain queries another regarding its capabilities.

**FIGURE 37:** HSTP OPERATION example: simple contract



In Figure 37, we see a slightly more complicated scenario where a simple ACTIVITY/CONTRACT is resolved with little chatter.

**FIGURE 38:** HSTP OPERATION example: contract negotiation



]

In Figure 38, we see a more complicated scenario where the two parties negotiate back and forth before arriving upon an agreement.

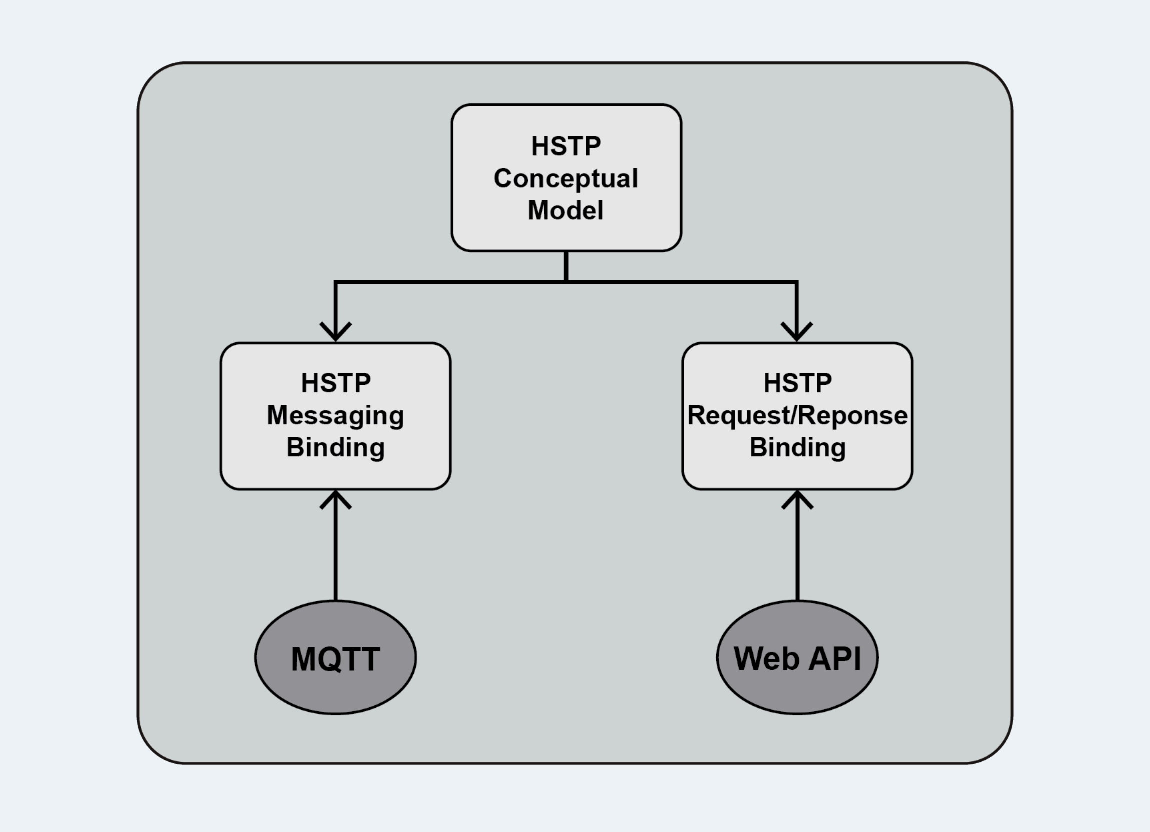
### 7.3.4. HSTP and protocol bindings

HSTP is designed to be consistent with multiple protocol bindings, including the following (see also Figure 39):

- MQTT (Message Queuing Telemetry Transport)
- Web APIs using HTTP (Hypertext Transfer Protocol) (see IETF RFC 9113)
- GraphQL (Graph Query Language)
- RPC (Remote Procedure Call)
- QUIC (Quick UDP Internet Connections)

These protocol bindings are used to facilitate communication and data transfer between systems in various contexts. HSTP provides a common semantic layer for each of these protocol bindings, enabling HSTP-compliant systems to communicate with one another regardless of the specific protocol binding being used. This allows HSTP to provide a consistent and standardized way of exchanging information and executing functionality across different types of systems and applications.

**FIGURE 39:** HSTP bindings



### 7.3.5. Requirements

- HSTP shall use HSTP OPERATIONS to route and encapsulate HSML Activity Schemas as the structure of the protocol commands which can be sent to HSTP-compliant systems.
- HSTP shall use the specified MIME-type-like identifier of the types of data contained, alongside the data, whether it be text, media, binary, and/or encrypted information.
- HSTP shall use the specified method of providing declarations that alert communicating systems as to the capabilities of each system via providing a catalog of the HSML Activities they can resolve and perform.
- HSTP messages shall include the system's self-understood position in the Spatial Web's Distributed UDG System by providing its SWID and the SWIDs of its publicly listed known neighbors to a graph distance specified by the HSTP request or response, by at a minimum distance of 1.
- HSTP messages shall include information needed by Distributed UDG System, either spatial domains or SWIDs, to locate the networked addresses, be it TCP/IP addresses or other.
- HSTP messages shall include information that designates the types of desired and allowed connections from both the requester and responder, enabling HSTP-compliant systems to negotiate their preferred or required transport method on a per HSML activity basis.
- HSTP messages shall include the last known geospatial or other spatial locations where such information is available, as well as the system's status and readiness for communication.
- HSTP shall achieve "Unconditional Compliance" with HSML 1.0 by using HSML CREDENTIALs, Domains, Spaces, Activities, and Channels to be specified in HSML implementation specification when executing or resolving an HSML Activity within an HSTP message.
- Domain-specific architectures shall promote interoperability between diverse ecosystems using Internet standards as defined in IETF's "Internet_Standards" (See Internet Standards).
- Domain-specific architectures shall allow the use of multiple payload formats which are commonly used on the Internet.
- Domain-specific architectures shall not constrain implementation internal to Spatial Web.
- HSTP shall define profiles of HSTP for HTTP, MQTT, and GraphQL 7.3.4.

## 7.4. Distributed computing use cases

### 7.4.1. Introduction

Use cases in this clause show exchanges of messages between the Spatial Web nodes listed in computing architectures (7.1) and Spatial Web Nodes (7.2). The messages in the use cases make use of HSML (6.6) and HSTP (7.3). Use cases are defined as generally as possible in order to allow a minimum number of use cases to achieve events in a diverse set of scenarios. Coherence of the Spatial Web architecture is demonstrated by the use cases satisfying the needs of the Application Scenarios (5.3). Each use case is defined using a sequence diagram. The sequence diagrams show dynamic behavior as interactions among distributed Spatial Web nodes via sequences of HSTP messages exchanged. A summary of the Spatial Web use cases is provided in Table 4.

**TABLE 4:** Summary of Spatial Web use cases

| Prepare for activities | Conduct activities |
|---|---|
| Public & top domain SWID registration process | Update DOMAIN state |
| Create and register a new DOMAIN | Discover DOMAIN using UDG (Spatial DNS) |
| Create child DOMAIN of a DOMAIN | Update DOMAIN state |
| Create SPACE representation of a DOMAIN | Query DOMAIN state |
| Issue CREDENTIAL for DOMAIN | Create route DOMAIN in SPACE |
|  | Transfer DOMAIN between DOMAINs |
|  | Monitor CHANNEL for ACTIVITY |

## 7.4.2. Requirements and Recommendations

- HSTP shall implement the use cases in 7.4.
- Domain-specific architectures shall implement the relevant use cases in 7.4.
- UDG shall implement the use cases: 7.4.4, and 7.4.11.

## 7.4.3. Public & Top Domain SWID Registration Process

Figure 40 is a diagram of the Public & Top Domain SWID Registration Process.

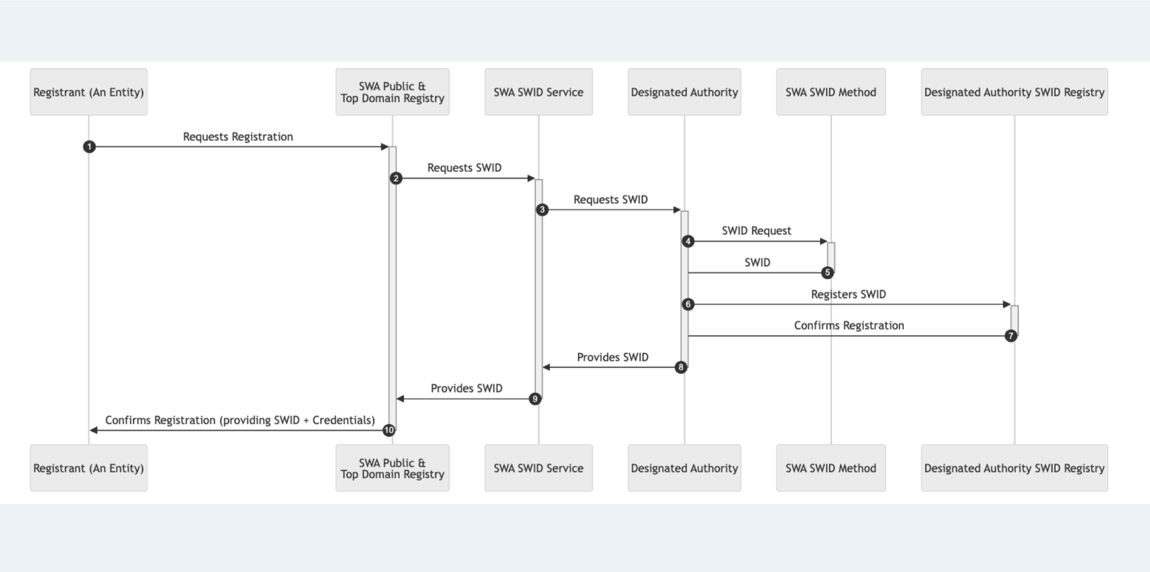
Note that *SWID methods*, as used in this section, refers to *SWID methods* as defined in section 6.3.3.2.

1. A registrant requests to register an ENTITY with the SWA Public and Top Domain registry
2. The SWA Public and Top Domain registry takes the request and makes a corresponding request to the SWA SWID service
3. The SWA SWID service makes a corresponding request to a Designated Authority
4. The Designated Authority requests a SWID from the SWA SWID method service
5. SWA SWID method provides a SWID to the Designated Authority upon invocation

6. The Designated Authority sends the SWID to be added in the Designated Authority SWID registry
7. The Designated Authority SWID registry confirms the registration
8. The Designated Authority returns the SWID to the SWA SWID service
9. The SWA SWID service returns the SWID to the SWA Public and Top Domain registry
10. The SWA Public and Top Domain registry returns the SWID to registrant

Note that the SWA Public and Top Domain registry is responsible for any verification service required before continuing the registration process.

