SPATIAL WEB
FOUNDATION

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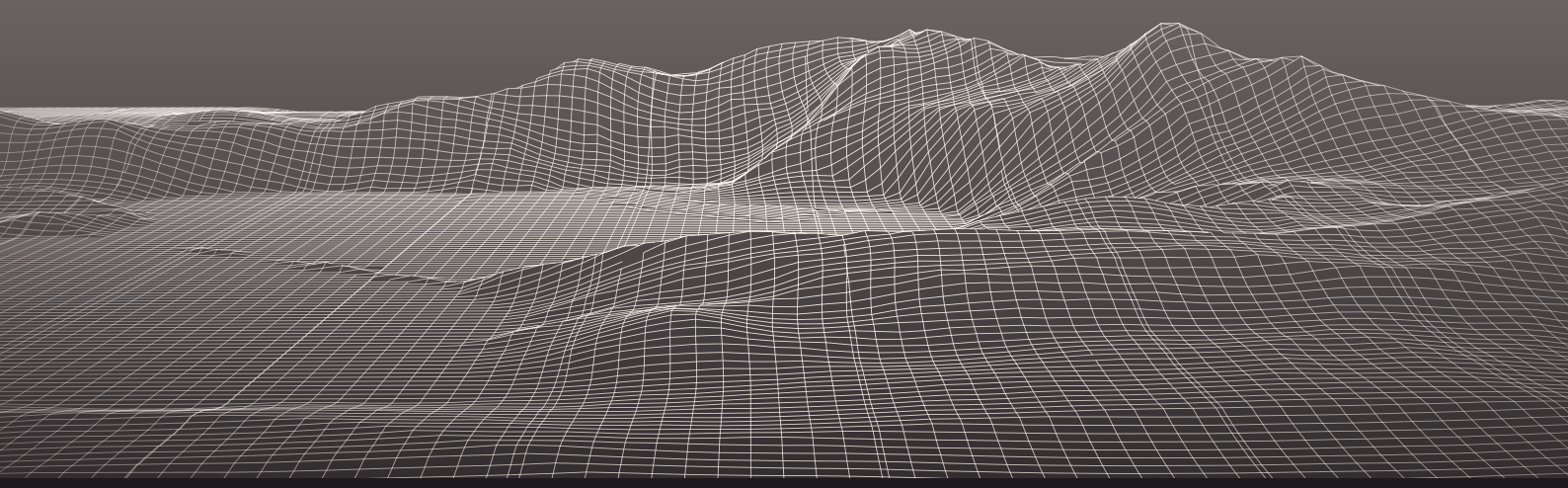
The Spatial Web

Hyperspace Modeling Language (HSML) Implementation Specification

September 26, 2025



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Contents

List of tables

List of figures

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Abstract

The Hyperspace Modeling Language (HSML) Implementation Specification, a core compliance target of IEEE P2874™ Standard for Spatial Web Protocol, Architecture, and Governance, defines a human- and machine-readable semantic modeling language and ontology for the Spatial Web. It establishes a shared vocabulary for Entities, Domains, Agents, Activities, Credentials, Channels, Hyperspaces, and Governance, providing a unifying framework for modeling structure, behavior, and trust.

HSML supports multiple spatial structures through the Hyperspace Module, including topological, metric, vector, cellular, graph, and datatype spaces. These are expressed using well-defined constructs such as points, paths, subspaces, tensor products, and functors, ensuring flexible yet precise representation of spatial and relational contexts.

The specification leverages W3C Semantic Web standards (RDF 1.1/1.2, RDF-star, OWL 2, SHACL, JSON-LD 1.1) to declare formal axioms, constraints, and validation shapes across heterogeneous implementations. It also introduces the Hyperspace Semantic Query Language (HSQL), a query and validation language aligned with SPARQL 1.2 and extended for hyperspace constructs, enabling advanced reasoning over topological, metric, and vector relationships.

Every entity is identified by a Spatial Web Identifier (SWID) conformant with W3C DID Core, embedding DID-compliant documents and referenceable endpoints to provide decentralized identity, provenance, and discoverability.

HSML aligns with the Hyperspatial Transaction Protocol (HSTP) for message encapsulation and activity routing, and with the Universal Domain Graph (UDG) architecture for distributed discovery, linkage, and state management. Together, these enable interoperable, semantically consistent interactions among autonomous agents, digital twins, IoT devices, and distributed services.

As an Implementation Specification, HSML fulfills the compliance requirements of IEEE P2874™/D-3.3.1-2025-03, Annex A, providing the foundation for cross-domain semantic interoperability, verifiable credential exchange, governed contract execution, explainable AI, and secure, zero-trust operations within the global Spatial Web ecosystem.

Introduction

This document specifies the Hyperspace Modeling Language (HSML) Implementation Specification, a core component of the IEEE P2874 Spatial Web Standard. HSML provides the semantic backbone for representing **entities, domains, activities, channels, tools, and digital twins** in a unified framework. It is both human- and machine-readable, designed to ensure semantic precision, governance, and interoperability at web scale.

As envisioned in IEEE P2874™/D-3.3.1-2025-03, the Spatial Web is a globally interoperable socio-technical fabric connecting humans, autonomous systems, and the Internet of Things (IoT). Its purpose is to integrate the digital and physical worlds into a **shared semantic fabric** where information is contextual, interactions are secure, and governance is intrinsic. Realizing this vision requires a data model capable of:

- representing complex, compositional systems;
- supporting automated activities and contracts;
- embedding governance and credentialing;
- enabling explainability and compliance across diverse domains.

HSML fulfills this role by defining a **normative ontology and modeling language** for the Spatial Web. It specifies how entities are identified, how domains declare spatial structure (via hyperspaces), and how activities, permissions, and governance rules are semantically represented. HSML does not itself provide query or transaction mechanisms; these are addressed by complementary specifications such as the **Hyperspace Query Language (HSQL)** and the **Hyperspace Transaction Protocol (HSTP)**. Instead, HSML forms the semantic layer upon which those protocols depend.

> *IMPORTANT*
>
> *IEEE P2874™/D-3.3.1-2025-03 is an approved draft of a proposed IEEE Standard and remains subject to change. This HSML Implementation Specification has been developed to meet the Implementation Specification requirements defined within the IEEE P2874 Draft Standard.*

0.1. Background and Motivation

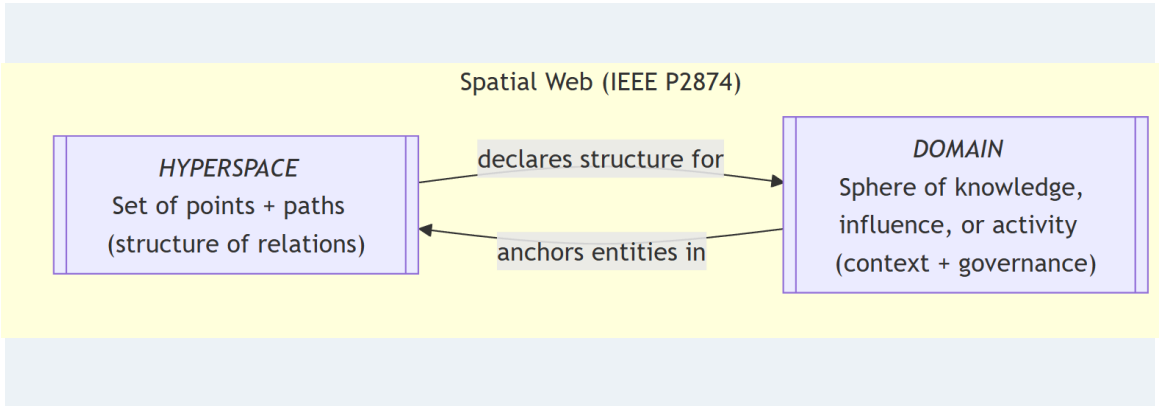
The Spatial Web is built on an integrated framework of **protocol, architecture, and governance**, embodied in the Hyperspace Transaction Protocol (HSTP) and the Hyperspace Modeling Language (HSML). Together these provide the foundation for a **globally interoperable system of systems**, defining how entities are modeled, how transactions are conducted, and how governance is embedded at every layer. IEEE P2874 unifies these elements into a reference model for Spatial Web components, systems, and services.

At the core of this foundation is the concept of **HYPERSPACE**. Formally, a hyperspace is a set of points where, for every ordered pair, there may exist a set of paths between

them, plus an identity path for each point. This abstraction generalizes the notion of "space" beyond geography: points may represent entities, and paths may represent relationships, adjacencies, or transformations. Hyperspace enables the Spatial Web to merge the physical and virtual into a **shared semantic fabric** that transcends national and geographic boundaries. Entities that are physically distant may still be tightly coupled in other dimensions (e.g., logical, organizational, or contextual), allowing new forms of interaction, coordination, and governance.

Complementing **HYPERSPACE** is the concept of **DOMAIN**, defined as a "sphere of knowledge, influence, or activity." Domains provide the semantic scaffolding of the Spatial Web: they anchor identifiable entities, declare the hyperspaces they inhabit, and establish rules of interaction (see Figure 1). Through shared and linkable domain architectures, HSML ensures that entities and their interrelationships can be consistently described, discovered, and governed across contexts.

FIGURE 1: Hyperspace and Domain in the Spatial Web



The development of the Spatial Web is driven by converging technological and societal forces, including:

- The increasingly **graph-like nature of global data**.
- The opportunity for **automation and autonomic activities** enabled by context-aware AI.
- The need for **composable and governable systems** spanning organizations and jurisdictions.
- The requirement for **secure, verifiable transactions**.
- The rise of **machine learning, neural computation, and edge intelligence**, demanding semantic integration.
- The imperative for **explainable AI and robotic governance** to ensure trust and accountability.
- The global proliferation of the **IoT and sensor meshes**, requiring scalable, standards-based models.

Ultimately, the Spatial Web is conceived as a **socio-technical system of systems**. Its realization must address not only technical challenges of modeling, computation, and communication, but also the **social, cultural, ethical, and legal dimensions** of technology use. IEEE P2874™/D-3.3.1-2025-03 is therefore designed as a socio-

technical standard, balancing technical infrastructure with governance frameworks to ensure a secure, interoperable, and human-centered digital-physical reality.

0.2. Relationship to IEEE P2874 (Spatial Web Foundation)

This HSML Implementation Specification is directly derived from and builds upon the IEEE P2874™/D-3.3.1-2025-03 Draft Standard for Spatial Web Protocol, Architecture and Governance, dated March 2025. Material from the Spatial Web Foundation's "Spatial Web Protocol, Architecture and Governance," Version D3.3, copyright © 2025 Spatial Web Foundation, was used with permission as the base for this standard.

As a reference model, the IEEE P2874™/D-3.3.1-2025-03 standard establishes the set of required modules and sub-modules for Spatial Web-compliant implementations, along with their minimum functions and associated information models. It defines requirements for a set of Implementation Specifications, such as this HSML document, and identifies existing technologies and standards to be integrated into these implementations.

0.3. Goals and Benefits of HSML

The overarching purpose of the IEEE P2874™/D-3.3.1-2025-03 standard, and by extension this HSML Implementation Specification, is to provide a holistic and coherent technical framework for implementing a collaborative, interactive Spatial Web and shared world system. HSML is designed as a human- and machine-readable modeling language and semantic data ontology schema that describes objects, relations, actions, activities, and their permissions.

Specifically, HSML aims to achieve the following key goals:

- Spatially Defined Digital Content Fulfillment: Enable a functional layer stack capable of fulfilling spatially defined real-world and virtual requests for digital content while respecting governance authorities and self-sovereign identity.
- Comprehensive Data Ontology: Define a data ontology for describing objects, relationships, and activities, which is foundational for consistent data interpretation.
- Verifiable Credentialing: Specify a verifiable credentialing and certification method for permissioning create, retrieve, update, and delete access to devices, locations, users, and data.
- Automated Contracting: Support a machine- and human-readable contracting language that enables expression and automated execution of legal, financial, and physical commitments, tied to activities and governed by explicit norms and policies.
- Shared Understanding: Facilitate semantic interoperability between humans and AIs by ensuring that contextual meaning, intent, and activity outcomes are represented in a common HSML framework.
- Explainable AI:: Advance AI transparency and accountability by enabling explicit modeling of decision-making processes, conditions, and credentials required for activities.

- Universal Interoperability: Drive interoperability of models, data, and activities to enable cross-domain collaboration across organizations, networks, and geopolitical boundaries.
- Compliance and Governance: Provide the semantic hooks for ensuring compliance with local, regional, national, and international regulatory, ethical, and cultural norms—while maintaining auditability through credential checks and policy evaluation.
- Secure Identity and Authentication: Ensure that identity, privacy, authentication, and transparency are embedded by design, contributing to robust verification of critical activities, agents, and data flows.

Together, these goals ensure that HSML delivers not just a data model, but a governable, interoperable, and trustworthy foundation for the Spatial Web—capable of unifying physical, digital, and agentic domains into a shared semantic fabric.

1. 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.

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2. Terms, definitions and abbreviated terms

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

2.1. Terms and definitions

2.1.1. Activity PREFERRED

A temporally-extended process defined by a set of changes an `agt:Agent` can effect.

An **Activity Schema** provides a template with conditions, parameters, and variables.

An **Activity** (instance) is the execution of such a schema. Activities are central to entity-to-entity execution and state change and may be composed of other Activities.

In HSML, Activity Schemas are expressed in RDF/OWL/SHACL for validation and reasoning.

2.1.2. Agent PREFERRED

An `core:Entity` that senses and responds to its environment, maintains a model of that environment, and performs Activities to achieve goals. Agents communicate using Spatial Web protocols.

2.1.3. Channel PREFERRED

A Spatial Web entity (`comm:Channel`) that groups a stream of HSML entities related to an Activity in a specific context that does not itself warrant a Domain or hierarchy. Channels support ad-hoc coordination, limited-scope data exchange, and contextual search.

2.1.4. Contract PREFERRED

Represents contractual agreements governing transactions. A Contract typically specifies obligations, rights, and conditions for the performance of an HSML Activity. Contracts can be linked to negotiation or execution phases across multiple Domains.

2.1.5. Credential PREFERRED

Represents verifiable claims about an Entity. HSML adopts the W3C Verifiable Credentials model for authentication, authorization, and trust verification. Credentials are used to validate access to protected entities, activities, or domains.

2.1.6. Domain PREFERRED

A central element of the Spatial Web representing any Entity with a persistent identity. Domains are identified by Spatial Web Identifiers (SWIDs). Domains provide a conceptual area to describe reality, declare hyperspaces, and establish rules of interaction. Relationships between Domains are managed in the Universal Domain Graph (UDG).

2.1.7. Domain Authority PREFERRED

A governing authority responsible for the lifecycle and trust model of a Domain, including resolution of its SWID Document and validation of credentials associated with the Domain.

2.1.8. Entity PREFERRED

The base class for all Spatial Web entities (`core:Entity`). Entities with persistent identity are modeled as Domains. All Entities must have an associated SWID.

2.1.9. Holon PREFERRED

A recursive unit of organization within the Spatial Web that is simultaneously a **whole** and a **part**.

2.1.10. Hyperspace PREFERRED

A generalized concept of space, fundamental to the Spatial Web. HSML defines abstract classes for specialized hyperspaces (e.g., TopologicalSpace, MetricSpace, VectorSpace, CellularSpace) that specify relationships among elements of a Domain.

2.1.11. MetricSpace PREFERRED

A specialization of Hyperspace (`metric:MetricSpace`) where relationships between elements are determined by a defined metric (distance or similarity function).