**FIGURE 40:** Sequence diagram: Public & Top Domain SWID Registration Process

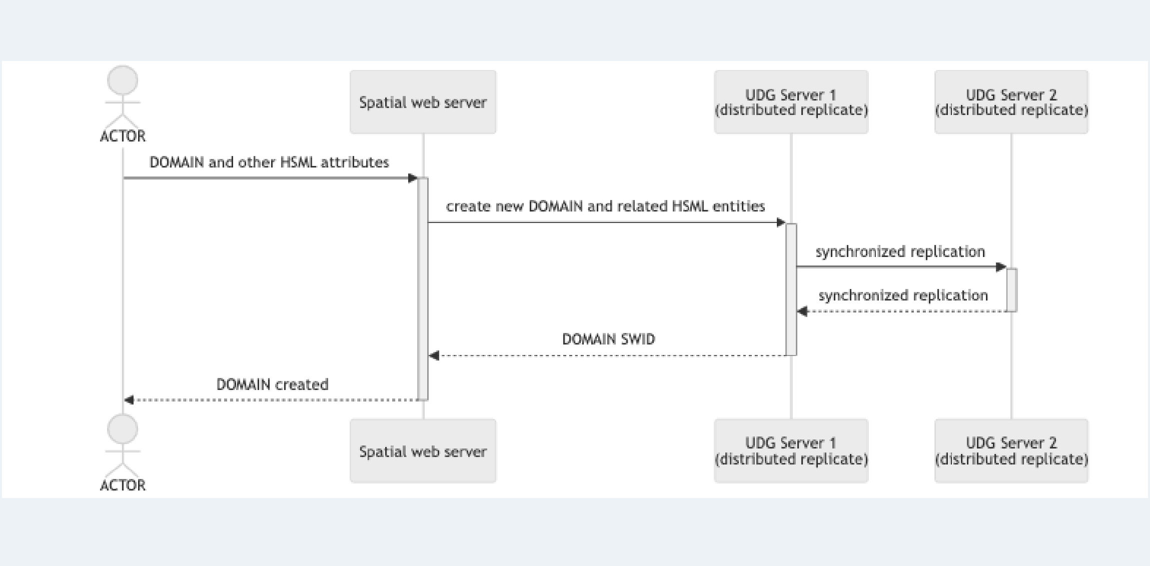


## 7.4.4. Create and register a new DOMAIN

An administrator for the DOMAIN (actor) accesses a local server to populate the server with information about the new DOMAIN. The Server sends the DOMAIN and other HSML entity information to the UDG Server to register the DOMAIN. The UDG Server creates a SWID for the DOMAIN and replicates the new DOMAIN's information with other UDG Servers. The DOMAIN SWID is returned to the Spatial Web Server. The DOMAIN is now registered in the Spatial Web.

The server needs to be authorized to register a new domain. It is assumed that all needed permissions are previously obtained for the use case. [Messages to establish CREDENTIALs are not shown in the sequence diagram (Figure 41)].

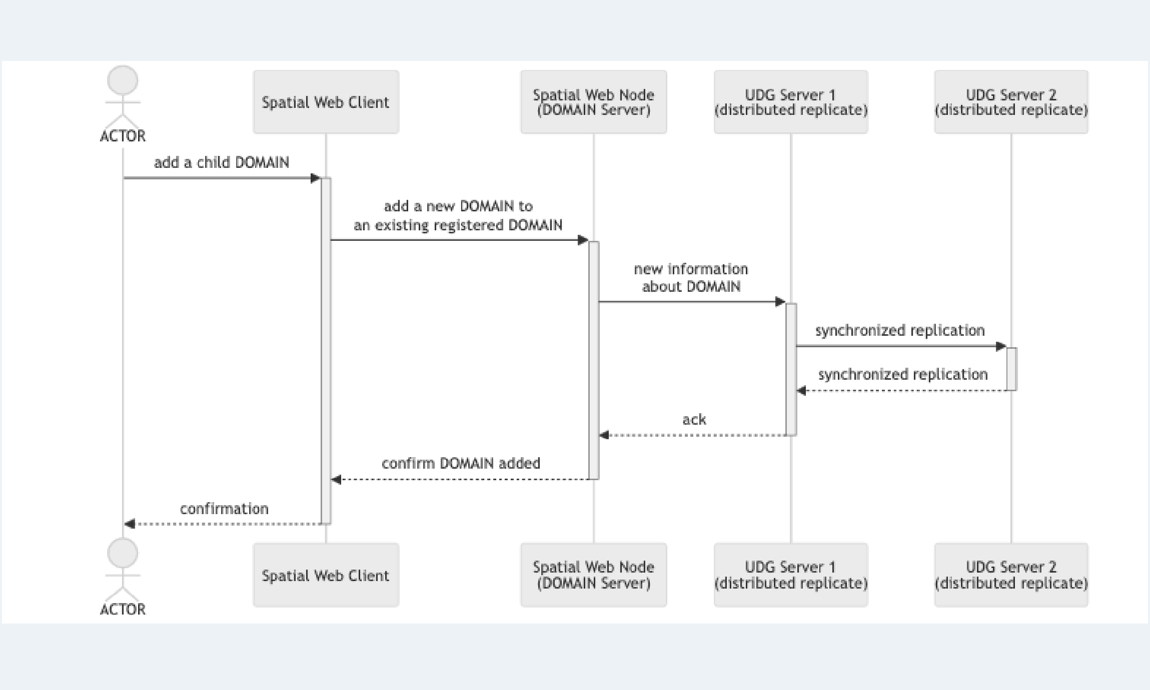
**FIGURE 41:** Sequence diagram: Create and register a DOMAIN



## 7.4.5. Create child DOMAIN of a DOMAIN

This use case (see Figure 42) shows the addition of information to an existing DOMAIN including defining new DOMAINS. The information is added to the local Spatial Web Node. The Spatial Web Node updates the UDG server with the new information by adding to the previously existing DOMAIN in the UDG Server. The UDG server synchronizes with other UDG servers which hold replicated information.

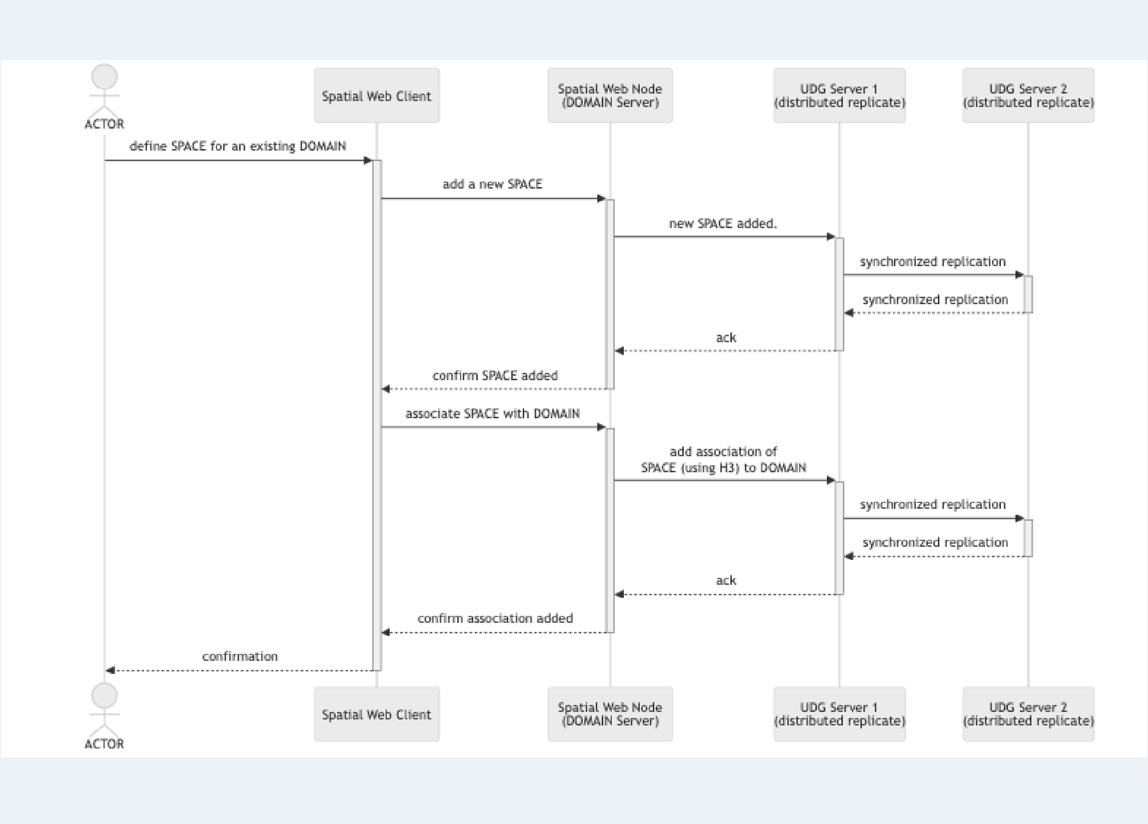
**FIGURE 42:** Sequence diagram: Create child DOMAIN of a DOMAIN



### 7.4.6. Create SPACE representation of a DOMAIN

This use case (see Figure 43) adds a SPACE association to an existing DOMAIN. Here it is assumed that the SPACE is new and so the first step is to add the SPACE entity to the Spatial Web Node and then to associate the existing DOMAIN to the newly added SPACE. The SPACE may be any kind of hyperspace. If the new SPACE is a geographic space, the Spatial Web Node embeds the geographic space into H3 DGGS. The Spatial Web Node then provides the H3 Index for the DOMAIN to the UDG server. If the new SPACE is a graph (or categorical) space, the Spatial Web Node provides the definition of the graph (or categorical) space to the UDG Server along with the association of the DOMAIN to the graph (or categorical space). The UDG Servers synchronize and replicate the information.

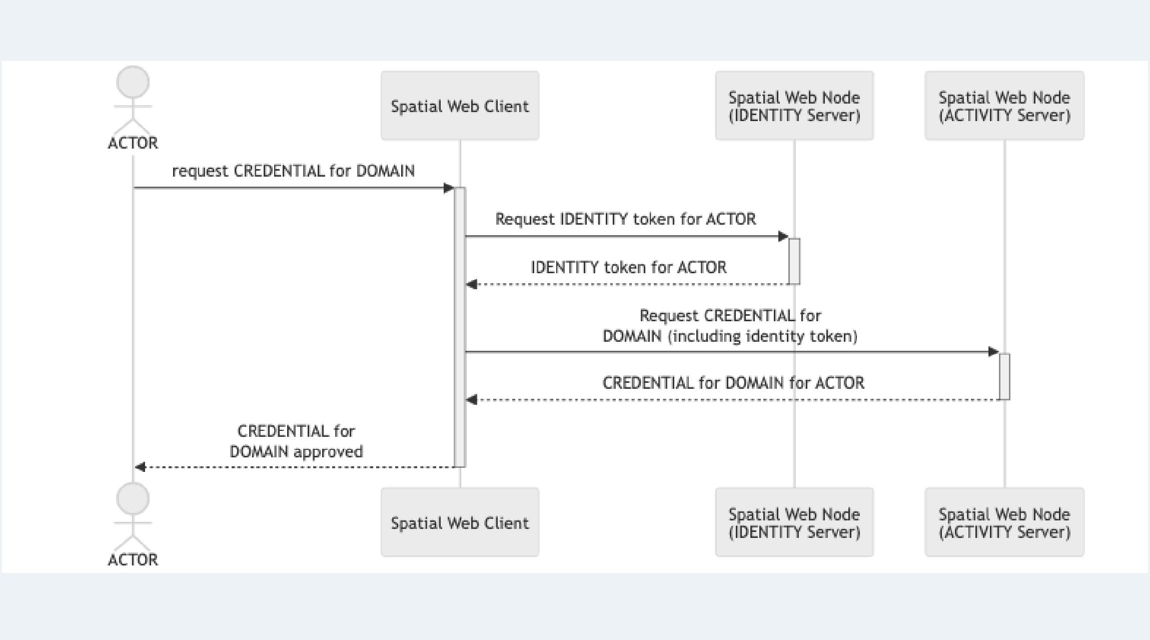
**FIGURE 43:** Sequence diagram: Create SPACE representation of a DOMAIN



### 7.4.7. Issue CREDENTIAL for DOMAIN

This use case (see Figure 44) shows an actor first getting an identity token. Then the actor identity CREDENTIAL is recognized by a DOMAIN for future activities.