A MetricSpace declares one or more metrics (e.g., Euclidean distance, cosine similarity) that quantify how "close" or "similar" its elements are. MetricSpaces support quantitative operations such as nearest-neighbor search, clustering, threshold filtering, and path cost evaluation. They separate structural representation (the Hyperspace itself) from the semantics of measurement (metrics), enabling consistent and portable evaluation across implementations.

2.1.12. Policy PREFERRED

A set of constraints or rules governing the behavior of Entities, Domains, and Activities. Defined in IEEE P2874™/D-3.3.1-2025-03, Clause 6.6.7, Policies specify permissions, prohibitions, or obligations, expressed declaratively (e.g., SHACL, OWL, SPARQL).

2.1.13. Norm PREFERRED

A socially or organizationally defined expectation governing behavior within a Domain or Activity. Defined in IEEE P2874™/D-3.3.1-2025-03, Norms complement Policies by specifying conventions, standards, or best practices that guide interactions among Entities.

2.1.14. SWID PREFERRED

Spatial Web Identifier. A unique identifier for a Domain. SWIDs conform to the W3C Decentralized Identifier (DID) Core specification. Each SWID resolves to a SWID Document describing endpoints, credentials, and governance.

2.1.15. Time PREFERRED

Represents temporal aspects within the Spatial Web. Time can be attached to Entities, Activities, or Hyperspaces, and is aligned with OWL-Time for temporal reasoning.

2.1.16. TopologicalSpace PREFERRED

A specialization of Hyperspace (`topo:TopologicalSpace`) where relationships are defined by **adjacency, neighborhoods, and continuity**, independent of numeric distance. TopologicalSpaces describe how elements are connected (e.g., graph structures, cellular complexes, networks) and which subsets are considered "open." They enable reasoning about connectivity, boundaries, regions, and continuity, making them suitable for domains such as graphs, GIS geometries, cellular automata, and process flows. HSML allows both standard classes (e.g., Region, Boundary) and custom topology definitions by extending the TopologicalSpace model.

2.1.17. UDG (Universal Domain Graph) PREFERRED

A distributed metagraph containing relationships between all known Domains and Entities in the Spatial Web. The UDG provides routing, discovery, and contextual metadata.

2.1.18. UDG Context PREFERRED

Metadata about a Domain's position in the UDG, including its SWID, known neighbor SWIDs, and spatial or routing hints.

Note 1 to entry: In HSML, only the semantic entities (Activity, Domain, Agent, Channel, Contract, Credential, Hyperspace, SWID, UDG, etc.) are normative. This section is under development and will be expanded in future drafts.

2.2. Abbreviated terms

DID	Decentralized Identifier
HSTP	Hyperspace Transaction Protocol
HTTP	Hypertext Transfer Protocol
JSON-LD	JSON for Linked Data
OWL	Web Ontology Language
SHACL	Shapes Constraint Language
SPARQL	SPARQL Protocol and RDF Query Language
SWID	Spatial Web Identifier
UDG	Universal Domain Graph
VC	Verifiable Credential

3. Participants

3.1. Working group

Contributors to this specification are listed on the back cover.

4. Overview

This document provides a high-level overview of the Hyperspace Modeling Language (HSML) specification. HSML is the **semantic foundation of the Spatial Web**, enabling consistent representation of entities, domains, activities, spaces, and governance across distributed systems. It describes the modeling paradigm, guiding principles, modular structure, and formal extension mechanisms needed to support diverse domains while ensuring interoperability and compliance with IEEE P2874™/D-3.3.1-2025-03.

4.1. HSML Modeling Paradigm

The Spatial Web is founded on eight interdependent dimensions that, together, distinguish it from the conventional Semantic Web. HSML integrates these dimensions into a coherent modeling paradigm.

- **Entities:** The fundamental units of description in the Spatial Web. Every entity is globally identifiable by a Spatial Web Identifier (SWID) that conforms to W3C Decentralized Identifier (DID) syntax. Unlike Linked Data URIs, which depend on centralized DNS resolution, SWIDs are cryptographically verifiable, self-sovereign, and portable across networks. This guarantees persistence of reference and enables interoperable interactions across distributed systems.
- **Domains:** A specialized kind of entity that functions as a holon — a self-contained whole that is also part of larger systems. A domain defines a "sphere of knowledge, influence, or activity" in which governance rules apply. Examples include agents, persons, organizations, places, and things. Domains carry identity, enforce norms, and govern activities within their scope. Domains naturally form **holarchies**, where they can be linked through ad hoc memberships, component-of relations, or aggregation into more complex structures.
- **Hyperspace:** The structural layer that defines how entities in a domain relate spatially or structurally. Hyperspaces generalize the notion of "space" beyond geography, encompassing topological, metric, vector, cellular, or graph-based structures. A domain may be bound to one or more hyperspaces, which define adjacency, connectivity, and distance among its entities. This allows HSML to uniformly represent physical, logical, and abstract spatial structures.
- **Semantics:** Every element and relationship in HSML has a well-defined, machine-readable meaning. By adopting RDF, OWL, and SHACL, HSML ensures that data is not just syntactically structured but also contextually understood. This enables reasoning, validation, and interoperability across heterogeneous systems. Semantics provide the interpretive layer that makes entities discoverable, explainable, and governable.
- **Distributed Graph Structure:** The Spatial Web is organized as a **distributed semantic hypergraph**. Entities and domains form the nodes, and their relationships form semantically typed edges (e.g., `isLocatedAt`, `isOwnedBy`, `performsActivity`). This distributed graph spans multiple domains and infrastructures, enabling global interconnection without centralized control. The

hypergraph model supports complex, multi-dimensional queries and compositional reasoning across contexts.

- Identity and Trust: Trust is not an external service but intrinsic to the model. Every entity's SWID is a DID, which anchors it in a decentralized identity framework. Verifiable Credentials (VCs) provide attestations about entities or domains, while Zero-Knowledge Proofs (ZKPs) allow selective disclosure of credentials for privacy-preserving validation. This creates a built-in trust layer, ensuring authentication, authorization, and provenance are verifiable across domains without reliance on centralized authorities.
- Activities: Activities are first-class entities that capture dynamic processes and state changes. They can be defined abstractly as schemas (with pre- and post-conditions) or realized as specific instances with execution states. Activities link agents, tools, and things, providing the means by which goals are pursued and domains interact. Modeling activities explicitly makes the Spatial Web executable, supporting workflows, coordination, and monitoring.
- Governance: The Spatial Web is not only technical but also social and ethical. Governance encompasses the rules, norms, contracts, and policies that domains declare and enforce. Governance by design ensures that interactions are not merely possible but accountable, lawful, and ethical. HSML provides formal hooks for embedding governance into domains, so that compliance, trust, and fairness are enforced natively rather than retrofitted.

4.2. Design Principles for HSML Implementation

The implementation of HSML is guided by design principles that ensure the specification is robust, adaptable, and widely reusable. These principles extend the modeling paradigm into practical rules for ontology engineering and system interoperability.

- Composability: HSML models are built from smaller, reusable units. Domains, activities, and hyperspaces are defined as modular components that can be assembled into larger systems. This allows complex applications to be constructed dynamically from standardized parts without redundancy.
- Interoperability: HSML provides a shared semantic layer that ensures systems developed by different organizations can interact without ambiguity. Interoperability extends beyond syntax to include identity, provenance, and trust by binding every entity to a SWID/DID.
- Leverage Existing Standards: HSML reuses existing standards wherever possible (RDF, OWL, SHACL, W3C DID/VC, GeoSPARQL, WoT, SAREF). By aligning with mature specifications, HSML avoids reinvention, accelerates adoption, and maintains compatibility with broader ecosystems.
- Extensibility: HSML anticipates evolving needs. Formal mechanisms such as profiles, custom schemas, and module extensions allow new data types, relationships, and governance models to be introduced without breaking backward compatibility. This ensures adaptability across industries and use cases.

- **Modularity and Minimal Ontological Commitment:** HSML is structured into **independent modules**, each addressing a specific functional concern (e.g., Agents, Activities, Hyperspaces, Channels, Governance). Each module makes only the minimal ontological commitments necessary for interoperability, avoiding prescriptive domain-specific assumptions. This maximizes flexibility, lowers barriers to adoption, and supports **plug-and-play reusability**.
- **Governance by Design:** Governance is intrinsic to the model, not an external layer. Domains can declare rules, norms, contracts, and policies as part of their identity and scope. This ensures compliance, accountability, and fairness are enforceable at the semantic level.
- **Decentralized Trust by Design:** Trust is anchored in decentralized identifiers (DIDs), verifiable credentials (VCs), and zero-knowledge proofs (ZKPs). This creates a built-in trust fabric where identity, authentication, and authorization are portable and verifiable across domains, without reliance on centralized authorities.
- **Holonic Organization:** Domains act as holons, enabling both autonomy and integration. Holarchies allow domains to be nested or linked in multiple ways — through membership, composition, or aggregation — ensuring scalability and resilience in distributed environments.
- **Separation of Concerns:** HSML distinguishes clearly between **entities** (what exists), **hyperspaces** (how things relate), **activities** (what happens), and **governance** (how things are regulated). This modularity ensures each dimension can evolve independently while remaining semantically aligned.
- **Validation and Assurance:** HSML employs SHACL shapes and OWL constraints to enforce structural and semantic consistency. Validation is a first-class concern, guaranteeing that data exchanged across domains is coherent, trustworthy, and policy-compliant.
- **Explainability and Reasoning:** HSML ensures that all relationships are explicit and machine-interpretable, enabling semantic reasoning and explainable AI. Agents and systems can not only act but also justify their actions against declared norms, goals, and rules, supporting transparency and accountability.

4.3. Core Model and Modules

To manage complexity and support broad adoption, the HSML specification is organized into a **Core Model** and a set of **modular extensions**. This modular design ensures maximum reusability with minimal ontological commitment, allowing implementers to adopt only the components relevant to their application while maintaining interoperability across the Spatial Web.

- **Core Model:** The Core Model defines the most fundamental and universal constructs of HSML. It establishes:
  - **Entity** – the universal superclass for all things in the Spatial Web, each identified by a Spatial Web Identifier (SWID/DID).

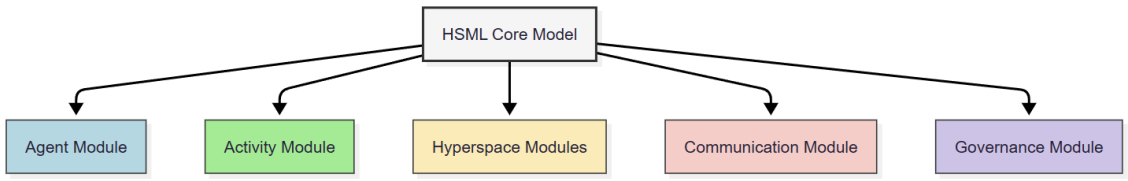
- Domain – a specialized kind of entity functioning as a holon, encapsulating identity, governance, and scope.
- Foundational relationships – common properties for identity, membership, composition, and linkage across entities and domains.

The Core Model is the **semantic foundation** upon which all other modules are built.

- **Modules:** Building on the Core Model, HSML defines a set of modules that introduce specialized constructs for particular functional areas. Each module adds only the minimum commitments necessary to support its scope, ensuring extensibility and reuse:
  - Agent Module – defines persons, organizations, and autonomous systems as domains with agency, goals, and capabilities.
  - Activity Module – defines structured processes, schemas, instances, and execution lifecycles that domains can perform.
  - Hyperspace Module – defines the spatial and structural contexts where entities relate.
    - The Hyperspace Module is itself **composed of submodules** for different space types: **Topological Space**, **Metric Space**, **Vector Space**, **Cellular Space**, **Graph Space**, and **Datatype Space**.
  - Communication Module – defines **Channels** as the semantic construct for communication and coordination.
    - A Channel is a stream of HSML entities bound to a specific Activity, enabling message exchange, data flow, and coordination among participants.
    - Channels are **transient**: unlike Domains, they do not carry persistent holonic identity but exist in relation to an Activity context.
    - The module provides constructs for sub-channels, membership, and message traceability, aligning with HSTP message envelopes for interoperable communication.
  - Governance Module – defines credentials, contracts, norms, and policies that domains declare and enforce.

This modular architecture enables **plug-and-play deployment**: implementers can select the subset of modules required for their application, while remaining compatible with the broader HSML ecosystem and the IEEE P2874™/D-3.3.1-2025-03 Spatial Web standard (see Figure 2).

FIGURE 2: HSML Core Model and Modules with Hyperspace Submodules



4.4. Extension Mechanisms

Recognizing that no single specification can anticipate all future needs, HSML provides formal mechanisms for extension. These ensure that the language can evolve and adapt to new technologies, industries, and governance requirements without breaking compatibility with the Core Model.

- Profiles: A profile is a curated collection of HSML modules, constraints, and optional extensions tailored for a particular application or industry. Profiles act as vertical specializations while remaining grounded in the common HSML core.

  EXAMPLE 1: A Smart Mobility Profile may combine the Agent, Activity, and Hyperspace modules with a custom Transportation schema to support autonomous vehicle networks.

  EXAMPLE 2: A Digital Health Profile may combine the Governance module with domain-specific ontologies for medical credentials, ensuring trust and compliance.

  Profiles promote interoperability by establishing shared constraints within a sector, while still ensuring cross-domain compatibility through the HSML foundation.
- Custom Schemas: For more granular or domain-specific needs, developers may define custom schemas by reusing Semantic Web standards:
  - OWL 2 for declaring new types of entities, domains, properties, and relationships.
  - SHACL for defining constraints, validation rules, and profiles that data instances must satisfy.
  - RDF-star and SHACL rules for expressing richer link types (e.g., weighted, temporal, or probabilistic edges).

  These schemas can be registered, published, and shared across domains, allowing the Spatial Web ontology to grow organically while preserving coherence.
- Hyperspace Extensions: The Hyperspace Module is intentionally open-ended. In addition to its current submodules (Topological, Metric, Vector, Cellular, Graph,

and Datatype Spaces), P2874 anticipates other space types that can be added as extensions. Examples include:

- Probabilistic Spaces – where paths carry uncertainty or probability weights, supporting stochastic modeling.
- State-Machine Spaces – where points represent states and paths represent transitions, aligning with process or workflow modeling.
- Observation/Data-Cube Spaces – treating multi-dimensional data (e.g., sensor arrays, statistical cubes) as hyperspaces.
- Quantum or Hilbert Spaces – supporting future quantum computation or simulation domains.

New types can be introduced simply by declaring subclasses of `hspace:Hyperspace`, ensuring extensibility without changes to the Core Model.

- Governance Extensions: Governance models vary across cultures and industries. HSML allows the definition of new contract forms, policy languages, and credential profiles. For example, a financial domain might introduce a RegulatoryComplianceProfile requiring specific verifiable credentials, while a social domain might define an EthicsProfile for AI agent behavior.
- Modularity and Minimal Commitment: All extensions follow the principle of minimal ontological commitment. Modules and schemas introduce only the constructs strictly necessary for their scope, ensuring that extensions remain lightweight, reusable, and composable. This preserves interoperability across domains and minimizes barriers to adoption.

This extension framework ensures that HSML can evolve alongside the Spatial Web: supporting innovation while maintaining stability, trust, and semantic coherence.

5. Conventions and Notation

5.1. URI and IRI Conventions

This specification uses IRIs for identifying HSML modules, classes, and properties. All HSML terms are defined under a single base namespace:

FIGURE 3

```
https://www.spatialwebfoundation.org/ns/hsml
```

HSML is modular: each module (Activity, Agent, Domain, Hyperspace, Policy, etc.) defines its own sub-namespace under this base. This hierarchy ensures that all HSML identifiers are globally unique, discoverable, and traceable to the Spatial Web Foundation. Submodules of Hyperspace (e.g., Metric, Topological, Vector, Cellular) extend `hspace:` with their own namespaces.