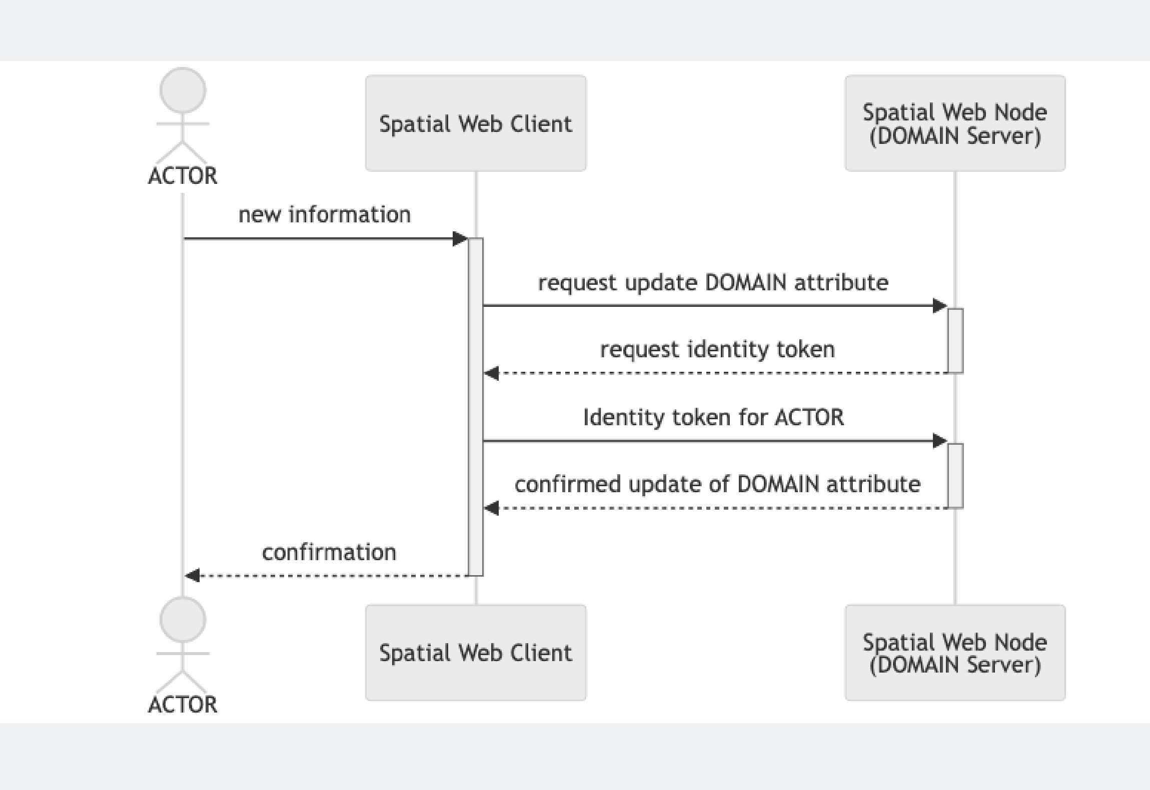
**FIGURE 44:** Sequence diagram: Issue CREDENTIAL for DOMAIN



## 7.4.8. Update DOMAIN state

This use case (see Figure 45) shows an actor updating the state of a DOMAIN. The update is not allowed until the server confirms the CREDENTIAL of the actor.

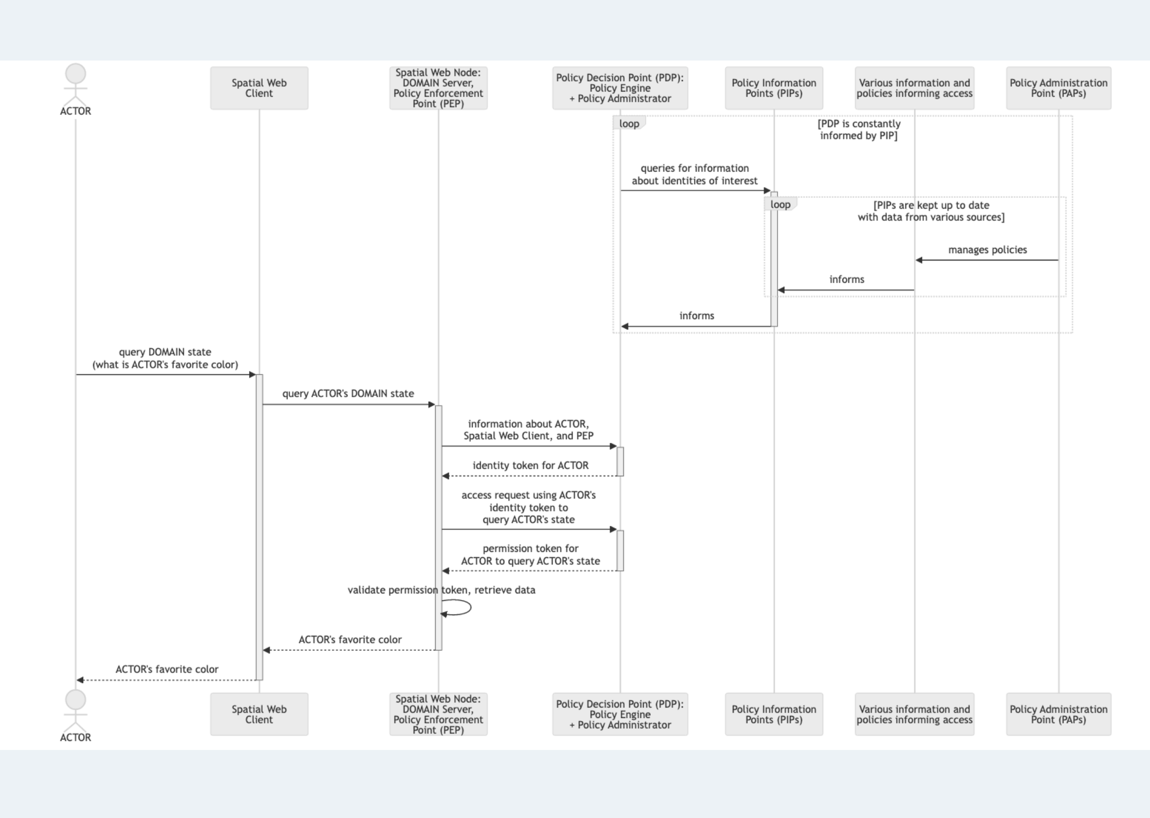
**FIGURE 45:** Sequence diagram: Update DOMAIN state



### 7.4.9. Query own DOMAIN state (including zero-trust concerns)

This use case (see Figure 46) shows an actor querying their own DOMAIN's state. The query is not allowed until the server confirms the CREDENTIAL of the actor, and the actor's authorization to query the domain. Some details of the zero-trust architecture are outlined here for clarity.

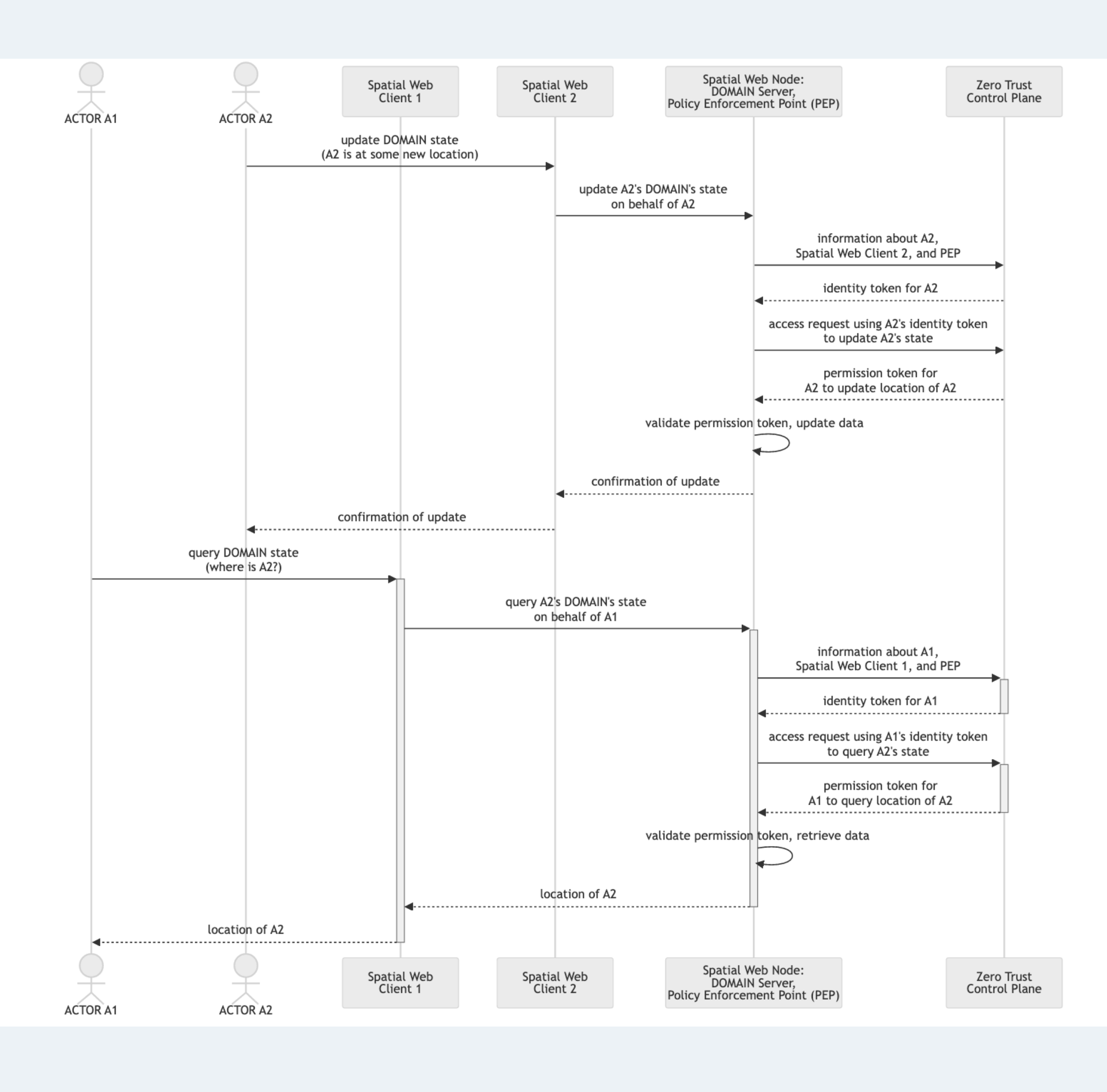
**FIGURE 46:** Sequence diagram: Query own DOMAIN state



### 7.4.10. Query other's DOMAIN state

This use case (see Figure 47) shows an actor querying the state of another actor's DOMAIN. The query is not allowed until the server confirms the CREDENTIAL of the actor, and the actor's authorization to query the domain.

**FIGURE 47:** Sequence diagram: Query another's DOMAIN state

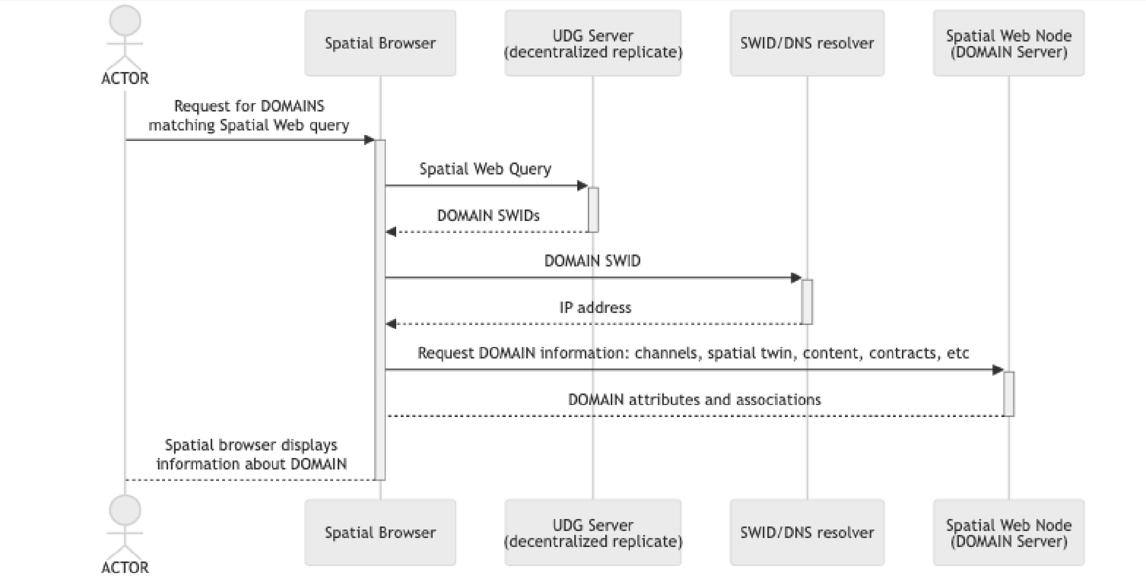


## 7.4.11. Discover DOMAINs using UDG

This use case (see Figure 48) shows an actor requesting information based on a Spatial Web query. The Spatial Web query may use any HSML entity to compose the query including hyperspace, categorical data, claims, CREDENTIALs, etc. The UDG server evaluates the query against the local copy of the UDG (and exchanges with other UDG servers as needed) resulting in a set of DOMAINS matching the query. The query response is primarily composed of SWIDs for the matching DOMAINS. The Spatial Browser interactions with the Distributed UDG System to get SWID address for a DOMAIN. The Spatial Browser requests DOMAIN information from the Spatial Web Server that hosts the DOMAIN.

It is assumed that all needed permissions are previously obtained for the use case. (Messages to establish CREDENTIALs are not shown in the sequence diagram).

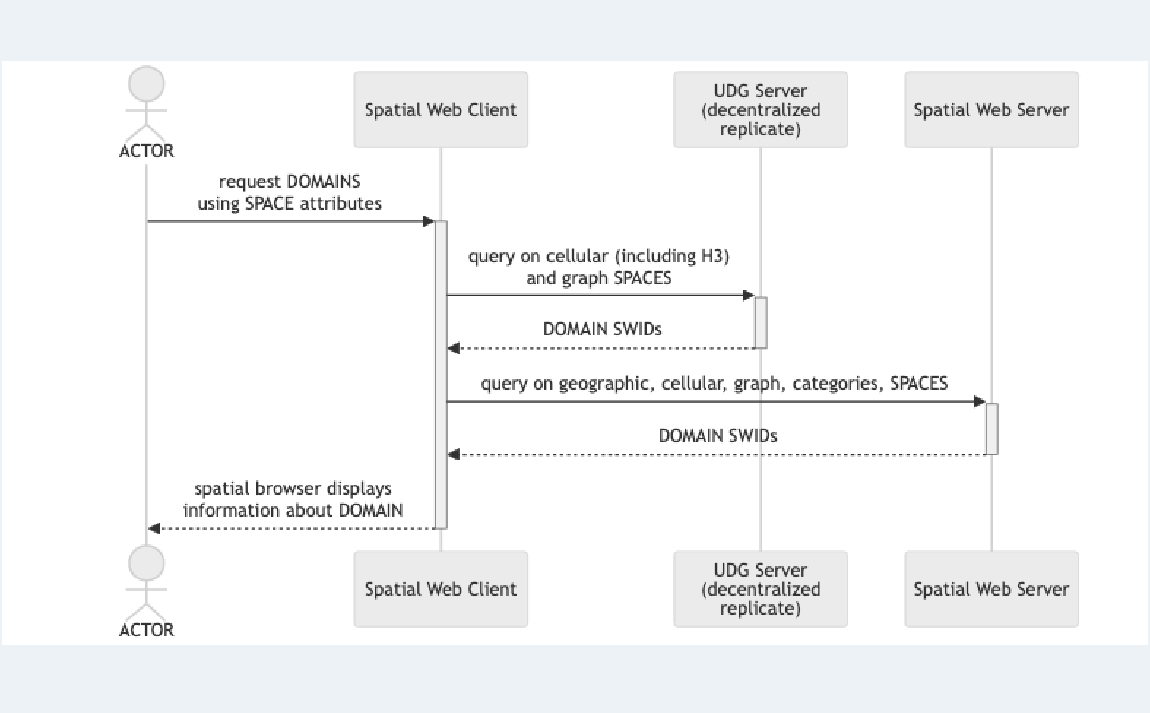
**FIGURE 48:** Sequence diagram: Discover DOMAINs using UDG



## 7.4.12. Discover DOMAINS using SPACEs

This use case (see Figure 49) shows discovery of DOMAINS using SPACE. SPACE may be any type of hyperspace. Queries on cellular and graph spaces may be posed to the UDG Server. The UDG Server can evaluate an H3 Cellular SPACE for geo-related queries. Arbitrary queries on any hyperspace may be posed to the Spatial Web Server hosting those SPACES and associated DOMAINS. This approach prevents the UDG server from having to perform resource intensive queries on geographic and categorical SPACEs. Each query returns a set of SWIDs for DOMAINs that satisfy the SPACE query.

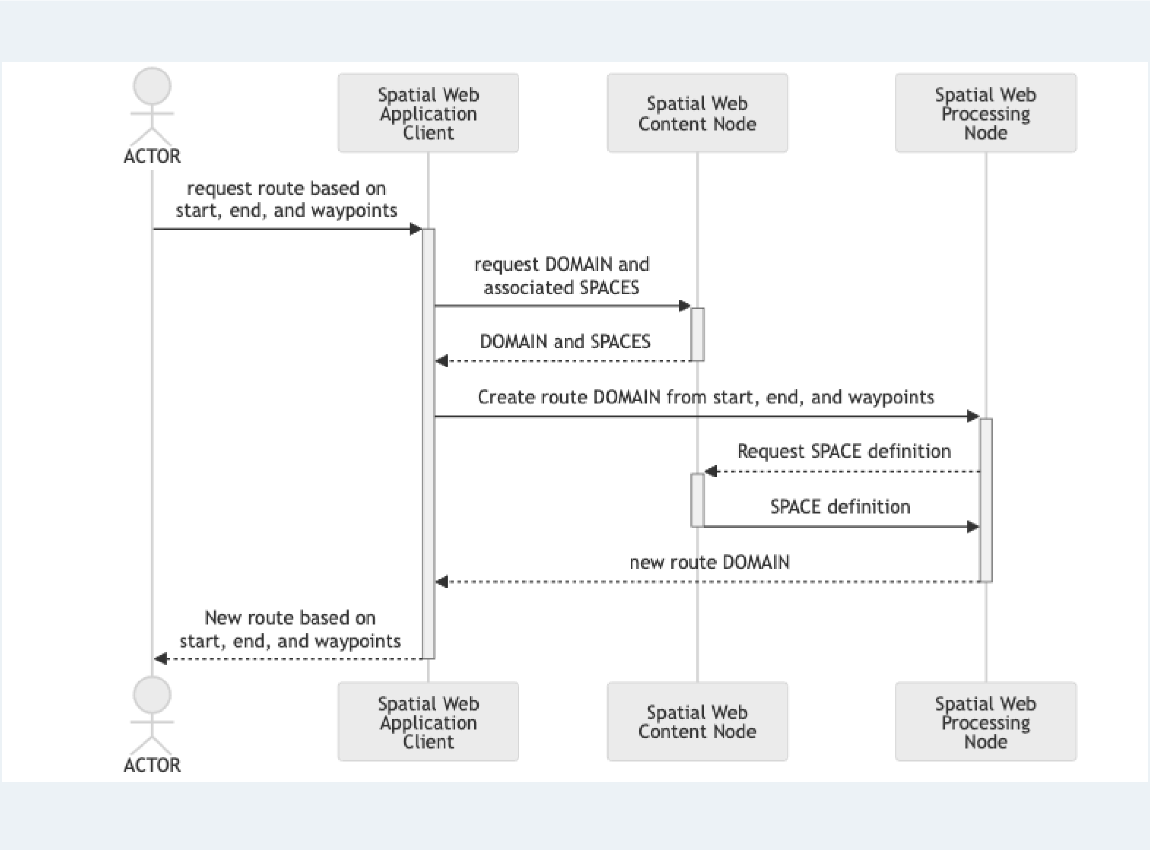
**FIGURE 49:** Sequence diagram: Discover DOMAINs using SPACEs



## 7.4.13. Create route DOMAIN in SPACE

This use case (see Figure 50) shows an actor requesting the calculation of a route based on start and end points, and possibly waypoints. The route is created for a DOMAIN that may be associated with several SPACEs. The Spatial Web Application client accesses the source DOMAIN and associated SPACES from the Spatial Web Content node. The client provides the source DOMAIN and the SPACE associations to a Spatial Web Processing Service that can create routes. The Processing service identifies a SPACE associated with the source DOMAIN and the start, end and waypoints. The Processing service creates the route (as a new DOMAIN) from the source DOMAIN. The route DOMAIN is provided to the client.