5.1.1. HSML Normative Namespaces

All HSML modules share the common base namespace:

FIGURE 4

```
https://www.spatialwebfoundation.org/ns/hsml
```

Each module extends this base by declaring its own sub-namespace. Hyperspace modules form a hierarchy: `hyperspace` is the root, and its specializations (`metric`, `topo`, `vector`, `cell`,...) extend from it.

TABLE 1: HSML Normative Namespaces

Prefix	Namespace IRI	Module
`core`	`https://www.spatialwebfoundation.org/ns/hsml/core#`	HSML Core
`agent`	`https://www.spatialwebfoundation.org/ns/hsml/agent#`	Agent Module
`act`	`https://www.spatialwebfoundation.org/ns/hsml/activity#`	Activity Module
`gov`	`https://www.spatialwebfoundation.org/ns/hsml/gov#`	Governance Module
`comm`	`https://www.spatialwebfoundation.org/ns/hsml/comm#`	Communication Module
`hspace`	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace#`	Hyperspace Core
`metric`	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace/metric#`	MetricSpace Submodule
`topo`	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace/topo#`	TopologicalSpace Submodule
`vector`	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace/vector#`	VectorSpace Submodule
`cell`	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace/cell#`	CellularSpace Submodule

5.1.2. External Referenced Namespaces

TABLE 2: External Referenced Namespaces

Prefix	Namespace IRI	Source
dct	http://purl.org/dc/terms/	DCMI Metadata Terms
foaf	http://xmlns.com/foaf/0.1/	FOAF
gsp	http://www.opengis.net/ont/geosparql#	OGC 22-047r1
org	http://www.w3c.org/ns/org#	W3C vocab-org
prov	http://www.w3.org/ns/prov#	W3C prov-dm
rdf	http://www.w3.org/1999/02/22-rdf-syntax-ns#	W3C rdf-syntax-grammar
rdfs	http://www.w3.org/2000/01/rdf-schema#	W3C rdf-schema
schema	http://schema.org/	Schema.org
sh	http://www.w3.org/ns/shacl#	W3C REC-shacl-20170720
skos	http://www.w3.org/2004/02/skos/core#	skos-reference
owl	http://www.w3.org/2002/07/owl#	W3C owl2-conformance
xsd	http://www.w3.org/2001/XMLSchema#	W3C xmlschema11-1
vc	https://www.w3.org/2018/credentials#	W3C REC-vc-data-model-20220303

5.2. RDF/Turtle Syntax Conventions

RDF examples in this specification use Turtle syntax W3C WD-rdf12-turtle-20250820.

The following conventions apply:

- All examples assume the namespace prefixes defined in 5.1.1 and 5.1.2.
- If a prefix is used in an example but not explicitly declared, it SHALL be interpreted as belonging to one of those normative tables.
- Example fragments are illustrative and *non-normative unless explicitly marked as normative.
- Literals use standard `xsd:` datatypes (e.g., `xsd:string`, `xsd:integer`, `xsd:dateTime`).
- Persistent identifiers (e.g., SWIDs) are preferred over blank nodes.
- Compact IRIs (CURIEs) are used when a prefix is declared.

EXAMPLE — Example Turtle syntax

```
did:swd:smarthome123:activity:1 a activity:Activity ;
    core:swid "did:swd:smarthome123:activity:1" ;
    act:activitySchema :TurnOnLight ;
    act:hasStatus "running"^^xsd:string .
```

5.3. JSON-LD Syntax Conventions

HSML entities, activities, and governance artifacts shall be serializable into JSON-LD W3C json-ld11.

For the sake of simplicity and consistency, HSML defines a single canonical JSON-LD context that covers all modules:

FIGURE 5

```
https://www.spatialwebfoundation.org/ns/hsml/context.
jsonld
```

This context performs the following functions:

- Provides prefix mappings for all HSML modules (`core`, `agent`, `activity`, `gov`, `comm`, `hspace`, `metric`, `topo`, `vector`, `cell`).
- Maps each HSML class IRI and property IRI to a simplified JSON key, corresponding to the "JSON name" column defined in the normative tables of this specification.
- Enables JSON developers to work with compact, human-readable field names while ensuring full semantic traceability to IRIs.
- Profiles and extensions MAY extend the canonical context with additional mappings.

EXAMPLE 1 — Example mapping excerpt (informative)

```
{
  "@context": {
    "core": "https://www.spatialwebfoundation.org/ns/hsml/core#",
    "act": "https://www.spatialwebfoundation.org/ns/hsml/activity#",
    "agent": "https://www.spatialwebfoundation.org/ns/hsml/agent#",
    "schema": "http://schema.org/",
    "dct": "http://purl.org/dc/terms/",
    "type": "@type",
    "swid": "core:swid",
    "name": "schema:name",
    "description": "schema:description"
    "Activity": "act:Activity",
    "Ongoing": "act:Ongoing",
    "activitySchema": "act:activitySchema",
    "hasStatus": "act:hasStatus"
    ....
   }
```

```
}
```

EXAMPLE 2 — Example instance

```
{
  "@context": "https://www.spatialwebfoundation.org/ns/hsml/context.
jsonld",
  "id": "did:swid:smarthome123:activity:1",
  "@id": "did:swid:smarthome123:activity:1",
  "@type": "Activity",
  "swid": "did:swd:smarthome123:activity:1",
  "activitySchema": "did:swd:smarthome123:schemas:TurnOnLight",
  "hasStatus": "Ongoing",
  "name": "Turn on light",
  "description": "Switches on the living room light"
}
```

5.4. SHACL Shape Syntax and Annotations

Validation in HSML is expressed using SHACL shapes W3C REC-shacl-20170720. The following conventions apply:

- Shapes are defined in Turtle syntax with the `sh:` namespace.
- If prefixes appear in a SHACL example without being explicitly declared, they SHALL be interpreted using the mappings in 5.1.1 or 5.1.2.
- NodeShapes target specific HSML classes (e.g., `activity:Activity`).
- Property shapes specify expected predicates, datatypes, or cardinality constraints.
- HSML-specific annotations may extend SHACL for Activity schemas.
- Shapes may serve as Activity payload templates, validating inputs and outputs.

EXAMPLE — Example SHACL shape

```
:TurnOnLightShape a sh:NodeShape ;
    sh:targetClass act:Activity ;
    sh:property [
        sh:path act:hasStatus ;
        sh:datatype xsd:string ;
        sh:in (act:Planned, act:Ongoing, act:Completed`, act:Failed)
 ;
        sh:minCount 1 ;
        sh:maxCount 1 ;
] .
```

6. The HSML Modeling Paradigm: Holons, Semantics, and Extensions

The Hyperspace Modeling Language (HSML) is meticulously designed around a set of core entities, with a pivotal emphasis on the "Domain" as a holonic entity, capable of containing and being contained within other Domains, forming a holonic graph. This inherent design choice is crucial for representing the intricate and interconnected real-world and virtual systems that comprise the Spatial Web. Within this framework, every entity inherently exists within a Domain.

The central question then becomes: what modeling language formalisms are necessary to achieve this complex representation, particularly given the holonic nature of Domains?

6.1. The Imperative for Semantics and the Semantic Web Stack

A strong semantic foundation is indispensable for HSML due to the inherent complexity and interoperability requirements of the Spatial Web. The Spatial Web aims to create interoperable, semantically compatible connections between network-connected hardware and software. Digital content in the Spatial Web is designed to be respectful of governance authorities and self-sovereign identity. This necessitates a shared understanding of meaning and context, not just between humans, but also between humans and Artificial Intelligence (AI) systems. Semantics allow for AI systems to have explainability, by explicitly modeling their decision-making processes, and for interoperability of models and data across organizations, networks, and borders.

The Semantic Web stack, utilizing technologies like Resource Description Framework (RDF), Web Ontology Language (OWL), SPARQL Protocol and RDF Query Language (SPARQL), and Shapes Constraint Language (SHACL), is the preferred modeling language formalism for HSML over a purely Labeled Property Graph (LPG) approach. The Semantic Web stack natively supports:

- Ontologies (OWL): OWL provides a rich set of constructs to define classes, properties, and complex relationships, enabling rigorous semantic modeling. This goes beyond simple key-value pairs, allowing for the expression of transitivity, symmetry, inversions, and other logical inferences crucial for reasoning about interconnected Domains and their behaviors.
- Linked Data (RDF): RDF allows for the creation of a "web of data" where entities are identified by URIs and described through triples. This inherently distributed nature aligns with the Spatial Web's decentralized vision and the Universal Domain Graph (UDG) as a distributed hypergraph.
- Querying Capabilities (SPARQL): SPARQL enables complex queries over distributed RDF data, allowing for sophisticated retrieval of information across interconnected Domains based on their semantic relationships, not just their direct links.
- Validation and Constraints (SHACL): SHACL provides a mechanism to define structural constraints on RDF graphs. This is critical for ensuring data quality,

consistency, and adherence to the defined ontology, thereby enforcing the rules and relationships necessary for a coherent holonic graph structure.

While LPGs are excellent for representing graph structures, their primary strength lies in their flexible schema and efficient traversal of direct relationships. However, they typically lack the inherent semantic expressiveness and formal reasoning capabilities that OWL provides, which are critical for defining nuanced relationships (like mereology for nested domains) and enforcing complex constraints needed for a governed Spatial Web. The document emphasizes the need for a shared, linkable knowledge domain architecture and a common language to describe interrelationships, which is precisely what the Semantic Web stack offers through its formal semantics and established standards for knowledge representation.

6.2. Limitations of Existing Standards in Accommodating Holonic Graphs Out of the Box

While the RDF model provides a flexible foundation for representing interconnected data as a graph of triples, certain aspects of its core design present challenges when attempting to natively accommodate holonic structures "out of the box." The concept of a holon, being both a whole and a part simultaneously, and possessing internal properties and governance while also participating in larger wholes, requires more nuanced modeling than basic triples can directly offer.

Here's what's missing in the foundational RDF model to fully accommodate holons, and how extensions like RDF-star, Named Graphs, and the concept of "ad-hoc relations" (as hinted at in RDF-H) attempt to address these gaps:

- Lack of Native Holonic Representation: Many graph databases and modeling languages, including traditional property graphs, primarily focus on explicit, pairwise relationships between nodes. While nesting can be *simulated* through parent-child relationships, they often lack built-in mechanisms to enforce the inherent properties of holons, where the whole is more than the sum of its parts, and parts maintain a degree of autonomy within the whole. The concept of a "Domain" as a self-contained entity that also participates as a part of a larger Domain, while retaining its own internal governance, is not a first-class citizen in many existing models. The document describes Domains as able to contain other Spatial Web Domains and that they are "partially or entirely within other Spatial Web Domains; fully or semi-nested and connected geophysical locations or logical structures".
- Limited Semantic Expressiveness for Complex Relationships: In a pure RDF model, a relationship (a predicate in a triple) is a simple link. It's difficult to attach metadata or properties to the relationship itself. For a holonic structure, the relationship between a "parent" holon and its "child" holon isn't just a simple `hasPart` link. This `hasPart` relationship might have properties like:
  - `startDate` (when the child became a part of the parent)
  - `authority` (which Domain Authority sanctioned this part-whole relationship)
  - `typeOfContainment` (e.g., physical, conceptual, administrative)

  - `permissionGranted` (specific permissions granted to the child within the parent's context)

Standard RDF reification (using `rdf:Statement`, `rdf:subject`, `rdf:predicate`, `rdf:object`) is verbose and can complicate querying. While some standards allow for typed relationships, they may not offer the rich ontological constructs found in OWL to define the *nature* of these relationships (e.g., mereological relations like `hasPart` or `isContainedIn` with their implied transitivity) or to reason over them abstractly. The document explicitly mentions drawing on ideas from mereology (the theory of parthood relations) and order theory, which are better supported by formal ontologies than by typical graph database schemas.

- Bounded Contexts and Graph Partitioning: A core aspect of holons is that they represent "bounded contexts" where internal rules and properties might apply differently than externally. While RDF allows for arbitrary connections, it doesn't inherently provide a mechanism to delineate distinct "sub-graphs" that represent the internal state or perspective of a holon. This makes it challenging to:
  - Manage Scope and Identity within a Holon: How do you say that a particular triple applies **only** within the context of a specific `CityDomain` holon, and not globally?
  - Enforce Internal Governance: If a `BuildingDomain` is a holon within a `CityDomain`, its internal operations might have specific rules. RDF alone doesn't provide direct support for these encapsulated rule sets.
- Focus on Specific Domains, Not Universal Interoperability: Many existing standards are highly optimized for specific domains (e.g., geographic information systems, IoT device models). While they provide excellent local solutions, they often struggle to achieve universal interoperability and semantic compatibility across vastly different domains, especially when considering non-physical dimensions or abstract concepts. The Spatial Web's requirement for a "universal domain graph" and its extension of "geography to hyperspace" highlights this gap.
- Governance and Identity Models Not Inherently Integrated: Existing graph standards often separate the data model from governance, identity, and access control mechanisms. The Spatial Web, however, integrates concepts like Domain Authorities, verifiable credentials, and self-sovereign identity directly into its core design, influencing how entities interact and how data is accessed and managed within Domains. This deep integration of governance, especially polycentric governance, with the data model is not an out-of-the-box feature of many current graph standards.
- Dynamic and Adaptive Relationships: The Spatial Web acknowledges that relationships can be dynamic and adaptive. While graph databases can update relationships, the formalisms to reason about *changes* in relationships or to model adaptive systems at an ontological level are more aligned with advanced semantic web capabilities.

How Extensions and Concepts Address These Gaps:

- RDF-star (RDF*): RDF-star directly addresses the limitation of expressing properties about statements. It introduces a concise syntax to assert triples *about* other triples (nested triples).
  - For Holons: This is invaluable for modeling holonic relationships. Instead of cumbersome reification, one could directly state `<< :CityA rdfh:hasPart :BuildingB >> schema:startDate "2023-01-01"^^xsd:date .` This allows the precise capture of metadata (like creation date, governing authority, or specific permissions) directly on the part-whole relationship between holonic Domains. It makes the model of a holon's internal composition much richer and more governable.
- Named Graphs: Named Graphs extend RDF by allowing a collection of triples to be identified by a URI (its "name" or context). This effectively partitions the RDF graph into distinct sub-graphs.
  - For Holons: Named Graphs are crucial for representing the "bounded contexts" of holons. Each holon (e.g., a `BuildingDomain` or `OrganizationDomain`) could be associated with its own Named Graph. This allows for:
  - Scoped Assertions: Triples asserted within a building's Named Graph would pertain specifically to that building's internal state, personnel, or operations, without polluting the global graph.
  - Contextual Queries: Queries can be made against specific Named Graphs, enabling retrieval of information relevant to a particular holon's internal context.
  - Access Control: Access permissions could be managed at the Named Graph level, dictating who can read or write triples within a specific holon's representation, aligning with Domain Authority concepts.
- "Ad-Hoc Relations" (drawing from RDF-H principles): In the dynamic and decentralized environment of a holonic graph like the Spatial Web, not all relationships between entities or domains are permanent, universally defined, or strictly dictated by a pre-existing, rigid schema. This is where the concept of "ad-hoc relations" becomes particularly relevant. These relations are emergent, contextual, and flexible, arising dynamically from the interactions or needs of specific entities or agents. For instance, a temporary collaboration between two geographically distant research `ConceptDomain`s might lead to a unique `"collaboratesOnProjectX" link that isn't part of the standard `rdfh:isRelatedTo` hierarchy. Holons' autonomy and interdependence necessitate these:
  - Internal Self-Organization: A `ProjectDomain` (a holon) might dynamically create temporary "taskDependency" relations between its internal `Activity` entities for a specific project phase, which are only relevant within that `ProjectDomain`.
  - Inter-Holon Collaboration: When two distinct `OrganizationDomain` holons form a joint venture, they might establish temporary `jointlyManagesResource` relations that exist only for the duration of that venture.
  - Domain Authority Assertions: A `DomainAuthority` (itself a holonic `Agent`) might assert an `administrativeLink` between two otherwise unconnected

sub-domains under its governance for a specific, temporary administrative purpose, such as a localized energy distribution optimization project within a larger `UrbanDigitalTwinDomain`. This link isn't a fundamental, ontological `isChildOf` relation, but an operational one.