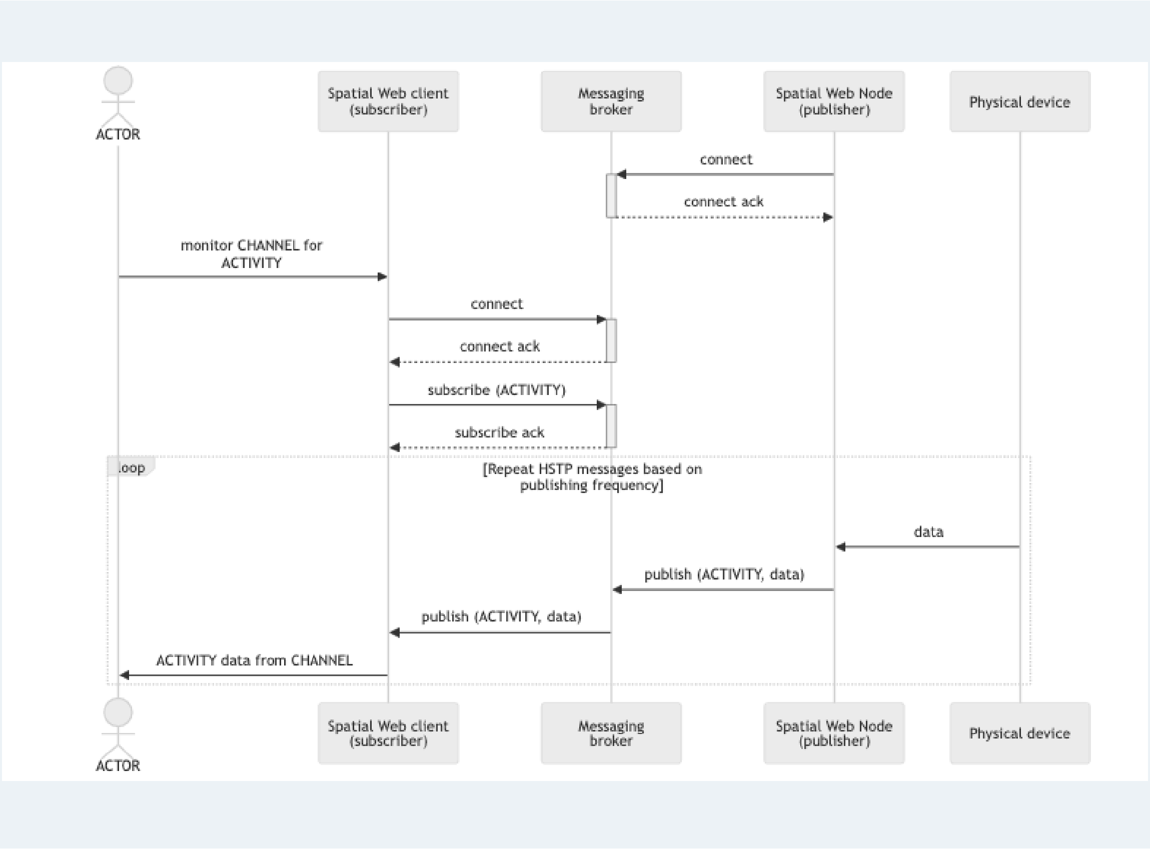
**FIGURE 50:** Sequence diagram: Create route DOMAIN in SPACE



## 7.4.14. Monitor CHANNEL for ACTIVITY

This use case (see Figure 51) shows an actor registering to receive updates when a device transmits data. The use case is defined using a messaging protocol paradigm. A Messaging broker is available for use in the Spatial Web. The actor subscribes to a messaging channel for ACTIVITY of the physical device. When the device publishes new data to the broker the actor receives the data through the CHANNEL.

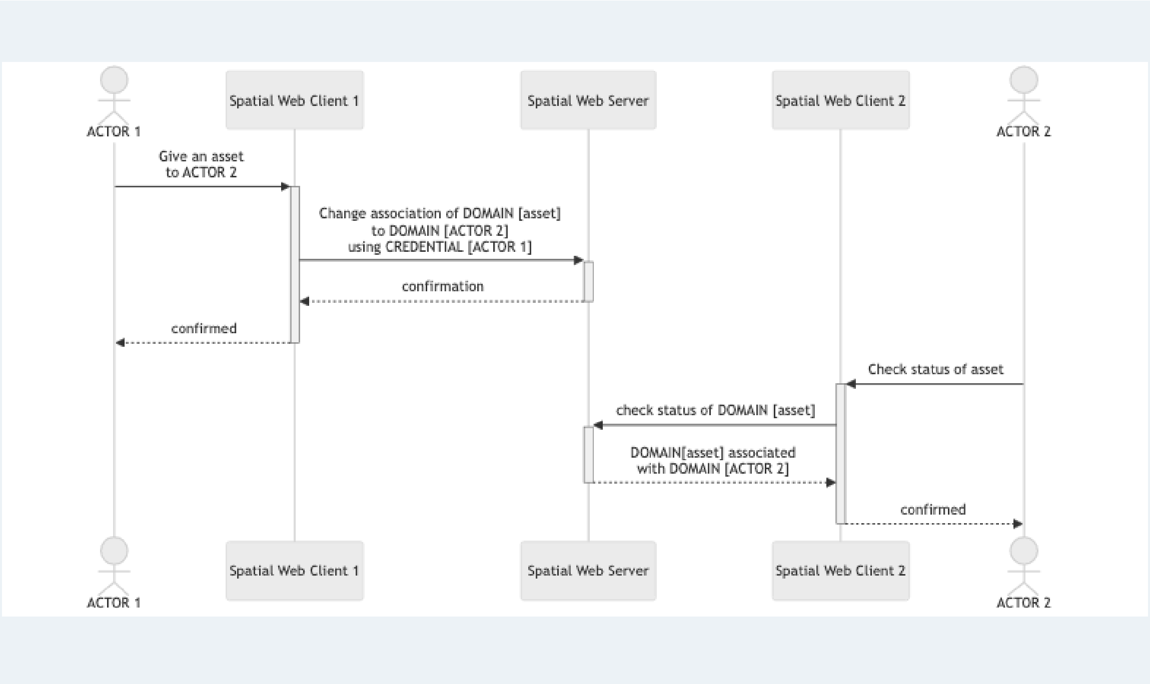
**FIGURE 51:** Sequence diagram: Monitor CHANNEL for ACTIVITY



## 7.4.15. Transfer DOMAIN between DOMAINs

This use case (see Figure 52) shows an actor requesting a DOMAIN asset be transferred to another actor's DOMAIN.

**FIGURE 52:** Sequence diagram: Transfer DOMAIN between DOMAINs



# Annex A
# **(normative)**

# Requirements for compliance targets

## A.1. Overview

The Reference Model identifies requirements for several compliance targets. Requirements for each target appear across the clauses of the reference model. This compliance annex groups requirements by compliance target. These succinct lists of requirements for each compliance target aids with the development of the target and compliance assessment.

This annex has one subclause for each of the following compliance targets:

- HSML
- HSTP
- UDG
- AIS Rating Framework
- Domain-specific architectures
- Spatial Web Governance

## A.2. HSML

The HSML Implementation Specification shall meet the following requirements. Each requirement is followed by the clause wherein the requirement appears in the conceptual model.

HSML shall support deployment and management of the Spatial Web by operations within organizations with defined secure boundaries, such as enterprises or communities. Source: 5.2.2.2.

HSML shall enable virtual representation of physical entities based on the principles of spatialization and trust 5.1. Source: 5.2.3.2.2.

HSML shall enable digital representation of physical entities synchronized at frequencies and fidelity needed for applications based on considerations of OGC 07-165r1,W3C REC-wot-architecture11-20231205, [73], [123] Source: 5.2.3.2.2.

HSML shall be able to represent real-time data from sensors and actuators. The data may subsequently be used to control remote processes. Source: 5.2.3.2.2.

HSML shall provide representation of physical and virtual entities using 3D encoding standards, i.e., glTF, USD or Web3d. Source: 5.2.3.3.2.

HSML shall enable the use of OGC 21-056r11. Source: 5.2.3.3.2.

HSML shall enable discovery of physical and virtual entities via discovery services. Source: 5.2.3.3.2.

HSTP shall enable discovery of physical and virtual entities via discovery services. Source: 5.2.3.3.2.

HSML shall provide an open, multi-domain UDG suitable for immersive shared experiences across multiple Spatial Web nodes and domains. Source: 5.2.3.3.2.

HSML hyperspace semantic modeling, extending beyond four spatial-temporal dimensions, shall be suitable for immersive experiences. Source: 5.2.3.3.2.

HSML shall enable representation and messaging of AI AGENTs in the Spatial Web. Source: 5.2.3.4.2.

HSML shall define representations of hyperspace which include representations of physical space. Source: 5.2.4.2.

HSML shall provide a globally unique index for any geographic domain listed in the Spatial Web using a DGGS as defined in ISO 19170-1. Source: 5.2.4.2.

HSML shall provide for metrics in the compound space of physical dimensions and semantic dimensions. Source: 5.2.4.2.

HSML shall enable the application of information from diverse domains, e.g., geographic, digital earth, economic and social systems, in order to assess the complex interactions of relevant systems. Source: 5.2.4.2.

HSML shall enable a multi-scale, distributed universal knowledge graph that supports reasoning. Source: 5.2.5.2.

HSML shall provide cross-domain interoperability which may include the use of cross-domain ontologies like the Basic Formal Ontology ISO/IEC 21838-2:2021. Source: 5.2.5.2.

HSML shall enable the reuse of semantic terminology across domains Source: 5.2.5.2.

HSML may use RDF, OWL and SHACL for semantic modeling. Source: 5.2.5.2.

HSML shall include SWIDs that enable decentralized identity management. Source: 5.2.6.2.

HSML shall implement the basic concept of hyperspace. Source: 6.2.4.

HSML may enable the representation of the points and paths of each hyperspace. If paths are represented in an implementation of HSML, then the composition of paths shall be implemented, and this composition shall be associative and unital with respect to the identity paths. Source: 6.2.4.

HSML shall implement the following basic classes of hyperspace: Euclidean vector spaces; graphs; hypergraphs; cellular spaces with finite schemata, including geographic space as a special case; and abstract data types. Source: 6.2.4.

HSML shall implement Coordinate Reference Systems using ISO 19111:2019 Source: 6.2.4.

HSML shall include an <Geo/Earth> attribute scheme for any geographic location using the H3 DGGS h3geo. Source: 6.2.4.

HSML should enable the representation of the hyperspaces of basic classes of hyperspace, including the hyperspace of hyperspaces. Source: 6.2.4.

HSML should enable the representation of finite-dimensional (discrete) probability distributions over any hyperspace. Source: 6.2.4.

HSML may enable the representation of more general hyperspaces of probability distributions, and these may be equipped with the Fisher information metric structure (Amari, 2016, §3.5). Source: 6.2.4.

HSML should, where applicable, implement the following basic additional structures on hyperspaces: origin; dimension; norm; inner product; metrics; similarity. Source: 6.2.4.

HSML should implement the following additional operations on spaces: 1) on vector spaces: subspace, direct sum, and tensor product; 2) on graphs, hypergraphs, cellular spaces, and topological spaces: subspace, direct sum, and quotient spaces; 3) on hyperspaces: subspace, and (categorical) product; and 4) on abstract data types: subspace (subtype), product type, and function type. Source: 6.2.4.

HSML representation of hyperspace should utilize a shared, open standard for common hyperspaces or common hyperspace dimensions (such as time). Source: 6.2.4.

HSML implementations (specific schemas associated with HSML elements) shall publish serialization mechanisms for their hyperspace representations. Source: 6.2.4.

HSML shall provide a domain type attribute; Acceptable values for Domain Type are Geographic, Concept, Organization, Agent, Person, Thing; other types may be added if they do not duplicate these. Source: 6.3.2.4.