To handle "Ad-Hoc Relations" within HSML's Semantic Web Stack:

- Dynamic Predicate Creation and Registration: New predicates (URIs for relations) could be generated and "registered" on the fly, perhaps within a specific Domain's context or by a Domain Authority. This implies a lightweight mechanism for declaring the *intent* or *scope* of these new predicates.
- Higher-Order Logic/Reasoning (OWL & SHACL): Even if specific ad-hoc predicates are dynamic, OWL can define broader patterns or categories for these relations (e.g., an `owl:Class` called `ex:TemporaryAdministrativeLink`). SHACL can then constrain the properties of these ad-hoc relations, ensuring data quality and consistency even for emergent links.
- Provenance of Relationships (RDF-star): Using RDF-star, the assertion of an "ad-hoc relation" itself can be treated as a statement with its own metadata. This allows the Spatial Web to precisely record who asserted this temporary relation, when, why, and for how long it is considered valid. This provenance is critical for auditability and maintaining trust in a decentralized, dynamic environment where relationships aren't always static.

In essence, while existing graph technologies provide foundational capabilities, the unique blend of holonic structures, multi-dimensional hyperspaces, and integrated governance within the Spatial Web necessitates a more semantically rich and extensible modeling language formalism. The Semantic Web stack provides the necessary expressiveness and extensibility to fully realize the vision of a truly holonic and interconnected Spatial Web.

7. HSML Core Module

7.1. Architectural Principles and Design Rationale

This clause describes the key architectural principles that underpin the Hyperspace Modelling Language (HSML) Core Module. This module provides the foundational concepts upon which all other HSML modules are built. Understanding this rationale is not required for conformance but is highly recommended for a robust and correct implementation, as it clarifies the intent behind the normative rules specified in subsequent clauses.

7.1.1. The Universal Foundation: core:Entity

The cornerstone of the HSML ontology is the `core:Entity` class, which serves as the universal root for every object, agent, and concept within the Spatial Web. This abstract class embodies the principle that everything which "is perceived, known, or inferred to exist" can be represented and managed within a single, coherent framework. By establishing `core:Entity` as the ultimate superclass, the standard ensures that all HSML-compliant software can uniformly ingest, validate, and manipulate heterogeneous constructs. This polymorphic foundation is the key to the semantic interoperability and extensibility mandated by IEEE P2874™/D-3.3.1-2025-03.

7.1.2. Decentralized Identity: The Spatial Web Identifier (SWID)

A core principle of the Spatial Web is that every core:Entity SHALL be uniquely identified by a Spatial Web Identifier (SWID). This is enforced via the core:swid property. The modeling of this identifier is a critical design choice.

The core:swid property SHALL contain a W3C Decentralized Identifier (DID) conformant URI. This value is modeled as a literal of type xsd:anyURI, not as a link to another resource. This ensures the SWID is a verifiable attribute of the entity.

More importantly, this design establishes a fundamental separation of concerns between the identifier for an entity and the identifier for its description.

core:swid (The "Thing"): This property identifies the entity itself—the person, device, or concept—independent of any single representation or network location. It is the stable, location-agnostic anchor for identity.

Subject IRI (The "Document"): This is the URI of the data record (e.g., an HTTP URL) that describes the entity. An entity can have many different descriptions at different locations, each with its own subject IRI.

This distinction, which aligns with the "Cool URIs for the Semantic Web" best practice, provides several key advantages:

Data Federation: A single conceptual entity, identified by one core:swid, can have multiple representations across the web—a record in a corporate database, a profile on a social network, a state entry in a distributed ledger. The shared SWID makes it possible to link and integrate this federated data.

Resilience & Flexibility: The entity's identity persists even if specific descriptions change or become unavailable. The core:swid provides a permanent identifier that can be resolved to discover current, valid representations of the entity.

Interoperability: It allows any existing web resource (e.g., from DBPedia or a corporate dataset) to be integrated into the Spatial Web non-invasively. By simply adding the core:swid attribute, the resource becomes part of the Spatial Web without altering its original, native identity.

In summary, modeling the SWID as a literal-valued property provides a robust, flexible, and architecturally sound foundation essential for building a distributed, interoperable, and resilient Spatial Web.

7.1.3. Contextual Scaffolding: core:Domain

The Spatial Web is not a flat collection of entities; it is a structured network of contexts. The `core:Domain` class provides the formal mechanism for this structure, and its placement in the Core Module is essential. While other modules define specific **types** of entities, the Core Module must provide the universal scaffolding **for** all entities. `core:Domain` is this scaffold, providing the foundational "where" for every "what" (`core:Entity`).

Domains are conceptualized as **holons**—a term coined by Arthur Koestler to describe an entity that is simultaneously a whole in and of itself, as well as a part of a larger whole. A holon is a semi-autonomous, self-reliant unit that can handle local contingencies, yet it is also integrated into and subject to the context of a larger system. For example, a cell is a whole, but it is also a part of an organ; the organ is a whole, but also part of an organism.

This nested structure of Domains (as holons) forms a **holarchy**—a hierarchy of holons. Unlike a traditional hierarchy based on top-down command, a holarchy emphasizes composition and interdependence. The relationship between levels is best described as "made up of" or "making up" the next level, where the whole exists only as an integration of its semi-independent parts.

This holonic model is critically important for modeling the Spatial Web for several reasons:

- **Reflects Real-World Complexity**: It allows for the creation of complex, multi-level systems that mirror natural and social structures, from biological organisms to human organizations.
- **Enables Polycentric Governance**: It provides a robust framework for distributed governance. Each Domain, as a holon, can maintain its own autonomy and internal rules while being an interdependent part of a larger containing Domain. This allows for policies and logic to be scoped at the appropriate level.
- **Promotes Scalability and Resilience**: The semi-autonomous nature of holons means they can manage local operations and disturbances without constant instruction from higher levels, creating a more resilient and scalable system.

By modeling Domains as holons within a holarchy, HSML provides a powerful and flexible framework for organizing the vast, interconnected, and multi-layered contexts of the Spatial Web.

7.1.4. Minimal Ontological Commitment and Pragmatic Reuse

To ensure maximum flexibility and interoperability, the Core Module adheres to a principle of minimal ontological commitment for its foundational classes. Classes like core:Thing, core:Concept, and core:SpatialFeature are defined with only the most essential properties, establishing them as base types without imposing a heavy, prescriptive structure. This minimalist approach allows them to serve as robust extension points for more detailed, domain-specific standards.

This is complemented by the pragmatic reuse of established vocabularies. For example, core:SpatialFeature leverages GeoSPARQL for its geometric representations

(geosparql:hasGeometry), ensuring out-of-the-box compatibility with a mature ecosystem of geospatial tools and data. Similarly, common metadata properties are drawn from Dublin Core (dct:) and Schema.org (schema:). This strategy lowers the barrier to adoption and enhances the integration of HSML data into the broader web of data.

7.2. Normative Classes

This clause provides the normative definitions for all class concepts within the HSML Activity Module. Each class is detailed in a table that specifies its URI, description, JSON-LD context name, usage notes, and relationship to other classes.

The namespace prefix `core:` refers to `https://www.spatialwebfoundation.org/ns/hsml/core#`.

TABLE 3: Summary of Core Module Classes

Class	Description
core:Entity	The abstract root class for all objects, agents, and concepts in the Spatial Web.
core:Domain	A foundational entity that represents a sphere of knowledge, influence, or activity, forming the contextual scaffolding of the Spatial Web.
core:SpatialFeature	A type of Domain representing a location-bound or geometry-bearing element, linking semantics to geospatial structure.
core:Thing	A type of Domain representing a bounded, passive item without agency that can be acted upon or sensed.
core:Concept	A type of Domain representing an abstract idea or category used for classification and knowledge organization.
core:Condition	An abstract class representing a logical condition that can be evaluated to be true or false.
core:SHACLCondition	A concrete condition that uses a SHACL shape for validation logic.
core:Participation	A reusable entity that explicitly models the involvement of another entity in a specific role within a given context.
core:Role	Represents the function or position of an entity within a core:Participation, typically defined in a controlled vocabulary.

7.2.1. Class: core:Entity

The class `core:Entity` realizes the base concept ENTITY in IEEE P2874™/D-3.3.1-2025-03, Clause 6.6.2, defined as “that which is perceived, known, or inferred to exist, has existed, or is anticipated to exist”.

As the root of the Spatial Web ontology, `core:Entity` provides the universal, abstract foundation upon which all other HSML classes are built. It establishes the mandatory requirements for universal identification and class declaration, ensuring that every object in the ecosystem is uniquely addressable and explicitly typed.

Key Requirements

- Identity: Every `core:Entity` SHALL possess a Spatial Web Identifier (`core:swid`) conformant with W3C DID Core syntax.
- Typing: Every instance SHALL declare its specific, concrete class via the `rdf:type` property.
- Extensibility: The `core:Entity` model is designed to be subclassed to create more specialized types. It SHALL NOT be instantiated directly.

These requirements ensure that all HSML constructs share a common, machine-readable foundation, enabling polymorphic processing, universal identification, and semantic interoperability.

7.2.1.1. Class Definition

TABLE 4: Class Definition for core:Entity

RDF Class	`core:Entity`
Is Abstract	Yes
Definition	An *ENTITY* is "that which is perceived, known, or inferred to exist, has existed, or is anticipated to exist."
Subclass Of	`owl:Thing`
Usage Note	`core:Entity` is an abstract class and SHALL NOT be instantiated directly. Only its concrete subclasses should be instantiated.
Rationale	As the root of the Spatial Web ontology, `core:Entity` provides a uniform, extensible foundation for all HSML constructs, enabling universal identification and semantic interoperability.

TABLE 5: Properties Summary for core:Entity

Predicate	JSON-LD name	Description	Range	Cardin	Requirement Level
`rdf:type`	`@type`	Declares the specific class of the resource.	`rdfs:Class`	1..*	Mandatory
`core:swid`	`swid`	The Spatial Web Identifier for the entity.	`xsd:anyURI`	1..1	Mandatory
`schema:name`	`name`	A short, human-readable name for the entity.	`xsd:string`	0..1	Recommended
`schema:description`	`description`	A detailed explanation of the entity's purpose.	`xsd:string`	0..1	Optional

7.2.1.2. Properties

This section provides the detailed normative definitions for the properties of the `core:Entity` class.

7.2.1.2.1. Property: type

TABLE 6: Property Definition: rdf:type

Property	`rdf:type`
IRI	`http://www.w.org/1999/02/22-rdf-syntax-ns#type`
JSON name	`@type`
Requirement Level	Mandatory
Cardinality	1..*
Domain	`core:Entity`
Range	`rdfs:Class`
Definition	Declares the specific class (or classes) of which this resource is an instance.
Usage Note	Every entity SHALL have at least one `rdf:type` that specifies a concrete (non-abstract) subclass of `core:Entity`. Multiple types may be present, for example, to include inferred classes.

7.2.1.2.2. Property: swid

TABLE 7: Property Definition: core:swid

Property	`core:swid`
IRI	`https://www.spatialwebfoundation.org/ns/hsml/core#swid`
JSON name	`swid`
Requirement Level	Mandatory
Cardinality	1..1
Domain	`core:Entity`
Range	`xsd:anyURI`
Definition	A globally unique Spatial Web Identifier conformant with W3C DID Core syntax.
Usage Note	This property provides the stable, universal identifier for the entity across all contexts and networks.

7.2.1.2.3. Property: name

TABLE 8: Property Definition: schema:name

Property	`schema:name`
IRI	`https://schema.org/name`
JSON name	`name`
Requirement Level	Recommended
Cardinality	0..1
Domain	`core:Entity`
Range	`xsd:string`
Definition	A short, human-readable name for the entity.
Usage Note	Recommended for all entities to improve usability in user interfaces, logs, and administrative tools. Reuses the widely adopted property from Schema.org.

7.2.1.2.4. Property: description

TABLE 9: Property Definition: schema:description

Property	`schema:description`
IRI	`https://schema.org/description`
JSON name	`description`
Requirement Level	Optional
Cardinality	0..1
Domain	`core:Entity`
Range	`xsd:string`
Definition	A detailed explanation of the entity's purpose or nature.
Usage Note	Useful for documentation and for providing context to human users or AI agents. Reuses the widely adopted property from Schema.org.

7.2.2. Class: core:Domain

The class core:Domain realizes the DOMAIN concept, defined in the Spatial Web ontology as an ENTITY with identity through time endowed with rights and credentials. It represents a sphere of knowledge, influence, or ACTIVITY.

As a foundational element, core:Domain provides the structure for all entities that have a persistent identity as their defining essence. It serves as a distinct container for people, places, things, and concepts, allowing reality to be described from multiple perspectives and through correlated hierarchies. Domains are hierarchical in nature, allowing for parent, child, and sibling relationships, and can be nested within one another to maintain coherence. They form a holarchy, where each domain is a self-contained whole (a holon) that can also be a constituent part of a larger domain.

- **Identity:** Every core:Domain SHALL possess a Spatial Web Identifier (core:swid).
- **Typing:** Every core:Domain SHALL have a domainType attribute specifying its classification (e.g., Geographic, Concept, Agent, etc.).
- **Authority:** Every core:Domain SHALL have a Domain Authority that governs its norms, terms, and contracts.
- **Spatial Context:** A core:Domain MAY reference a HYPERSPACE to define its location, boundaries, or paths.
- **Holonic Structure:** A core:Domain MAY be part of a parent domain via a holonic (part-whole) link to create nested and hierarchical structures.

7.2.2.1. Class Definition

TABLE 10: Class Definition for core:Domain

RDF Class	core:Domain
Is Abstract	No
Definition	An ENTITY with identity through time endowed with rights and credentials, representing a sphere of knowledge, influence, or ACTIVITY.
Subclass Of	core:Entity
Usage Note	Domains are used to partition the Spatial Web into manageable regions. For example, a “Metropolis Digital Twin” is a geographic Domain, while the “Regional Energy Grid” is a concept Domain. An AGENT is also a type of Domain.
Rationale	Provides a foundational, general-purpose mechanism for grouping entities. This enables the creation of scalable, hierarchical, and nested structures necessary for contextual awareness, governance, and decentralized administration in the Spatial Web.

TABLE 11: Properties Summary for core:Domain

core:has Space	hasSpace	Links the domain to the Hyperspace in which it applies or is located.	space: Hyperspace	0..*	Optional
core: managedBy	managedBy	Identifies the Domain Authority credentialed to define norms and govern the domain.	agent:Agent	1..1	Mandatory
rdfh:partOf	partOf	Establishes a holonic link, indicating this domain is a constituent part of a parent domain.	core:Domain	0..1	Optional

7.2.2.2. Properties

This section provides the detailed normative definitions for the properties of the core:Domain class. (Properties inherited from core:Entity such as core:swid and schema:name are not redefined here).

7.2.2.2.1. Property: domainType

7.2.2.2.2. Property: hasSpace

TABLE 12: Property Definition: core:hasSpace

Property	core:hasSpace
IRI	`https://www.spatialwebfoundation.org/ns/hsml/core#hasSpace`
JSON name	hasSpace
Requirement Level	Optional
Cardinality	0..*
Domain	core:Domain
Range	space:Hyperspace
Definition	Associates the domain with a HYPERSPACE, indicating the spatial boundary, location, or context in which the domain's rules and membership apply.
Usage Note	Essential for location-aware governance. For example, a geographic Domain is implicitly or explicitly associated with a location. The HYPERSPACE can be a geometry in Cartesian space or a range of values.

7.2.2.2.3. Property: managedBy

TABLE 13: Property Definition: core:managedBy

Property	core:managedBy
IRI	`https://www.spatialwebfoundation.org/ns/hsml/core#managedBy`
JSON name	managedBy
Requirement Level	Mandatory
Cardinality	1..1
Domain	core:Domain
Range	agent:Agent
Definition	Identifies the Domain Authority: an entity credentialed to define the norms and terms under which contracts are created for AGENTS, ACTIVITIES, and CREDENTIALS within that Domain.
Usage Note	Every Spatial Web Domain SHALL have a Domain Authority. The managing agent is responsible for defining domain policies and governing the entities and activities within it.

7.2.2.2.4. Property: partOf

TABLE 14: Property Definition: rdfh:partOf

Property	rdfh:partOf
IRI	`http://purl.org/rdfh/partOf`
JSON name	partOf
Requirement Level	Optional
Cardinality	0..1
Domain	core:Domain
Range	core:Domain
Definition	Establishes a holonic or mereological (part-whole) link, indicating this domain is a constituent part of a parent domain.
Usage Note	This property is used to create nested and hierarchical domain structures. It allows for parent, child, and sibling relationships, enabling domains to maintain coherence while being contained within other domains.

7.2.3. Class: core:Concept

The class core:Concept realises the CONCEPT DOMAIN type as described in IEEE P2874™/D-3.3.1-2025-03, Clause 6.3.2.1.3:

> A CONCEPT is a DOMAIN representing an abstract, non-physical entity or idea that provides semantic context or categorization for other Entities in the Spatial Web.

core:Concept is used to model abstract or symbolic constructs, classifications, or types that help structure knowledge, rules, or ontological categories in the Spatial Web. It does not represent physical or agentic entities, but rather supports semantic reasoning, categorization, and rule expression.

7.2.3.1. Class Definition

TABLE 15: Class Definition for core:Concept

RDF Class	core:Concept
Is Abstract	No
Definition	A core:Domain representing an abstract idea, category, or semantic construct used for classification and knowledge organization.
Subclass Of	core:Domain
Usage Note	Concepts provide the semantic scaffolding of the Spatial Web; they are not physical or agentic entities.
Rationale	Supports ontology modeling, classification, and reasoning consistent with P2874's Concept Domain type.

7.2.3.2. Properties

The core:Concept class inherits all properties from core:Domain and core:Entity. It introduces no new properties at this level, providing a minimal base class for semantic constructs.

7.2.4. Class: core:Thing

The class core:Thing realises the THING DOMAIN type defined in IEEE P2874™/D-3.3.1-2025-03, Clause 6.3.2.1.7:

> A THING is a DOMAIN representing a bounded item without agency that can be acted upon, sensed, or described in the Spatial Web.

core:Thing represents physical or virtual entities that lack autonomous action but may be observed, measured, manipulated, or referenced by Agents or Activities. Examples include devices, sensors, vehicles, digital files, or other discrete objects.

7.2.4.1. Class Definition

TABLE 16: Class Definition for core:Thing

RDF Class	core:Thing
Is Abstract	No
Definition	A passive core:Domain representing a bounded item without agency, which may be sensed, acted upon, or described.
Subclass Of	core:Domain
Disjoint With	agt:Agent
Usage Note	Things are passive entities; they do not possess goals or capabilities but may participate in Activities as targets, inputs, or outputs.
Rationale	Provides a formal category for all non-agentic entities in the Spatial Web, ensuring compliance with P2874's Domain taxonomy.

7.2.4.2. Properties

The core:Thing class inherits all properties from core:Domain and core:Entity. It introduces no new properties at this level, providing a minimal base class that can be extended by more specific standards (such as W3C WoT or SAREF) for detailed device modeling.

7.2.5. Class: core:SpatialFeature

The class core:SpatialFeature realises the SPATIAL FEATURE concept, corresponding to the GEOGRAPHIC DOMAIN type described in IEEE P2874™/D-3.3.1-2025-03, Clause 6.3.2.1.2:

> A SPATIAL FEATURE is an ENTITY representing a location-bound or geometry-bearing element within a Domain, corresponding to a GEOGRAPHIC DOMAIN type where position, extent, or spatial relationships are essential.

`core:SpatialFeature` represents real or abstract entities anchored in space—such as landmarks, boundaries, sensor sites, or natural features—that are meaningful in spatial reasoning and analysis. It is the fundamental class for binding semantic entities to geospatial structure in the Spatial Web.

Key Requirements

- Identity: Every core:SpatialFeature SHALL possess a Spatial Web Identifier (core:swid).
- Geometry: A core:SpatialFeature SHOULD have at least one geometric representation linked via the geosparql:hasGeometry property.

7.2.5.1. Class Definition

TABLE 17: Class Definition for core:SpatialFeature

RDF Class	core:SpatialFeature
Is Abstract	No
Definition	An entity that represents a location-bound or geometry-bearing element of the GEOGRAPHIC DOMAIN type in the Spatial Web.
Subclass Of	core:Domain
Usage Note	core:SpatialFeature instances link semantic entities to geospatial structures (geometry, topology) for reasoning, mapping, or analysis.
Rationale	Provides a formal mechanism to model GEOGRAPHIC DOMAIN instances (per P2874) and bind entities to spatial coordinates, shapes, and relationships, aligning with established geospatial standards like OGC GeoSPARQL.

TABLE 18: Properties Summary for core:SpatialFeature

Predicate	JSON-LD name	Description	Range	Cardin.	Requirement Level
geosparql:hasGeometry	hasGeometry	Links the feature to its geometric representation.	geosparql:Geometry	0..*	Recommended

7.2.6. Class: core:Role

The class `core:Role` represents a named capacity, position, or function that a bearer (e.g., person, agent, device, or service) may hold within some context. It is a **definition-level concept** (the role itself), distinct from any particular assignment or holding of that role.

Key Requirements

- **Typing**: Every instance **SHALL** declare its class via the `rdf:type` property.
- **Minimal Metadata**: Role definitions **SHOULD** provide a human-readable `schema:name` and **MAY** include a `schema:description`.
- **Neutral & Standalone**: `core:Role` **SHALL NOT** require any superclass from external ontologies and **SHALL** remain independent of assignment-specific data (e.g., time bounds, authority, or basis).

7.2.6.1. Class Definition

TABLE 19: Class Definition for core:Role

RDF Class	`core:Role`
Is Abstract	No

RDF Class	core:Role
Definition	A named capacity, position, or function that can be held by an agent, object, or service within a context.
Subclass Of	owl:Thing
Usage Note	core:Role captures the definition of a role. Assignment-specific details (bearer, time, authority, basis) SHOULD NOT be modeled on this class and belong in a separate assignment pattern if needed.
Rationale	Provides a lightweight, interoperable notion of "role" that can be reused across activities, memberships, stewardship, and other Spatial Web contexts without imposing external ontology dependencies.

TABLE 20: Properties Summary for core:Role

Predicate	JSON-LD name	Description	Range	Cardin	Requirement Level
rdf:type	@type	Declares the specific class of the resource.	rdfs:Class	1..*	Mandatory
schema:name	name	A short, human-readable name for the role.	xsd:string	0..1	Recommended
schema:description	description	A human-readable explanation of the role's purpose or scope.	xsd:string	0..1	Optional

7.2.6.2. Properties

This section provides the detailed normative definitions for the properties of the core:Role class.

7.2.6.2.1. Property: type

TABLE 21: Property Definition: rdf:type

Property	rdf:type
IRI	http://www.w3.org/1999/02/22-rdf-syntax-ns#type
JSON name	@type
Requirement Level	Mandatory
Cardinality	1..*
Domain	core:Role
Range	rdfs:Class
Definition	Declares the specific class (or classes) of which this resource is an instance.

Usage Note	Every role SHALL have at least one `rdf:type` equal to `core:Role`. Additional types (e.g., domain-specific categories) MAY be included.

7.2.6.2.2. Property: name

TABLE 22: Property Definition: schema:name

Property	`schema:name`
IRI	`https://schema.org/name`
JSON name	`name`
Requirement Level	Recommended
Cardinality	0..1
Domain	`core:Role`
Range	`xsd:string`
Definition	A short, human-readable name for the role.
Usage Note	Recommended for UI, documentation, and discoverability. Reuses widely adopted Schema.org semantics.

7.2.6.2.3. Property: description

TABLE 23: Property Definition: schema:description

Property	`schema:description`
IRI	`https://schema.org/description`
JSON name	`description`
Requirement Level	Optional
Cardinality	0..1
Domain	`core:Role`
Range	`xsd:string`
Definition	A human-readable explanation of the role's purpose, responsibilities, or scope.
Usage Note	Useful to clarify intent and distinguish similarly named roles in catalogs and governance artifacts.

7.2.7. Class: core:Participation

The class core:Participation is the generic link object that models an entity's involvement in a host resource (e.g., a gov:Contract, ev:Event, or act:Activity). It is a reified relationship that states:

- What entity is involved (via core:hasParticipant),
- What role it plays (via core:hasRole), and
- Optionally, the duration of the involvement (via schema:startTime and schema:endTime).

This pattern is fundamental in the Spatial Web because it provides a standardized, reusable mechanism for describing and querying participation across heterogeneous contexts. It prevents model duplication and ensures that agentic, legal, and procedural interactions are captured consistently—critical for maintaining trust, accountability, and semantic precision.

7.2.7.1. Class Definition

TABLE 24: Class Definition for core:Participation

RDF Class	core:Participation
Is Abstract	No
Definition	A reified relationship that captures an entity's specific involvement in a host resource, connecting the entity and its role to the context.
Subclass Of	owl:Thing
Usage Note	Host resources (like gov:Contract) SHOULD use a property such as gov:has Participation to link to one or more instances of core:Participation.
Rationale	Centralizes the {entity, role, time} pattern for maximum reuse. This single, robust pattern can describe the involvement of agents, artifacts, or other entities in any situation.

TABLE 25: Properties Summary for core:Participation

Predicate	JSON-LD name	Description	Range	Cardin.	Requirement Level
core:has Participant	has Participant	The entity playing the role.	core:Entity	1..1	Mandatory
core:hasRole	hasRole	The core:Role that describes the function of the participant.	core:Role	1..1	Mandatory
schema:start Time	startTime	The timestamp when the participation begins.	xsd:dateTime	0..1	Optional
schema:end Time	endTime	The timestamp when the participation ends.	xsd:dateTime	0..1	Optional

7.2.7.2. Properties

This section provides the detailed normative definitions for the properties of the core:Participation class.

7.2.7.2.1. Property: hasParticipant

TABLE 26: Property Definition: core:hasParticipant

Property	core:hasParticipant
IRI	`https://www.spatialwebfoundation.org/ns/hsml/core#hasParticipant`
JSON name	hasParticipant
Requirement Level	Mandatory
Cardinality	1..1
Range	core:Entity
Definition	The actual resource (agent, object, etc.) that is involved in the context.
Usage Note	This property links the core:Participation instance to the participating entity itself.

7.2.7.2.2. Property: hasRole

TABLE 27: Property Definition: core:hasRole

Property	core:hasRole
IRI	`https://www.spatialwebfoundation.org/ns/hsml/core#hasRole`
JSON name	hasRole
Requirement Level	Mandatory
Cardinality	1..1
Range	core:Role
Definition	The role the participant entity fulfills within the participation (e.g., client, sensor, certifier).
Usage Note	The value should be an IRI pointing to a concept in a controlled vocabulary of roles.

7.2.7.2.3. Property: startTime

TABLE 28: Property Definition: schema:startTime

Property	schema:startTime
IRI	`https://schema.org/startTime`
JSON name	startTime
Requirement Level	Optional
Cardinality	0..1
Range	xsd:dateTime
Definition	The specific date and time when the participation begins or becomes effective.
Usage Note	Reuses the property from Schema.org for standardized temporal metadata.

7.2.7.2.4. Property: endTime

TABLE 29: Property Definition: schema:endTime

Property	schema:endTime
IRI	`https://schema.org/endTime`
JSON name	endTime
Requirement Level	Optional
Cardinality	0..1
Range	xsd:dateTime
Definition	The specific date and time when the participation ends or is no longer effective.
Usage Note	Reuses the property from Schema.org for standardized temporal metadata.

7.2.8. Class: core:Condition

A core:Condition is an abstract class representing a logical condition that can be evaluated to be true or false.

7.2.8.1. Class Definition

TABLE 30: Class Definition for core:Condition

RDF Class	core:Condition
Is Abstract	Yes
Definition	An abstract representation of a logical condition that must be satisfied.
Subclass Of	owl:Thing
Usage Note	This class is never instantiated directly. Concrete subclasses like core:SHACLCondition must be used to provide the specific evaluation logic.
Rationale	Provides a single, abstract root for all types of logical validation, ensuring that the ontology can evolve to support new validation technologies without breaking changes.

7.2.9. Class: core:SHACLCondition

The class core:SHACLCondition is a concrete implementation of core:Condition that uses a SHACL shape for validation. It provides a standardized way to express constraints on the structure and values of RDF data.

As a foundational element of the Generic Condition Model, core:SHACLCondition is the primary mechanism for defining data types, cardinality, value ranges, and other structural rules for entities and variables throughout the HSML ontology.

Inheritance: Every core:SHACLCondition is a subclass of core:Condition.

Shape Definition: Every core:SHACLCondition SHALL link to exactly one sh:Shape via the core:hasShape property.

Validation Logic: The validation of a core:SHACLCondition is performed by evaluating the associated SHACL shape against a target RDF graph.

7.2.9.1. Class Definition

TABLE 31: Class Definition for core:SHACLCondition

RDF Class	core:SHACLCondition
Is Abstract	No
Definition	A condition defined by a SHACL shape, used to validate the structure and values of RDF data.
Subclass Of	core:Condition
Usage Note	This is the primary mechanism for defining data type, cardinality, and other structural constraints on variables and entities.
Rationale	Leverages the W3C SHACL standard for robust, standardized data validation, ensuring interoperability and machine-checkable conformance.

TABLE 32: Properties Summary for core:SHACLCondition

Predicate	JSON-LD name	Description	Range	Cardin	Requirement Level
core:has Shape	hasShape	Links the condition to the SHACL shape defining its logic.	sh:Shape	1..1	Mandatory

7.2.9.2. Properties

This section provides the detailed normative definitions for the properties of the core:SHACLCondition class.

7.2.9.2.1. Property: hasShape

TABLE 33: Property Definition: core:hasShape

Property	core:hasShape
IRI	`https://www.spatialwebfoundation.org/ns/hsml/core#hasShape`
JSON name	hasShape
Requirement Level	Mandatory
Cardinality	1..1
Domain	core:SHACLCondition
Range	sh:Shape
Definition	Links a core:SHACLCondition to the specific SHACL shape that defines its validation logic.
Usage Note	The object of this property must be a valid SHACL shape definition. This shape is used by validation engines to evaluate the condition.

8. HSML Activity Module

8.1. Architectural Principles and Design Rationale

This clause describes the architectural principles underlying the HSML Activity Module. These principles are *informative* and not required for conformance; however, understanding them is recommended to ensure robust and correct implementations.