HSML shall require a SWID for all ENTITIES; SWIDs shall conform to W3C Decentralized Identifier core standard and may conform to Decentralized Identity Foundation standards. Source: 6.3.3.4.

HSML shall require SWIDs to include an implicit referenceability to SWID Documents consistent with SWIDs being DIDs. Source: 6.3.3.4.

HSML shall define SWID Documents to include elements as defined in 6.3.3.2. Source: 6.3.3.4.

HSML shall include an attribute for .Earth DOMAINS using a SWID schema that uniquely identifies cells on the surface of the Earth. Source: 6.3.3.4.

HSML shall define attributes for DOMAINS for SWID methods as required in W3C Decentralized Identifier core standard and may require attributes from W3C NOTE-did-spec-registries-20240831. Source: 6.3.3.4.

HSML shall require that Person Domains have a globally-usable, Self-Sovereign Identity. Source: 6.3.3.4.

HSML shall include one SWID Method defined for the Spatial Web that meets all Spatial Web SWID requirements. Source: 6.3.3.4.

HSML shall enable representation of the Table 3, including representation of complex and dynamic domain interactions in a structured and coherent manner. Source: 6.3.4.9.

HSML shall enable cross-Domain entities as well as providing robust methods for defining Spatial Web Domain-specific entities. Source: 6.3.4.9.

HSML shall enable modeling of heterogeneous Spatial Web Domains, including comprehensive methods for constructing and maintaining a distributed UDG. Source: 6.3.5.3.

HSML shall enable modeling of heterogeneous Spatial Web Domains, including comprehensive methods for constructing and maintaining a distributed UDG, modeling of heterogeneous Spatial Web Domains, and modeling diverse and complex Spatial Web Domain structures. Source: 6.3.5.3.

HSML shall represent the world and its associated knowledge in a manner that is understandable by AGENTs. Source: 6.4.2.7.

HSML shall represent the world and its associated knowledge in a manner that is actionable by AGENTs. Source: 6.4.2.7.

HSML shall represent diverse types of environments, including virtual, physical, and hybrid spaces, using a universally understandable model. Source: 6.4.3.4.

HSML shall help ensure standardization by providing a common language or procedures for AGENT communication, ensuring messages are understood across diverse AGENT designs. Source: 6.4.3.4.

HSML shall support the development of infrastructures that enable AGENTs to identify and resolve conflicts related to contract assignment, goals, and resource allocation, ensuring harmonious collaboration. Source: 6.4.3.4.

HSML shall enable humans and Domain Authorities to specify interaction preferences or protocols through the HSML framework for enhanced customization. Source: 6.4.3.4.

HSML shall enable the representation of ACTIVITIES in a way that is compatible, understandable, shareable, and executable by diverse AGENTS or ENTITIES within the Spatial Web ecosystem. Source: 6.4.4.8.

HSML shall model ACTIVITY Schemas that specify templates for ACTIVITIES in terms of the conditions that they (are intended to) bring about, as well as any conditions presupposed for its execution, where such conditions are specified as predicates over HSML data structures (i.e., Domain descriptions) that may contain open variables. Source: 6.4.4.8.

HSML shall model the conditions associated with an HSML Activity Instance. Source: 6.4.4.8.

An HSML Activity Instance shall inherit from the conditions of the Activity Schema it instantiates, binding values as necessary to any variables left open at the level of the Activity Schema. Source: 6.4.4.8.

HSML shall provide guidance for registered HSML Activity Name to be intuitive, and easy to understand and interpreted by users or other interacting Entities. Source: 6.4.4.8.

HSML encoding of ACTIVITIES should be designed to be adaptable and flexible, allowing for the modification of plans and goals based on changes in the environment or the emergence of new information. Source: 6.4.4.8.

HSML shall encode Claims for an AGENT's ability to perform an Activity shall be certified by a registered Domain Authority. Source: 6.5.3.2.

HSML shall encode Encrypted digital Credentials that are independently verifiable without the notification of third parties. When a party verifies the issued Credentials, a record of this verification shall be created and made available to the Credential-issuing domain(s), in order to prevent the tracking of origins and contexts of verification requests. Source: 6.5.3.2.

HSML shall define a claims schema that supports spatial claims and identities, as well as generic claim mechanisms, via HSML Credentials. Source: 6.5.3.2.

HSML shall enable the negotiation, validation, monitoring and confirmation of contractual agreements that govern transactions on the Spatial Web. Source: 6.5.4.5.

HSML Contracts shall constitute agreements for the performance of an HSML Activity Instance. Contract status shall be a function of the status of the associated Activity instance, such that the Contract conditions can be evaluated as True or False against the relevant Domain description(s). Source: 6.5.4.5.

HSML shall enable the representation of issuing of Contracts as an HSML ACTIVITY, subject to norms and standards specified in further conditions, and subject to validation by relevant third parties as described in 6.5.4. Source: 6.5.4.5.

HSML shall implement the attributes and relationship of the Figure 23 for each Spatial Web entity. Source: 6.6.13.

HSML shall define several profile encoding formats, e.g., JSON (see ISO/IEC 21778), OData (See ISO/IEC 20802-1 and ISO/IEC 20802-2), JSON-LD (see W3C json-ld11), and GraphQL (see The Graph QL Specification Project). Source: 6.6.13.

HSML shall provide standard elements for SpaceType properties as defined in 6.2. Source: 6.6.13.

HSML shall enable Bootstrapping/Context queries Source: 6.7.3.

HSML shall enable Activity queries Source: 6.7.3.

HSML shall enable Hyperspace range queries Source: 6.7.3.

HSML shall enable Abstract data type query Source: 6.7.3.

HSML shall enable Graph queries Source: 6.7.3.

HSML shall enable Semantic queries Source: 6.7.3.

HSML shall enable Vector queries Source: 6.7.3.

HSML shall define a canonical approach suitable to cross domain, e.g., point, quaternion, hyperspace [with the latter consisting of a point (origin) and orientation (quaternion)]. Source: 7.2.2.

## A.3. HSTP

The HSTP Implementation Specification shall meet the following requirements. Each requirement is followed by the clause where the requirement appears in the concept model.

HSTP shall be interoperable with IoT systems in such a way that the entities are able to exchange information and mutually use the information in an efficient way consistent with IEEE Std 2413™-2019. Source: 5.2.3.2.2.

HSTP shall provide interoperability of observations coming from physical sensors based on considerations of OGC 07-165r1,W3C REC-wot-architecture11-20231205, [73], [123] Source: 5.2.3.2.2.

HSTP shall provide interoperability of robotics and other physical actuator devices. Source: 5.2.3.2.2.

HSML representation of entities shall include multiple modes of sensing, e.g., vision, touch, and smell. Source: 5.2.3.3.2.

HSTP shall enable requests for cognitive computing such as for inference (perception, learning, action selection). Source: 5.2.5.2.

HSTP shall enable machine learning operations on sensor data, i.e., observations and measurements, accessible in the Spatial Web. Source: 5.2.5.2.

HSTP shall enable machine learning by providing interoperability of AGENT nodes using information accessible in the Spatial Web. Source: 5.2.5.2.

HSTP shall enable message passing between nodes with AI functionality. Source: 5.2.5.2.

HSTP shall provide infrastructure and protocols for AGENTs with diverse intelligences to communicate and interact effectively. Source: 6.4.2.7.

HSTP shall provide infrastructure and protocols for AGENTs with diverse intelligences to communicate and interact effectively. Source: 6.4.3.4.

HSTP shall help ensure communication protocols are reliable and efficient, facilitating information transmission between AGENTs regardless of their underlying implementation or the network over which they communicate. Source: 6.4.3.4.

HSTP shall support AGENT communication and interactions of varying levels of contextual and syntactic complexity, from simple command and control signals to semantically rich high-dimensional vector representations. Source: 6.4.3.4.

HSTP shall enable AGENTs to communicate over necessary timescales for optimal function and integrate an autonomous rating framework to support understanding of AGENTs' capabilities, responsibilities, and interaction behaviors within multi-agent systems. Source: 6.4.3.4.

HSTP shall support scalability, enabling increased AGENT interactions without compromising performance, crucial for large-scale operations. Source: 6.4.3.4.

HSTP shall incorporate mechanisms for authentication, authorization, and encryption to safeguard interactions. Source: 6.4.3.4.

HSTP shall provide methods for HSML Activity models to adhere to security measures and protocols to protect sensitive information and prevent unauthorized access or malicious behaviors. Source: 6.4.4.8.

HSTP shall enable CRUD on HSML entity relations and attributes. Source: 6.6.13.

HSTP shall enable queries on HSML ENTITIES Source: 6.7.3.

HSTP shall allow Spatial Web domain architectures to enable location awareness. Source: 7.1.3.

HSTP shall allow Spatial Web domain architectures to enable clients to ascertain the physical location of the distributed computing equipment that is hosting the Spatial Web node that the client is accessing. Source: 7.1.3.

HSTP shall be designed to be resilient to faults: The network of Spatial Web nodes should have only transient loss of function when a single node becomes non-operational Source: 7.1.3.

HSTP shall be designed to operate with varied communication network performance. This includes support for both high latency / low connectivity support and scenarios where bandwidth ranges from hundreds of gigabits per second to several terabits per second (i.e., having latency in the sub-millisecond range). Source: 7.1.3.

HSTP shall enable independent implementations that are interoperable. Source: 7.1.3.

HSTP shall implement a zero-trust security model. Source: 7.1.3.

HSTP shall provide interoperability of digital messages between nodes. Source: 7.1.3.

HSTP shall provide protocols for automatic configuration that allow Spatial Web nodes to react on the addition and removal of nodes such as devices and networks. Source: 7.1.3.

HSTP shall support accessing Spatial Web nodes in the local network from the outside of the local network (the internet or another local network), considering network address translation. Source: 7.1.3.

HSTP shall work in centralized or distributed computing environments. Source: 7.1.3.

HSTP shall support the implementation of a Spatial Web ecosystem, including support for: Spatial Web client nodes, Spatial Web Servers, Spatial Indices, Spatial Web adapters, Distributed consensus and distributed ledger infrastructure, Spatial rendering servers, and Peer-to-peer servers Source: 7.2.2.

HSTP shall use HSTP OPERATIONS to route and encapsulate HSML Activity Schemas as the structure of the protocol commands which can be sent to HSTP-compliant systems. Source: 7.3.5.

HSTP shall use the specified MIME-type-like identifier of the types of data contained, alongside the data, whether it be text, media, binary, and/or encrypted information. Source: 7.3.5.

HSTP shall use the specified method of providing declarations that alert communicating systems as to the capabilities of each system via providing a catalog of the HSML Activities they can resolve and perform. Source: 7.3.5.

HSTP messages shall include the system's self-understood position in the Spatial Web's Distributed UDG System by providing its SWID and the SWIDs of its publicly listed known neighbors to a graph distance specified by the HSTP request or response, by at a minimum distance of 1. Source: 7.3.5.

HSTP messages shall include information needed by Distributed UDG System, either spatial domains or SWIDs, to locate the networked addresses, be it TCP/IP addresses or other. Source: 7.3.5.

HSTP messages shall include information that designates the types of desired and allowed connections from both the requester and responder, enabling HSTP-compliant systems to negotiate their preferred or required transport method on a per HSML activity basis. Source: 7.3.5.

HSTP messages shall include the last known geospatial or other spatial locations where such information is available, as well as the system's status and readiness for communication. Source: 7.3.5.

HSTP shall achieve “Unconditional Compliance” with HSML 1.0 by using HSML CREDENTIALs, Domains, Spaces, Activities, and Channels to be specified in HSML implementation specification when executing or resolving an HSML Activity within an HSTP message. Source: 7.3.5.

HSTP shall define profiles of HSTP for HTTP, MQTT, and GraphQL 7.3.4. Source: 7.3.5.

HSTP shall implement the use cases in 7.4 Source: 7.4.2.

## A.4. UDG

The UDG Implementation Specification shall meet the following requirements.
Each requirement is followed by the clause where the requirement appears in the conceptual model.

UDG shall enable discovery of the virtual representation of physical entities. Source: 5.2.3.2.2.

UDG shall enable discovery of physical and virtual entities via discovery services. Source: 5.2.3.3.2.

UDG shall validate SWIDs generated using SWID Method prior to issuance, e.g., assess uniqueness. Source: 6.3.3.4.

UDG shall include a Spatial Web registration service for Public and Top domains. Source: 6.3.3.4.

UDG shall, for audit purposes, register all SWIDs related to all public and top domains in a Spatial Web Registry. Source: 6.3.3.4.

UDG shall enable verification and validation services for domains prior to their registration. Source: 6.3.3.4.

UDG shall support the generation of SWIDs one at a time, such as for Top Domains, or generate many at a time, such as for Public Domains. Source: 6.3.3.4.

UDG shall ensure SWID uniqueness. Source: 6.3.3.4.

UDG shall ensure that SWIDs are maintained in the Spatial Web Registry. Source: 6.3.3.4.

UDG operations shall be resilient to inconsistencies in relationships between nodes and in the content of nodes. Source: 6.3.4.9.

UDG shall provide for distributed operations of the UDG including propagation of changes and consistency. Source: 6.3.5.3.

UDG shall provide Spatial Web Domain interactions that are seamlessly managed and integrated. Source: 6.3.5.3.

UDG shall implement Spatial Web Domain registration processes as defined in clause 6.3.6. Source: 6.3.5.3.

UDG design and procedures shall enable a range of methods for accessing the UDG from basic, open access to UDG access services with enhanced value in accord with economic exchange, e.g, fee, advertising, etc. Source: 6.3.5.3.

UDG shall provide the capability to register and manage ACTIVITIES that are associated with AGENTs, reflecting their capabilities and permissions. Source: 6.4.4.8.

UDG shall keep a record of HSML ACTIVITIES that were executed as part of a Contract, providing a history of the Activity, verification of the execution of the Activity, and enabling the tracking of the Activity’s progress. Source: 6.4.4.8.

UDG shall be designed to operate with communication network performance where bandwidth ranging from hundreds of gigabits per second to several terabits per second (i.e., having latency in the sub-millisecond range). Source: 7.1.3.

UDG shall provide mechanisms for automatic discovery of nodes, and their properties and capabilities as well as the means to access them. Source: 7.1.3.

UDG shall support the ability to accommodate an increasing number of connectivity endpoints, reaching internet scale. Source: 7.1.3.

UDG shall include Spatial Index Servers that make maps ranging from simple SQL indexes to graph-based databases to widely adopted and standard spatial indexing services which deliver spatial indexing. Source: 7.2.2.

UDG shall manage entity replication and update with consideration of how quickly the entities are changing. Source: 7.2.2.

UDG shall manage rapidly changing entities using a peer-to-peer methodology between Spatial Servers, managed by cloud instance(s), but bound by spatial CONTRACTs stored in a DLT Spatial Domain. Source: 7.2.2.

UDG shall manage slow-changing cross-ledger entities and CONTRACTs on a distributed ledger. Source: 7.2.2.

UDG System may incur latency when achieving consensus. Source: 7.2.2.

UDG shall implement the use cases: 7.4.4, and 7.4.11. Source: 7.4.2.

## A.5. AIS Rating Framework

The AIS Rating Framework Implementation Specification shall meet the following requirements. Each requirement is followed by the clause wherein the requirement appears in the conceptual model.

AIS Rating Framework shall enable ecosystems of intelligence across the Spatial Web which may use [85] to enable levels of multi-scale cognitive computing. Source: 5.2.5.2.

AIS Rating Framework shall define procedures for real-time CREDENTIAL and certification management, based on an AGENT's attributes, capabilities, and relationships. Source: 6.4.2.7.

AIS Rating Framework shall facilitate the dynamic adjustment of AGENT permissions, authorizations, and access based on changes in an AGENT's attributes, operational context, and ACTIVITIES. Source: 6.4.2.7.

AIS Rating Framework should support the integration of a credential and certification management framework that is compatible with different access-control methods and systems, such as attribute-based, relationship-based, or trust-based access-control frameworks. Source: 6.4.2.7.

AIS Rating Framework shall offer flexibility, allowing dynamic interactions among AGENTs with varied capabilities, intelligence, and objectives across a broad spectrum of ACTIVITIES and contexts. Source: 6.4.3.4.

AIS Rating Framework should be interoperable with different encryption frameworks, allowing or restricting AGENT communications and interactions based on their verifiable and certifiable attributes and capabilities. Source: 6.4.3.4.

AIS Rating Framework shall enable governance of AGENT interactions, ensuring safety, reliability, and responsibility, while prioritizing functionality, fairness, transparency, and governance rule adherence, thus creating a trustworthy and efficient Spatial Web ecosystem. Source: 6.4.3.4.

## A.6. Spatial Web Governance

The Spatial Web Governance Recommended Practice shall meet the following requirements. Each requirement is followed by the clause where the requirement appears in the conceptual model.

Spatial Web Governance shall consider the Universal Declaration of Human Rights as established by the United Nations. Source: 5.2.2.2.

Spatial Web Governance shall address societal-technical considerations regarding AI as defined in standards developed by [68] and [64] . Source: 5.2.3.4.2.

Spatial Web Governance shall enable multi-scale cognitive computing and shared intelligence, and may be based on [85]. Source: 5.2.5.2.

Spatial Web Governance shall establish strategic goals and objectives, organizational policies, and performance parameters for governance of the Spatial Web. Source: 5.2.6.2.

Spatial Web Governance shall establish a process to broadly gather stakeholder input regarding polycentric governance of the Spatial Web. Source: 5.2.6.2.

Spatial Web Governance shall address PII, location information, and identity management. Source: 5.2.6.2.

Spatial Web Governance shall include policy guidance for the distributed UDG system. Source: 5.2.6.2.

Spatial Web Governance should implement IEEE Std 7000™-2021. Source: 5.2.6.2.

Spatial Web Governance should implement IEEE Std 7002™-2022. Source: 5.2.6.2.

Spatial Web Governance should implement [63]. Source: 5.2.6.2.

Spatial Web Governance shall monitor emerging laws pertaining to AI and, when applicable to the Spatial Web, observe and comply with those laws. Source: 5.2.6.2.

Spatial Web Governance shall provide decentralized identity management. Source: 5.2.6.2.

Spatial Web Governance shall require a Domain Authority for every Spatial Web Domain Source: 6.3.2.4.

Spatial Web Governance shall enable credentialed Domain Authorities to set the norms and terms under which contracts are created for: AGENT, ACTIVITIES, and CREDENTIALS with a Domain Source: 6.3.2.4.

Spatial Web Governance shall assess the Domain Authority management of a domain using the criteria of Trust, Interoperability, Privacy and Security (TIPS). Source: 6.3.2.4.

Spatial Web Governance shall enable each individual human in the Spatial Web to maintain Self-Sovereign Identity (SSI) Source: 6.3.2.4.

Spatial Web Governance shall enable general categories of things to be publicly owned in perpetuity Source: 6.3.2.4.

Spatial Web Governance shall enable human persons to receive without cost an irrevocable and non-transferable individual Spatial Web Domain at birth Source: 6.3.2.4.

Spatial Web Governance shall enable the Spatial Web to be a Global Commons owned by all living and future humanity Source: 6.3.2.4.

Spatial Web Governance shall enable the stewardship of all Spatial Web assets in trust Source: 6.3.2.4.

Spatial Web Governance shall enable the temporary use rights of Domains to entities for the general benefit of all life. Source: 6.3.2.4.

Spatial Web Governance shall manage a .Earth DOMAIN including a scheme for SWIDs uniquely identifying cells on the surface of the Earth. Source: 6.3.3.4.

Spatial Web Governance shall enable Domains to include digitally mediated rights and permissions regarding who and what is authorized to access the Domain, what content or data is available to view, who may publish and modify content, and who may transact or interact within the space. Source: 6.3.3.4.

Spatial Web Governance shall enable “privacy by design” at all levels. Source: 6.3.4.9.

Spatial Web Governance shall define policies for managing the UDG. Source: 6.3.5.3.

Spatial Web Governance shall define management practices consistent with the UDG as a public utility. Source: 6.3.5.3.

Spatial Web Governance shall foster development of Spatial Web Nodes that provide open and free access to the UDG. Source: 6.3.5.3.

Spatial Web Governance shall enable the Spatial Web Registration Authority to be the Registration Authority for Spatial Web Domains. Source: 6.3.6.3.

Spatial Web Governance shall enable the Spatial Web to be a Global Commons network of networks Source: 6.3.6.3.

Spatial Web Governance shall enable each listing in the UDG to be accompanied by a contract between the central UDG and a registry network administrator Source: 6.3.6.3.

Spatial Web Governance shall accredit Registrars as companies to sell usage rights of Spatial Web Domain name registrations Source: 6.3.6.3.

Spatial Web Governance shall accredit Registries as companies that maintain the database of Spatial Domain names for a particular top-level Spatial Web Domain Source: 6.3.6.3.

Spatial Web Governance shall enable the registry to generate the authoritative address resolution file for converting between Spatial Domain names and Spatial Web addresses Source: 6.3.6.3.

Spatial Web Governance shall enable individuals and organizations a means to provide proof of usage credentials in order to register a Spatial Web Domain Source: 6.3.6.3.

Spatial Web Governance shall define standardized procedures in order to help ensure consistency, reliability, and efficiency in domain registration activities. Source: 6.3.6.3.

Spatial Web Governance shall define a no-fee domain registration option. Source: 6.3.6.3.

Spatial Web Governance shall require the no-fee option for the singular Self-Sovereign Identity of a Person Domain managed by the individual. Source: 6.3.6.3.

Spatial Web Governance shall define procedures and processes for governing autonomous and intelligent AGENTs based on the AIS Rating Framework, to facilitate a trustworthy, interoperable, privacy-preserving, and secure Spatial Web ecosystem. Source: 6.4.2.7.

Spatial Web Governance shall provide a framework for Domain Authorities to define, register, and manage Domain-specific norms and regulations that govern the execution of ACTIVITIES within their respective Domains. Source: 6.4.4.8.

Spatial Web Governance shall define a decentralized identity architecture based around Credentials comprised of: 1) A network steward shall define regulatory standards bodies and establish trust anchors; 2) A standards body shall then define schemas for specific Activities; 3) An issuer shall follow those schemas, assigning identifiers that are written to a registry and provided to individual Credential holders (see 6.3.6); and 3) Credential holders shall then prove those Credentials to a requester-verifier in response to a challenge/opportunity request. Source: 6.5.3.2.