8.1.1. The Schema/Instance Pattern: Enabling Scalable Governance

A fundamental principle of this standard is the strict separation between the *definition* of an activity and the *record of its execution*. This separation is realized through two distinct HSML classes:

- `act:ActivitySchema` — A reusable, design-time template that specifies the type of action, its required inputs, expected outputs, and the conditions under which it is valid.
- `act:Activity` — An execution-time entity representing a single, concrete, stateful instance of an `act:ActivitySchema` performed by a specific agent at a specific time.

This separation is a cornerstone of governance and scalability within the Spatial Web. It enables a "trust-by-reference" model where an orchestration engine can validate an action with high efficiency. Rather than analyzing the internal logic of the action itself, the validator only needs to check whether the `act:Activity` references an `act:ActivitySchema` from an approved registry. This decouples the high-level, infrequent work of policy definition (approving schemas) from the high-frequency, operational work of validation (checking activities), producing a highly scalable and secure governance framework.

8.1.2. The Parameter/Binding Pattern: Achieving Contextual Reusability

Complementing the schema/instance pattern is the separation of abstract parameters from their concrete values. This is achieved through the `act:Variable` and `act:VariableBinding` classes.

- `act:Variable` is used within an `act:ActivitySchema` to define a placeholder for an input or output (e.g., "target_location"), including its name, description, and constraints, but no specific value.
- `act:VariableBinding` is used within an `act:Activity` to connect a specific `act:Variable` from the schema to a concrete value (e.g., linking "target_location" to a specific address).

This design allows `act:ActivitySchema` definitions to be generic and broadly reusable. A single schema for "TransferAsset" can be instantiated in thousands of different `act:Activity` instances, each using `act:VariableBinding` to supply the concrete assets and accounts for a specific transaction. This promotes standardization while ensuring every `act:Activity` is a complete, self-contained, and auditable record.

A key architectural decision in this pattern is how a `VariableBinding` references its corresponding `Variable`. This model mandates the use of the `Variable's locally unique` `schema:identifier` (e.g., `"targetLocation"`) rather than its global URI. This choice is deliberate and provides two main benefits:

1. Consistency: It establishes a single, predictable pattern across the entire Activity model. Just as `act:DataLink` uses local identifiers to wire steps together within a composite schema, `act:VariableBinding` uses the same mechanism to bind values at runtime. This consistency simplifies implementation and makes the model easier to learn.
2. Portability: It treats the `ActivitySchema` as a true, self-contained template. An `Activity` instance is bound to the *role* a variable plays within the schema (its local identifier), not to a rigid, globally unique URI. This decouples the execution record from the schema definition, allowing the schema to be versioned or reused more flexibly without invalidating existing activity instances.

This approach requires the processing engine to resolve the reference by looking up the identifier within the context of the activity's schema. This is a standard pattern and a worthwhile trade-off for the significant gains in consistency, portability, and developer experience.

8.1.3. The Composite Model: First-Class Workflows

For composite (multi-step) activities, a simple list of sub-activities is insufficient. A robust model must also describe the sequence of steps, the flow of data between them, and the control flow logic (e.g., conditional branches). The Activity Module addresses this by elevating the core components of a workflow to be first-class citizens:

- `act:ActivityStep`: A node in the workflow graph. It represents a discrete stage of execution and is a rich, self-describing object.
- `act:DataLink`: An edge in the workflow graph. It represents the explicit flow of data from one step's output to another's input.

The decision to model `act:ActivityStep` and `act:DataLink` as distinct `owl:Class` instances, rather than simple properties, is a cornerstone of this architecture. It makes the entire workflow—its structure, logic, and data flow—explicit, addressable, and governable.

This design allows for sophisticated patterns: * Documentable and Addressable Steps: Each `act:ActivityStep` can have a human-readable `schema:name` and `schema:description`, making the workflow self-documenting. It is given a simple, local `schema:identifier` (e.g., "validate-user") for easy reference by `act:DataLink` instances. * Conditional Control Flow: An `act:ActivityStep` can carry its own `core:Condition`. This enables powerful, declarative control flow, such as an "if/then/else" branch, where the execution of a step depends on the outcome of a formal condition. * Governable and Self-Describing Data Flow: Because a `act:DataLink` is a first-class entity, it can be documented with its own `schema:name` and `schema:description` (e.g., "Pass User ID to Validator"). Furthermore, metadata can be attached directly to the data transfer itself, allowing for quality-of-service requirements (e.g., `ex:maxLatency`), security classifications, or even a `core:Condition` to enforce a policy on the data link.

This approach transforms a simple sequence of tasks into a fully governable, introspectable, and self-describing graph of actions that can be validated, audited, and reused with high fidelity.

8.1.4. The Generic Condition Model: Future-Proofing Logic

The HSML architecture separates semantic intent from technical implementation. This is exemplified by the `core:Condition` model, defined in the HSML Core Module and used extensively by this Activity Module for properties like `act:hasPrecondition`, `act:hasEffect`, and for enabling conditional logic on an `act:ActivityStep`.

The `core:Condition` class is abstract; it represents the idea that a condition exists without specifying *how* that condition must be evaluated. The actual evaluation logic is delegated to concrete subclasses, such as `core:SHACLCondition` or `core:SPARQLCondition`. This architectural choice is a powerful future-proofing mechanism. By having models reference the abstract `core:Condition`, the standard is not locked into any single validation technology. New condition types can be introduced in the future without requiring breaking changes to the core models, ensuring the long-term relevance and extensibility of the standard.

8.1.5. Domain-Specific Governance of Referenced Schemas

A core tenet of the Spatial Web's architecture is that domains can apply local, context-specific governance to universal, standardized `act:ActivitySchema` definitions without modifying the original schema. This is achieved by separating the activity's definition from the rules governing its execution within a domain. The primary mechanism for enforcing these domain-specific rules is the requirement of a domain-specific CREDENTIAL.

A Domain Authority (DA) can incorporate a universal schema by reference and then configure its domain policies to require that any agent performing the activity must present a specific credential. This model ensures that while the schema remains a universal standard, its execution is always subject to the explicit, verifiable, and non-negotiable rules of the domain in which it is performed.

8.2. Modeling of Composite Activities

This clause specifies the normative rules for constructing complex, multi-step workflows using the `act:CompositeActivitySchema` class.

8.2.1. The Composite Pattern: ActivityStep and DataLink

A `CompositeActivitySchema` `shall` be composed of one or more `act:ActivityStep` instances and zero or more `act:DataLink` instances.

An `act:ActivityStep` `shall` function as an addressable node within the workflow graph defined by the composite schema. Each `act:ActivityStep` `shall` use the `act:usesSchema` property to reference exactly one `act:ActivitySchema` that defines the logic for that step. This referenced schema may be either atomic or another composite schema, allowing for nested workflows.

An `act:DataLink` `shall` function as a directed edge in the workflow graph, representing the flow of data. This formal "wiring" is necessary for composite logic, as it makes the dependencies between steps explicit and machine-checkable.

8.2.2. Control Flow Constructs

An act:CompositeActivitySchema shall define its internal control flow by using exactly one of the following three properties: act:hasOrderedSteps, act:hasChoice, or act:hasUnorderedSteps. This mutual exclusivity is normatively enforced by the sh:xone constraint in the act:CompositeActivitySchemaShape (see Annex B).

- Sequence (act:hasOrderedSteps): If this property is used, its value shall be a well-formed rdf:List where each member of the list is an act:ActivityStep. The steps shall be executed by an orchestration engine in the strict order defined by the list.
- Choice (act:hasChoice): If this property is used, it shall link to two or more act:ActivityStep instances. These steps represent mutually exclusive execution paths. An orchestration engine shall select and execute exactly one of the specified choice steps.
- Set (act:hasUnorderedSteps): If this property is used, it shall link to one or more act:ActivityStep instances. These steps have no prescribed execution order and may be executed in any sequence or in parallel, subject to data dependencies defined by act:DataLink instances.

8.2.3. Interface Wiring and Data Flow Management

The act:DataLink class is used to manage the flow of data between steps and across the boundary of the composite schema. The following normative rules apply, as enforced by the act:DataLinkInterfaceShape and act:DataLinkTypeConsistencyShape (see Annex B).

- Internal Wiring: To connect the output of one step to the input of another, an act:DataLink shall specify the act:sourceStep, act:sourceVariable, act:targetStep, and act:targetVariable.
- Input Wiring: To connect a public input of the CompositeActivitySchema to the input of an internal step, an act:DataLink shall be created that omits the act:sourceStep property. For such a link, the act:sourceVariable shall be a variable that is declared as an act:hasInput on the parent CompositeActivitySchema.
- Output Wiring: To expose the output of an internal step as a public output of the CompositeActivitySchema, an act:DataLink shall be created that omits the act:targetStep property. For such a link, the act:targetVariable shall be a variable that is declared as an act:hasOutput on the parent CompositeActivitySchema.
- Type Consistency: For any act:DataLink, the type constraint of the act:sourceVariable should be compatible with the type constraint of the act:targetVariable. The act:DataLinkTypeConsistencyShape provides a normative check for this compatibility.

8.3. Execution and Traceability Model

This clause specifies the normative requirements for creating a run-time trace of an executed activity. This model ensures that a complete and auditable record of all actions is preserved.

8.3.1. Instantiation of Composite Activities

When an orchestration engine begins the execution of a `CompositeActivitySchema`, it `shall` first create a parent `act:Activity` instance corresponding to the composite schema itself. As the engine proceeds to execute each constituent `act:ActivityStep` defined within the composite, it `shall` create a new, distinct child `act:Activity` instance for each step executed.

8.3.2. Normative Requirements for Traceability Links

To ensure a complete and unambiguous provenance graph, the following linking properties `shall` be used on all child `act:Activity` instances created during the execution of a composite activity.

- Compositional Link (`act:subActivityOf`): Every child `Activity` created from an `ActivityStep` `shall` be linked to its parent composite `Activity` using exactly one `act:subActivityOf` property. This creates the compositional hierarchy, clearly defining which actions are part of a larger workflow.
- Sequential Link (`act:precededBy`): For workflows defined with `act:hasOrderedSteps`, every child `Activity` (except for the first one in the sequence) `shall` be linked to the `Activity` instance of the immediately preceding step using exactly one `act:precededBy` property.

The combined use of these two properties creates a comprehensive, dual-axis traceability graph. The `act:subActivityOf` links provide the compositional or "part-of" hierarchy, while the `act:precededBy` links provide the temporal and causal sequence. Together, they allow for the complete and unambiguous reconstruction of a complex event, which is critical for auditing, debugging, and establishing legal or operational accountability.

8.4. Normative Classes

This clause provides the normative definitions for all class concepts within the HSML Activity Module. Each class is detailed in a table that specifies its URI, description, JSON-LD context name, usage notes, and relationship to other classes.

The namespace prefix `act:` refers to `https://www.spatialwebfoundation.org/ns/hsml/activity#`.

8.4.1. Summary of Normative Classes

TABLE 34: Summary of HSML Activity Module Classes

Class	Description
act:Activity	A concrete, stateful record of a specific action that has been, is being, or is planned to be performed.
act:ActivitySchema	A reusable, design-time template that defines the logic, interface, and conditions for a type of activity.
act:AtomicActivity Schema	A specialization of act:ActivitySchema for simple, indivisible activities whose internal logic is opaque to the model.
act:CompositeActivity Schema	A specialization of act:ActivitySchema for complex workflows composed of multiple steps and data links.
act:ActivityStep	A structural node within a act:CompositeActivitySchema that represents a single step in a workflow.
act:DataLink	A structural entity that explicitly defines the "wiring" or flow of data between steps in a composite workflow.
act:Variable	An abstract parameter placeholder within an act:ActivitySchema that defines an input or output slot.
act:VariableBinding	A concrete link within an act:Activity that connects an act:Variable to a specific value for an execution.

8.4.2. Class: act:Activity

The class `act:Activity` realises the ACTIVITY concept defined in IEEE P2874™/D-3.3.1-2025-03, Clause 6.6.3:

> An ACTIVITY is an execution-time entity representing a single, concrete, stateful instance of an `act:ActivitySchema` performed by a specific agent at a specific time.

`act:Activity` is the primary entity for recording and tracking the execution of an action in the Spatial Web. It serves as a stateful, auditable record that links the abstract `act:ActivitySchema` to the concrete agents and values involved in a specific occurrence.

Key Requirements

- Identity: Every `act:Activity` SHALL possess a Spatial Web Identifier (`core:swid`, W3C DID Core-compliant).
- Schema Conformance: An `act:Activity` SHALL reference exactly one `act:ActivitySchema` via the `act:activitySchema` property.
- Agent Assignment: An `act:Activity` SHALL identify the `agt:Agent`(s) responsible for its execution via the `act:performedBy` property.
- Parameter Binding: An `act:Activity` SHALL provide concrete values for all required inputs of its schema using `act:VariableBinding` instances.
- Lifecycle Tracking: An `act:Activity` SHALL have its current state tracked via the `act:status` property, using the normative HSML Activity Status vocabulary.

- **Temporality**: An `act:Activity` **SHOULD** record the time execution began (`schema:startTime`) and concluded (`schema:endTime`).
- **Execution Traceability**: If an `act:Activity` is part of a composite workflow, it **SHOULD** link to its parent activity (`dct:isPartOf`) and the step it realized (`act:realizedStep`).

These requirements ensure that every executed action is a complete, self-contained, and verifiable record that is traceable to its defining schema and responsible agent.

8.4.2.1. Class Definition

TABLE 35: Class Definition for act:Activity

RDF Class	`act:Activity`
Is Abstract	No
Definition	A concrete, stateful execution of an `act:ActivitySchema`. It is the record of an action that has been, is being, or is planned to be performed.
Subclass Of	`core:Entity`
Usage Note	An `act:Activity` instance is created for every action that is initiated via a `gov:Contract`. It contains `act:VariableBinding` instances for all required inputs and its `act:status` property tracks its lifecycle.
Rationale	Provides the normative record of execution for all actions, ensuring that every event is auditable, governable, and traceable to its formal definition and responsible parties.

TABLE 36: Properties Summary for act:Activity

Predicate	JSON-LD name	Description	Range	Cardin.	Requirement Level
`act:activitySchema`	`activitySchema`	Links the `act:Activity` instance to the `act:ActivitySchema` it implements.	`act:ActivitySchema`	1..1	Mandatory
`act:performedBy`	`performedBy`	Identifies the `agt:Agent`(s) responsible for performing the `act:Activity`.	`agt:Agent`	1..*	Mandatory
`act:status`	`status`	The current lifecycle state of the `act:Activity`.	`skos:Concept`	1..1	Mandatory
`act:hasBinding`	`hasBinding`	Associates an `act:VariableBinding` with the `act:Activity`.	`act:VariableBinding`	0..*	Conditional
`schema:startTime`	`startTime`	The timestamp when the activity execution began.	`xsd:dateTime`	0..1	Recommended
`schema:endTime`	`endTime`	The timestamp when the activity execution concluded (completed or failed).	`xsd:dateTime`	0..1	Recommended

Predicate	JSON-LD name	Description	Range	Cardin	Requirement Level
dct:isPartOf	isPartOf	Links this activity instance to its parent composite activity instance.	act:Activity	0..1	Optional
act:realizedStep	realizedStep	Identifies the specific act:ActivityStep that this instance realized.	act:ActivityStep	0..1	Optional

8.4.2.2. Properties

This section provides the detailed normative definitions for the properties of the act:Activity class.

8.4.2.2.1. Property: activitySchema

TABLE 37: Property Definition: act:activitySchema

Property	act:activitySchema
IRI	https://www.spatialwebfoundation.org/ns/hsml/activity#activitySchema
JSON name	activitySchema
Requirement Level	Mandatory
Cardinality	1..1
Domain	act:Activity
Range	act:ActivitySchema
Definition	Links an act:Activity instance to the act:ActivitySchema it implements.
Usage Note	This is a critical link for governance, as it allows validators to check the activity's conformance against its approved template.

8.4.2.2.2. Property: performedBy

TABLE 38: Property Definition: act:performedBy

Property	act:performedBy
IRI	https://www.spatialwebfoundation.org/ns/hsml/activity#performedBy
JSON name	performedBy
Requirement Level	Mandatory
Cardinality	1..*

Domain	act:Activity
Range	agt:Agent
Definition	Identifies the agt:Agent (or agents) responsible for performing an act:Activity.
Usage Note	Establishes accountability for the action's execution and outcomes.

8.4.2.2.3. Property: status

TABLE 39: Property Definition: act:status

Property	act:status
IRI	https://www.spatialwebfoundation.org/ns/hsml/activity#status
JSON name	status
Requirement Level	Mandatory
Cardinality	1..1
Domain	act:Activity
Range	skos:Concept
Definition	The current lifecycle state of an act:Activity.
Usage Note	The value SHALL be an IRI from the normative HSML Activity Status vocabulary (e.g., act:Planned, act:Ongoing, act:Completed, act:Failed). Provides real-time tracking of the action's progress and is used to determine the status of the governing gov:Contract.

8.4.2.2.4. Property: hasBinding

TABLE 40: Property Definition: act:hasBinding

Property	act:hasBinding
IRI	https://www.spatialwebfoundation.org/ns/hsml/activity#hasBinding
JSON name	hasBinding
Requirement Level	Conditional
Cardinality	0..*
Domain	act:Activity

Range	`act:VariableBinding`
Definition	Associates an `act:VariableBinding` with an `act:Activity`, indicating that a variable has been bound to a value.
Usage Note	An `act:Activity` **should** have a binding for each required input (`act:hasInput`) of its schema.

8.4.2.2.5. Property: startTime

TABLE 41: Property Definition: schema:startTime

Property	`schema:startTime`
IRI	`https://schema.org/startTime`
JSON name	`startTime`
Requirement Level	Recommended
Cardinality	0..1
Domain	`act:Activity`
Range	`xsd:dateTime`
Definition	The specific date and time when the activity execution began.
Usage Note	Essential for temporal reasoning and auditing. Should be populated when the status transitions to `act:Ongoing`. Reuses the property from Schema.org.

8.4.2.2.6. Property: endTime

TABLE 42: Property Definition: schema:endTime

Property	`schema:endTime`
IRI	`https://schema.org/endTime`
JSON name	`endTime`
Requirement Level	Recommended
Cardinality	0..1
Domain	`act:Activity`
Range	`xsd:dateTime`
Definition	The specific date and time when the activity execution concluded (completed or failed).

Usage Note	Essential for temporal reasoning and auditing. Should be populated when the status transitions to a terminal state (`act:Completed` or `act:Failed`). Reuses the property from Schema.org.

8.4.2.2.7. Property: isPartOf

TABLE 43: Property Definition: dct:isPartOf

Property	`dct:isPartOf`
IRI	`http://purl.org/dc/terms/isPartOf`
JSON name	`isPartOf`
Requirement Level	Optional
Cardinality	0..1
Domain	`act:Activity`
Range	`act:Activity`
Definition	Links a child activity instance to its parent composite activity instance.
Usage Note	Used for execution traceability in composite workflows. If populated, the range must be an instance of an activity whose schema is an `act:CompositeActivitySchema`.

8.4.2.2.8. Property: realizedStep

TABLE 44: Property Definition: act:realizedStep

Property	`act:realizedStep`
IRI	`https://www.spatialwebfoundation.org/ns/hsml/activity#realizedStep`
JSON name	`realizedStep`
Requirement Level	Optional
Cardinality	0..1
Domain	`act:Activity`
Range	`act:ActivityStep`
Definition	Identifies the specific `act:ActivityStep` within the parent composite schema that this activity instance realized.

Usage Note	Provides a precise link between the execution trace and the workflow definition. Should be used in conjunction with `dct:isPartOf`.

8.4.3. Class: `act:ActivitySchema`

The class `act:ActivitySchema` realises the ACTIVITY SCHEMA concept defined in IEEE P2874™/D-3.3.1-2025-03, Clause 6.6.3:

> An ACTIVITY SCHEMA is an ENTITY that defines the template, structure, or plan for an ACTIVITY, specifying its preconditions, postconditions, roles, and expected outcomes.

`act:ActivitySchema` provides the abstract, reusable blueprint for an `act:Activity`. It enables the consistent modeling of repeatable processes by defining the action's interface (inputs/outputs), its required logical state (preconditions), and its expected results (effects).

Key Requirements

- Identity: Every `act:ActivitySchema` SHALL possess a Spatial Web Identifier (core:swid, W3C DID Core-compliant).
- Condition Specification: An `act:ActivitySchema` SHOULD define its required state and results using act:hasPrecondition and act:hasEffect.
- Parameterization: An `act:ActivitySchema` SHALL declare its interface of expected parameters using act:hasInput and act:hasOutput, which reference act:Variable instances.

These requirements ensure that activities based on schemas are machine-checkable, consistent, and reusable in Spatial Web systems.

8.4.3.1. Class Definition

TABLE 45: Class Definition for act:ActivitySchema

RDF Class	`act:ActivitySchema`
Is Abstract	No
Definition	A reusable, design-time template for a type of activity, defining its logic, interface (inputs and outputs), preconditions, and effects.
Subclass Of	`core:Entity`
Usage Note	Schemas are published and reused across multiple act:Activity instances. They are the foundation of the "trust-by-reference" governance model.
Rationale	Provides a formal mechanism for modeling reusable processes and workflows in compliance with the P2874 Activity model, separating the definition of an action from its execution.

8.4.3.2. Property Definitions

This section provides the detailed normative definitions for the properties of the `act:ActivitySchema` class.

TABLE 46: Properties Summary for act:ActivitySchema

Predicate	JSON-LD name	Description	Range	Cardin.	Requirement Level
rdf:type	@type	Declares the resource as an instance of `act:ActivitySchema`.	rdfs:Class	1..n	Mandatory
core:swid	swid	Spatial Web Identifier conformant with W3C DID Core.	xsd:anyURI	1..1	Mandatory
act:hasInput	`hasInput`	Declares an act:Variable as a required input parameter.	`act:Variable`	0..n	Optional
act:hasOutput	"hasOutput"	Declares an act:Variable as an expected output parameter.	`act:Variable`	0..n	Optional
act:has Precondition	"has Precondition"	Specifies a logical condition that must be satisfied before the activity can be executed.	`core:Condition`	0..n	Optional
act:hasEffect	"hasEffect"	Describes the expected state of the world after the successful completion of the activity.	`core:Condition`	0..n	Optional

8.4.3.2.1. Property: hasInput

TABLE 47: Property Definition: act:hasInput

Property	`act:hasInput`
IRI	`https://www.spatialwebfoundation.org/ns/hsml/activity#hasInput`
JSON name	"hasInput"
Requirement Level	Optional
Cardinality	0..n
Domain	`act:ActivitySchema`
Range	`act:Variable`
Definition	Declares an input parameter required by the Activity Schema.
Usage Note	Defines the "interface" for the schema. Each input act:Variable must be bound to a value in an act:Activity instance.

8.4.3.2.2. Property: hasOutput

TABLE 48: Property Definition: act:hasOutput

Property	`act:hasOutput`
IRI	`https://www.spatialwebfoundation.org/ns/hsml/activity#hasOutput`
JSON name	"hasOutput"
Requirement Level	Optional
Cardinality	0..n
Domain	`act:ActivitySchema`
Range	`act:Variable`
Definition	Declares an output parameter produced by the Activity.
Usage Note	Defines the "interface" for the schema. Each output act:Variable will be bound to a resulting value in a completed act:Activity instance.

8.4.3.2.3. Property: hasPrecondition

TABLE 49: Property Definition: act:hasPrecondition

Property	`act:hasPrecondition`
IRI	`https://www.spatialwebfoundation.org/ns/hsml/activity#hasPrecondition`
JSON name	"hasPrecondition"
Requirement Level	Optional hasPrecondition
Requirement Level	Optional
Cardinality	0..n
Domain	`act:ActivitySchema`
Range	`core:Condition`
Definition	Specifies a logical condition on the world state that must be satisfied before the activity can be executed.
Usage Note	Used by governance engines to validate a gov:Contract before allowing an activity to proceed.

8.4.3.2.4. Property: hasEffect

TABLE 50: Property Definition: act:hasEffect

Property	`act:hasEffect`
IRI	`https://www.spatialwebfoundation.org/ns/hsml/activity#hasEffect`
JSON name	"hasEffect"
Requirement Level	Optional
Cardinality	0..n
Domain	`act:ActivitySchema`
Range	`core:Condition`
Definition	Describes the expected state of the world after the successful completion of the activity.
Usage Note	Used for validation of outcomes and success criteria.

8.4.4. Class: act:AtomicActivitySchema

The class `act:AtomicActivitySchema` realizes the ATOMIC ACTIVITY SCHEMA concept, a specialization of `act:ActivitySchema` as defined in IEEE P2874™/D-3.3.1-2025-03, Clause 6.6.3.

An `act:AtomicActivitySchema` is a schema for a simple, indivisible activity that is not broken down into smaller steps within the HSML model. It represents a fundamental operation whose internal logic is treated as a "black box."

Key Requirements

- Inheritance: An `act:AtomicActivitySchema` SHALL inherit all requirements from `act:ActivitySchema`.
- Indivisibility: An `act:AtomicActivitySchema` SHALL NOT contain any `act:ActivityStep` instances or control flow properties (`act:hasOrderedSteps`, `act:hasChoice`, `act:hasUnorderedSteps`).

8.4.4.1. Class Definition

TABLE 51: Class Definition for act:AtomicActivitySchema

RDF Class	`act:AtomicActivitySchema`
Is Abstract	No
Definition	A schema for a simple, indivisible activity that does not internally reference other `act:ActivitySchema` instances.

RDF Class	act:AtomicActivitySchema
Subclass Of	act:ActivitySchema
Usage Note	Used for fundamental operations whose internal logic is opaque to the HSML model (e.g., invoking an external API, performing a cryptographic operation).
Rationale	Provides a clear distinction between simple, black-box tasks and complex, multi-step workflows (act:CompositeActivitySchema), which simplifies validation and execution logic.

8.4.4.2. Properties

An act:AtomicActivitySchema defines no new properties. It inherits all of its properties, including act:hasInput, act:hasOutput, act:hasPrecondition, and act:hasEffect, from its superclass, act:ActivitySchema.

8.4.5. Class: act:CompositeActivitySchema

The class act:CompositeActivitySchema realizes the COMPOSITE ACTIVITY SCHEMA concept, which extends the act:ActivitySchema to model complex, multi-step workflows as defined in IEEE P2874™/D-3.3.1-2025-03, Clause 6.6.3.

A act:CompositeActivitySchema is a schema for a complex workflow composed of other activities. It acts as a container for a set of act:ActivityStep instances and defines the control and data flow between them. This enables the modeling of sophisticated processes like sequences, choices, and parallel operations.

Key Requirements

- Composition: A act:CompositeActivitySchema SHALL be composed of one or more act:ActivityStep instances linked via act:hasStep.
- Control Flow: A act:CompositeActivitySchema SHALL define its execution logic using exactly one of the control flow properties: act:hasOrderedSteps, act:hasChoice, or act:hasUnorderedSteps.
- Data Flow: A act:CompositeActivitySchema MAY define the data wiring between its steps and its public interface using act:DataLink instances.

8.4.5.1. Class Definition

TABLE 52: Class Definition for act:CompositeActivitySchema

RDF Class	act:CompositeActivitySchema
Is Abstract	No
Definition	A schema for a complex workflow defined in terms of a sequence or combination of other activities.
Subclass Of	act:ActivitySchema

RDF Class	act:CompositeActivitySchema
Usage Note	This class is the basis for modeling multi-step processes. It must contain act:ActivityStep instances and define a control flow.
Rationale	Provides a formal, governable structure for modeling complex workflows, making both the process logic and data dependencies explicit and auditable.

TABLE 53: Properties Summary for act:CompositeActivitySchema

Predicate	JSON-LD name	Description	Range	Cardin	Requirement Level
act:hasStep	hasStep	Connects the composite schema to a constituent act:ActivityStep.	act:ActivityStep	1..*	Mandatory
act:hasDataLink	hasDataLink	Connects the composite schema to a act:DataLink that defines data wiring.	act:DataLink	0..*	Optional
act:hasOrderedSteps	hasOrderedSteps	Defines a strict sequence of `act:ActivityStep`s.	rdf:List	0..1	Conditional
act:hasChoice	hasChoice	Defines a set of mutually exclusive act:ActivityStep options.	act:ActivityStep	0..*	Conditional
act:hasUnorderedSteps	hasUnorderedSteps	Defines a set of `act:ActivityStep`s with no prescribed execution order.	act:ActivityStep	0..*	Conditional

8.4.5.2. Properties

This section provides the detailed normative definitions for the properties of the act:CompositeActivitySchema class.

8.4.5.2.1. Property: hasStep

TABLE 54: Property Definition: act:hasStep

Property	act:hasStep
IRI	https://www.spatialwebfoundation.org/ns/hsml/activity#hasStep
JSON name	hasStep
Requirement Level	Mandatory
Cardinality	1..*
Domain	act:CompositeActivitySchema
Range	act:ActivityStep

Definition	Connects a composite schema to a constituent `act:ActivityStep`.
Usage Note	Every composite schema must contain at least one step.

8.4.5.2.2. Property: hasDataLink

TABLE 55: Property Definition: act:hasDataLink

Property	`act:hasDataLink`
IRI	`https://www.spatialwebfoundation.org/ns/hsml/activity#hasDataLink`
JSON name	`hasDataLink`
Requirement Level	Optional
Cardinality	0..*
Domain	`act:CompositeActivitySchema`
Range	`act:DataLink`
Definition	Connects a composite schema to a `act:DataLink` that defines data wiring.
Usage Note	Used to make the data dependencies between steps explicit.

8.4.5.2.3. Property: hasOrderedSteps

TABLE 56: Property Definition: act:hasOrderedSteps

Property	`act:hasOrderedSteps`
IRI	`https://www.spatialwebfoundation.org/ns/hsml/activity#hasOrderedSteps`
JSON name	`hasOrderedSteps`
Requirement Level	Conditional
Cardinality	0..1
Domain	`act:CompositeActivitySchema`
Range	`rdf:List`
Definition	Defines a strict sequence of `act:ActivityStep`s. The value `shall` be a well-formed `rdf:List`.
Usage Note	A composite schema shall use exactly one control flow property. This property defines a sequential workflow.

8.4.5.2.4. Property: hasChoice

TABLE 57: Property Definition: act:hasChoice

Property	`act:hasChoice`
IRI	`https://www.spatialwebfoundation.org/ns/hsml/activity#hasChoice`
JSON name	`hasChoice`
Requirement Level	Conditional
Cardinality	0..*
Domain	`act:CompositeActivitySchema`
Range	`act:ActivityStep`
Definition	Defines a set of mutually exclusive `act:ActivityStep` options.
Usage Note	A composite schema **shall** use exactly one control flow property. If used, this property **shall** link to two or more steps.

8.4.5.2.5. Property: hasUnorderedSteps

TABLE 58: Property Definition: act:hasUnorderedSteps

Property	`act:hasUnorderedSteps`
IRI	`https://www.spatialwebfoundation.org/ns/hsml/activity#hasUnorderedSteps`
JSON name	`hasUnorderedSteps`
Requirement Level	Conditional
Cardinality	0..*
Domain	`act:CompositeActivitySchema`
Range	`act:ActivityStep`
Definition	Defines a set of `act:ActivityStep`s with no prescribed execution order.
Usage Note	A composite schema **shall** use exactly one control flow property. This defines a set of steps that may be executed in parallel, subject to data dependencies.