Spatial Web Governance shall define HSML CONTRACT conditions that shall apply to the entire Spatial Web. Source: 6.5.4.5.

Spatial Web Governance shall authorize Domain Authorities to validate (either directly or via an appropriately designated proxy) requests to perform Activities (i.e., Contracts) within a governed Domain. Source: 6.5.5.4.

Spatial Web Governance shall define Domain Authority validation procedures to include the functional equivalent of a Boolean evaluation of whether a given Contract's completion conditions are consistent with allowable states of the Domain model according to Domain rules, which may themselves be encoded as queries on the state of the Domain model, and may include the possession of Credentials by various parties, as well as the registration of Activity types with relevant Domain Authorities (see 6.3.6). Source: 6.5.5.4.

Spatial Web Governance shall help ensure that HSML Activities that occur within the jurisdiction of a Domain Authority, including instances of those Activities (i.e., Contracts), as well as the rules defined by that Authority, shall be evaluated as queries against the state of the relevant HSML Domain model(s). Source: 6.5.5.4.

Spatial Web Governance shall help ensure that Activities and Contracts that enable the definition of abstract normative conditions on Activity execution by Domain Authorities, be automatically applied to Activity performance within governed Domains. Source: 6.5.5.4.

Spatial Web Governance shall help ensure that Activities and Contracts that allow requirements on Activity performance imposed by Domain Authorities to be interoperable with the conditions that define an Activity of a given type, such that more fine-grained Activity types sanctioned by such Authorities can be created automatically or with minimal effort. Source: 6.5.5.4.

## A.7. Domain-specific architectures

All Domain-specific Architecture Specifications shall meet the following requirements. Each requirement is followed by the clause wherein the requirement appears in the conceptual model.

Domain-specific architectures shall be consistent with IEEE Std 2413™-2019. Source: 5.2.3.2.2.

Domain-specific architectures for Smart Cities shall extend the Spatial Web using concepts from IEC SRD 63188. Source: 5.2.4.2.

Domain-specific architectures should reuse existing semantic terms from other domains. Source: 5.2.5.2.

Domain-specific architectures should define governance for their domains consistent with the Spatial Web governance. Source: 5.2.6.2.

Domain-specific architectures shall design identity management that meet the requirements of the domain and are compliant with the Spatial Web system requirements. Source: 5.2.6.2.

Domain-specific architecture specifications shall enable the creation of Domains as containers for Domains. Source: 6.3.2.4.

Domain-specific architectures shall provide a system of distributed, decentralized registries for SWIDs Source: 6.3.3.4.

Domain-specific architectures shall enable objects to be searchable within the Spatial Web Domains in which they are nested. Source: 6.3.3.4.

Domain-specific architectures shall provide methods that allow SWIDs associated with entities involved in transactions to be verified by the issuer of such SWIDs. The Domain-relevant provenance may take the form of historical records or structural validity checks. Source: 6.3.3.4.

Domain-specific architectures shall enable Domains to be defined using Table 3 Source: 6.3.4.9.

Domain-specific architectures shall enable a nested architecture that allows Spatial Web Domains to maintain their intra-relational and inter-relational domain coherence via a Spatial Web sub-Domain Source: 6.3.4.9.

Domain-specific architectures should enable “privacy by design” at all levels Source: 6.3.4.9.

Domain-specific architectures shall enable a publicly accessible UDG that efficiently and accurately models domain relationships. Source: 6.3.5.3.

Domain-specific architectures shall enable Spatial Web entities to be indexed within Spatial Web Domains with the UDG knowledge graph Source: 6.3.5.3.

Domain-specific architectures should provide a basic, open access to domains critical to cross-domain interoperability. Source: 6.3.5.3.

Domain-specific architectures shall implement mechanisms and procedures for handling aberrant component behavior. Source: 6.4.2.7.

Domain-specific mechanisms and procedures shall be specific to the risks associated with the DOMAIN’s applications. Source: 6.4.2.7.

Domain-specific architectures should specify requirements for AGENT response latencies and temporal processing capabilities. Source: 6.4.2.7.

Domain-specific architectures shall provide guidance for how HSML ACTIVITIES are to be performed within acceptable time-frames and meet performance criteria such as response time, throughput, and resource utilization. Source: 6.4.4.8.

Domain-specific architectures shall define guidance for ACTIVITIES to adhere to ethical guidelines and principles, ensuring fairness, transparency, and accountability in their execution. Source: 6.4.4.8.

Domain-specific architectures shall define HSML CONTRACT Contract conditions to be explicitly defined and agreed upon by all relevant parties and shall enable the automatic execution of contracts when such mutually agreed conditions (as encoded in an HSML CONTRACT entity) are reached. Conditions may be represented at the level of granularity required by the situation, as agreed upon by relevant parties. Source: 6.5.4.5.

Domain-specific architectures shall define how CONTRACT evaluation is performed by Domains in as close to real time as possible. Source: 6.5.4.5.

Domain-specific architectures shall be subject to the possession of CREDENTIALS by the parties to the CONTRACT, as specified in condition(s) contained within the relevant ACTIVITY definition. Source: 6.5.4.5.

Domain-specific architectures shall define how Contract evaluation at the edge of the network shall be implemented to optimize performance and transparency such that client and server, edge and cloud, can have a priori parity on contracts and code execution between them. (See clause 7.1.1 for computing nodes and networks.) Source: 6.5.4.5.

Domain-specific architectures shall define how workflows are to be consistently designed across different identities, Domains, and Spaces having necessary permissions, and subsequently chained together to help ensure that trust accrues with every interaction. Source: 6.5.4.5.

Domain-specific architectures shall define how Claims in a Credential to a relevant status or identity may be subject to certification by a third-party testing organization. Source: 6.5.4.5.

Domain-specific architectures may accept verified Credentials as sufficient to provisionally establish that an AGENT is qualified for an Activity. Source: 6.5.4.5.

Domain-specific architectures operating in safety critical operations shall undertake safety design evaluations to help ensure the risk is appropriate for the application. Source: 7.1.3.

Domain-specific architectures shall address the risk of centralization. Source: 7.1.3.

Domain-specific architectures shall be defined using the tiers identified in Figure 30. Source: 7.1.3.

Domain-specific architectures shall encrypt HSTP payloads, controlling access to decryption keys via CREDENTIALs. Source: 7.1.3.

Domain-specific architectures shall use HSTP over the transport layer to provide minimal context required to route requests. Source: 7.1.3.

Domain-specific Spatial Web nodes shall conform to all HSTP and HSML requirements. Source: 7.2.2.

Domain-specific Communications between Spatial Web Nodes shall use HSTP. Source: 7.2.2.

Domain-specific Spatial Web nodes shall interact with the Distributed UDG System. Source: 7.2.2.

Domain-specific Spatial Web clients shall provide spatial transaction ledger functionality. Source: 7.2.2.

Domain-specific Spatial Web servers shall respond to queries with Entities based on identifiers while locating and prioritizing Entities that fit within a specific spatial query, that prioritization is based upon the frustum of the volumetric range query as expressed in an HSTP statement. Source: 7.2.2.

Domain-specific nodes may include Spatial rendering and mapping nodes that render spatial results into simplified views on the server. Source: 7.2.2.

Domain-specific nodes may include Spatial rendering and mapping nodes that use mapping and volumetric media formats which provide a mixture of vector and rasterization mechanisms expanded to 3-dimensional, perspective-correct content types to support streaming media comparable to current video streaming formats. Source: 7.2.2.

Domain-specific architectures shall promote interoperability between diverse ecosystems using Internet standards as defined in IETF's "Internet_Standards" (See "Internet Standards"). Source: 7.3.5.

Domain-specific architectures shall allow the use of multiple payload formats which are commonly used on the Internet. Source: 7.3.5.

Domain-specific architectures shall not constrain implementation internal to Spatial Web. Source: 7.3.5.

Domain-specific architectures shall implement the relevant use cases in 7.4. Source: 7.4.2.

# Annex B
# **(informative)**

## Participants

The list below includes persons who participated in the Spatial Web Foundation Working Group that developed this Specification and who consented to appear on this list.

Mahault Albarracin
Flores Bakker
Scott Carroll
Tom De Block
Bastiaan den Braber
Geert Devos
Jason Fox
Karl Friston
Jacqueline Hynes
Alex Kiefer
Martin Laskowski
Sarah Grace Manski
Dan Mapes
George Percivall
Christine Perey
Capm Petersen
Reese Plews
Maxwell Ramstead
Gabriel René
Dan Richardson
Mikel Salazar
Philippe Sayegh
Prasaanth Sridharan
Toby St Clere Smithe
Alec Tschantz

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## Document contributors

G. Percivall (Lead Editor), S. Carroll, B. den Braber, J. Fox, K. Friston, J. Hynes, A. Kiefer, S. Manski, D. Mapes, C. Perey, C. Petersen, R. Plews, M. Ramstead, G. René, D. Richardson, P. Sayegh, P. Sridharan, T. St Clere Smithe, A. Tschantz

## Spatial Web Foundation leadership

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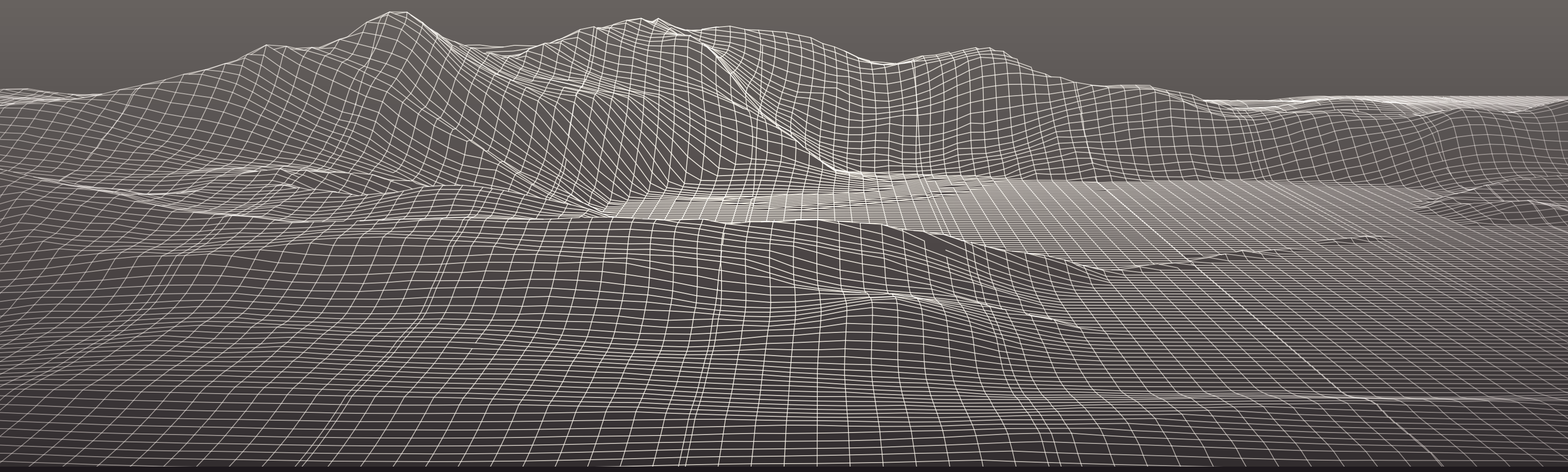

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