8.4.6. Class: act:ActivityStep

The class `act:ActivityStep` realizes the ACTIVITY STEP concept as part of a `act:CompositeActivitySchema` in IEEE P2874™/D-3.3.1-2025-03, Clause 6.6.3.

> An ACTIVITY STEP is an addressable node within a composite activity's workflow, representing a discrete stage of execution that uses a specific `act:ActivitySchema` to define its logic.

`act:ActivityStep` is a structural component used to build complex workflows. It acts as a placeholder or node in a workflow graph, separating the structure of the workflow from the logic of the individual steps. This allows for the creation of modular, reusable, and governable multi-step processes with declarative control flow, including conditional branching.

Key Requirements

- **Context**: An `act:ActivityStep` **SHALL** only exist as part of a `act:CompositeActivitySchema`, linked via properties like `act:hasStep`.
- **Logic Definition**: An `act:ActivityStep` **SHALL** reference exactly one `act:ActivitySchema` via the `act:usesSchema` property to define its executable logic.
- **Identification**: An `act:ActivityStep` **SHOULD** have a simple, locally-unique `schema:identifier` to simplify referencing within the workflow definition.
- **Description**: An `act:ActivityStep` **SHOULD** have a human-readable `schema:name` for display purposes and **MAY** have a `schema:description` for detailed documentation.
- **Conditional Execution**: An `act:ActivityStep` **MAY** include an `act:hasCondition` to enable conditional branching within a workflow.

8.4.6.1. Class Definition

TABLE 59: Class Definition for act:ActivityStep

RDF Class	`act:ActivityStep`
Is Abstract	No
Definition	A unique, addressable step within a `act:CompositeActivitySchema`. Each step is an element of the workflow that points to an `act:ActivitySchema` it executes and can be annotated with names, descriptions, and conditional logic.
Subclass Of	`owl:Thing`
Usage Note	An `act:ActivityStep` acts as a node in a workflow graph. It is a structural placeholder that defines a unit of work.
Rationale	Modeling steps as first-class entities makes the workflow structure explicit, addressable, and governable, allowing metadata, documentation, and conditional logic to be attached to individual stages of a process.

TABLE 60: Properties Summary for act:ActivityStep

Predicate	JSON-LD name	Description	Range	Cardin	Requirement Level
act:usesSchema	usesSchema	Links the step to the act:ActivitySchema defining its logic.	act:ActivitySchema	1..1	Mandatory
schema:name	name	A short, human-readable name for the step.	xsd:string	0..1	Recommended
schema:description	description	A detailed explanation of the step's purpose.	xsd:string	0..1	Optional
act:hasCondition	hasCondition	A condition that must be met for this step to be executed.	core:Condition	0..1	Optional
schema:identifier	identifier	A unique identifier for the step within its composite schema.	xsd:string	0..1	Recommended

8.4.6.2. Properties

This section provides the detailed normative definitions for the properties of the act:ActivityStep class.

8.4.6.2.1. Property: usesSchema

TABLE 61: Property Definition: act:usesSchema

Property	act:usesSchema
IRI	https://www.spatialwebfoundation.org/ns/hsml/activity#usesSchema
JSON name	usesSchema
Requirement Level	Mandatory
Cardinality	1..1
Domain	act:ActivityStep
Range	act:ActivitySchema
Definition	Links an act:ActivityStep to the act:ActivitySchema that defines its executable logic.
Usage Note	The referenced schema can be either atomic or another composite schema, allowing for nested workflows.

8.4.6.2.2. Property: name

TABLE 62: Property Definition: schema:name

Property	`schema:name`
IRI	`https://schema.org/name`
JSON name	`name`
Requirement Level	Recommended
Cardinality	0..1
Domain	`act:ActivityStep`
Range	`xsd:string`
Definition	A short, human-readable name for the activity step.
Usage Note	This property is intended for display in user interfaces, such as workflow diagrams or logs. For example: "Validate User Credentials". Reuses the property from Schema.org.

8.4.6.2.3. Property: description

TABLE 63: Property Definition: schema:description

Property	`schema:description`
IRI	`https://schema.org/description`
JSON name	`description`
Requirement Level	Optional
Cardinality	0..1
Domain	`act:ActivityStep`
Range	`xsd:string`
Definition	A detailed explanation of the step's purpose, inputs, outputs, or behavior.
Usage Note	This property is for documentation and maintainability, helping developers understand the role of the step in the overall process. Reuses the property from Schema.org.

8.4.6.2.4. Property: hasCondition

TABLE 64: Property Definition: act:hasCondition

Property	`act:hasCondition`
IRI	`https://www.spatialwebfoundation.org/ns/hsml/activity#hasCondition`
JSON name	`hasCondition`
Requirement Level	Optional
Cardinality	0..1
Domain	`act:ActivityStep`
Range	`core:Condition`
Definition	An optional condition that must evaluate to true for this step to be eligible for execution.
Usage Note	This property provides the mechanism for conditional control flow. When multiple steps are presented as part of an `act:hasChoice` construct, the runtime engine SHALL evaluate the `act:hasCondition` for each step. The first step whose condition evaluates to true SHALL be the path that is executed.

8.4.6.2.5. Property: identifier

TABLE 65: Property Definition: schema:identifier

Property	`schema:identifier`
IRI	`https://schema.org/identifier`
JSON name	`identifier`
Requirement Level	Recommended
Cardinality	0..1
Domain	`act:ActivityStep`
Range	`xsd:string`
Definition	A locally unique, human-friendly identifier for the step.
Usage Note	This identifier provides a simple, stable "nickname" (e.g., "stepA", "validateUser") that SHOULD be used to uniquely identify the step within its parent `act:CompositeActivitySchema`. This makes it easier for `act:DataLink` instances to reliably reference the step as a source or target without using long, complex URIs.

8.4.7. Class: act:DataLink

The class `act:DataLink` realizes the DATA LINK concept as part of a `act:CompositeActivitySchema` in IEEE P2874™/D-3.3.1-2025-03, Clause 6.6.3.

> A DATA LINK is a construct for connecting the data flow between steps in a composite activity.

`act:DataLink` is a structural entity that explicitly models the "wiring" of data within a complex workflow. It connects the output of one step to the input of another, or links the inputs and outputs of the composite schema to its internal steps. By modeling data flow as a first-class entity, the standard makes it addressable, auditable, and governable.

Key Requirements

- Context: An `act:DataLink` SHALL only exist as part of a `act:CompositeActivitySchema`, linked via the `act:hasDataLink` property.
- Source Specification: An `act:DataLink` SHALL identify its data source via `act:sourceVariable` and, if internal, `act:sourceStep`. The link is made using the `schema:identifier` of the respective components.
- Target Specification: An `act:DataLink` SHALL identify its data target via `act:targetVariable` and, if internal, `act:targetStep`. The link is made using the `schema:identifier` of the respective components.
- Interface Wiring: To wire the composite's interface, a `DataLink` SHALL omit either the `sourceStep` (for an input) or `targetStep` (for an output).

8.4.7.1. Class Definition

TABLE 66: Class Definition for act:DataLink

RDF Class	`act:DataLink`
Is Abstract	No
Definition	A directed "wire" defining data flow. It can connect two internal steps, a composite's input to a step, or a step's output to a composite's output.
Subclass Of	`owl:Thing`
Usage Note	Making `act:DataLink` a class allows the data flow itself to be an addressable and governable entity. Metadata (e.g., encryption requirements, Quality of Service policies, names, descriptions) can be attached directly to the link.
Rationale	Elevates the workflow's data flow to be an explicit, governable, and self-describing entity, enabling more sophisticated security and management patterns.

TABLE 67: Properties Summary for act:DataLink

Predicate	JSON-LD name	Description	Range	Cardin	Requirement Level
schema:name	name	A short, human-readable name for the data link.	xsd:string	0..1	Optional
schema:description	description	A detailed explanation of the data link's purpose.	xsd:string	0..1	Optional
act:sourceStep	sourceStep	The identifier of the source act:ActivityStep.	xsd:string	0..1	Conditional
act:targetStep	targetStep	The identifier of the target act:ActivityStep.	xsd:string	0..1	Conditional
act:sourceVariable	sourceVariable	The identifier of the source act:Variable.	xsd:string	1..1	Mandatory
act:targetVariable	targetVariable	The identifier of the target act:Variable.	xsd:string	1..1	Mandatory

8.4.7.2. Properties

This section provides the detailed normative definitions for the properties of the act:DataLink class.

8.4.7.2.1. Property: name

TABLE 68: Property Definition: schema:name

Property	schema:name
IRI	https://schema.org/name
JSON name	name
Requirement Level	Optional
Cardinality	0..1
Domain	act:DataLink
Range	xsd:string
Definition	A short, human-readable name for the data link.
Usage Note	Useful for documenting the workflow. For example: "Pass User ID to Validator". Reuses the property from Schema.org.

8.4.7.2.2. Property: description

TABLE 69: Property Definition: schema:description

Property	schema:description

IRI	`https://schema.org/description`
JSON name	`description`
Requirement Level	Optional
Cardinality	0..1
Domain	`act:DataLink`
Range	`xsd:string`
Definition	A detailed explanation of the data link's purpose or any transformations.
Usage Note	Can be used to explain complex wiring or data handling logic to developers. Reuses the property from Schema.org.

8.4.7.2.3. Property: sourceStep

TABLE 70: Property Definition: act:sourceStep

Property	`act:sourceStep`
IRI	`https://www.spatialwebfoundation.org/ns/hsml/activity#sourceStep`
JSON name	`sourceStep`
Requirement Level	Conditional
Cardinality	0..1
Domain	`act:DataLink`
Range	`xsd:string`
Definition	The identifier of the source `act:ActivityStep` for the data link.
Usage Note	The value of this property SHALL match the `schema:identifier` of an `act:ActivityStep` within the same composite schema. This property is omitted for data links that wire a public input of the composite schema to an internal step.

8.4.7.2.4. Property: targetStep

TABLE 71: Property Definition: act:targetStep

Property	`act:targetStep`
IRI	`https://www.spatialwebfoundation.org/ns/hsml/activity#targetStep`
JSON name	`targetStep`

Requirement Level	Conditional
Cardinality	0..1
Domain	`act:DataLink`
Range	`xsd:string`
Definition	The identifier of the target `act:ActivityStep` for the data link.
Usage Note	The value of this property SHALL match the `schema:identifier` of an `act:ActivityStep` within the same composite schema. This property is omitted for data links that expose the output of an internal step as a public output of the composite schema.

8.4.7.2.5. Property: sourceVariable

TABLE 72: Property Definition: act:sourceVariable

Property	`act:sourceVariable`
IRI	`https://www.spatialwebfoundation.org/ns/hsml/activity#sourceVariable`
JSON name	`sourceVariable`
Requirement Level	Mandatory
Cardinality	1..1
Domain	`act:DataLink`
Range	`xsd:string`
Definition	The identifier of the source `act:Variable` for the data link.
Usage Note	The value of this property SHALL match the `schema:identifier` of an `act:Variable` defined in the source step's schema (or the composite schema itself).

8.4.7.2.6. Property: targetVariable

TABLE 73: Property Definition: act:targetVariable

Property	`act:targetVariable`
IRI	`https://www.spatialwebfoundation.org/ns/hsml/activity#targetVariable`
JSON name	`targetVariable`
Requirement Level	Mandatory

Cardinality	1..1
Domain	`act:DataLink`
Range	`xsd:string`
Definition	The identifier of the target `act:Variable` for the data link.
Usage Note	The value of this property **SHALL** match the `schema:identifier` of an `act:Variable` defined in the target step's schema (or the composite schema itself).

8.4.8. Class: act:Variable

The class `act:Variable` realizes the **VARIABLE** concept as part of an `act:ActivitySchema` in IEEE P2874™/D-3.3.1-2025-03, Clause 6.6.3.

> A VARIABLE represents a typed parameter or binding placeholder within an ACTIVITY SCHEMA, used to specify required inputs, produced outputs, or contextual bindings.

`act:Variable` is a structural component that formally defines the interface for a single parameter within a schema. It supports the **declaration → binding → validation** pipeline by separating the declaration of a variable's expected type from the formal conditions used to enforce its validity.

Key Requirements

- **Identification**: A variable **SHALL** have a locally unique, machine-readable `schema:identifier`. It **SHOULD** also be described with a `schema:name` and **MAY** have a `schema:description`.
- **Declaration**: A variable **SHOULD** declare its expected data type(s) via the `act:expects` property. This serves as a clear, human- and machine-readable declaration of intent.
- **Enforcement**: A variable **MAY** be constrained by one or more `core:Condition` instances. This is the formal mechanism for enforcing complex validation rules.
- **Usage**: Variables **SHALL** be used in an `act:ActivitySchema` to define inputs (`act:hasInput`) or outputs (`act:hasOutput`).

8.4.8.1. Class Definition

TABLE 74: Class Definition for act:Variable

RDF Class	`act:Variable`
Is Abstract	No
Definition	A formal parameter definition for an `act:ActivitySchema`, representing an input, output, or contextual binding.

RDF Class	act:Variable
Subclass Of	owl:Thing
Usage Note	A Variable is a structural component of a schema's interface. It defines the complete signature for a parameter, including its identifier, name, expected type(s), and validation logic.
Rationale	Provides a formal structure for parameterizing Activities, ensuring correctness and reusability. Separating type declaration from validation conditions improves both usability and robustness.

TABLE 75: Properties Summary for act:Variable

Predicate	JSON-LD name	Description	Range	Cardin	Requirement Level
schema:identifier	identifier	A locally unique, machine-readable identifier for the variable.	xsd:string	1..1	Mandatory
schema:name	name	A short, human-readable name for the variable.	xsd:string	0..1	Recommended
schema:description	description	A detailed explanation of the variable's purpose.	xsd:string	0..1	Optional
act:expects	expects	The expected data type or class of the variable's value.	rdfs:Class	0..*	Recommended
core:hasCondition	hasCondition	Declares formal conditions (e.g., value range) applied to the variable's value.	core:Condition	0..*	Optional

8.4.8.2. Properties

This section provides the detailed normative definitions for the properties of the act:Variable class.

8.4.8.2.1. Property: identifier

TABLE 76: Property Definition: schema:identifier

Property	schema:identifier
IRI	https://schema.org/identifier
JSON name	identifier
Requirement Level	Mandatory
Cardinality	1..1
Domain	act:Variable
Range	xsd:string

Definition	A locally unique, machine-readable identifier for the variable.
Usage Note	This identifier SHALL be unique within the scope of the `act:ActivitySchema` where it is defined. It is used for programmatic binding via `act:VariableBinding` and for referencing variables in `act:DataLink` instances (e.g., "targetLocation"). Reuses the property from Schema.org.

8.4.8.2.2. Property: name

TABLE 77: Property Definition: schema:name

Property	`schema:name`
IRI	`https://schema.org/name`
JSON name	`name`
Requirement Level	Recommended
Cardinality	0..1
Domain	`act:Variable`
Range	`xsd:string`
Definition	A short, human-readable name for the variable.
Usage Note	This property provides a human-friendly label for user interfaces and documentation. For example: "Target Location". Reuses the property from Schema.org.

8.4.8.2.3. Property: description

TABLE 78: Property Definition: schema:description

Property	`schema:description`
IRI	`https://schema.org/description`
JSON name	`description`
Requirement Level	Optional
Cardinality	0..1
Domain	`act:Variable`
Range	`xsd:string`
Definition	A detailed explanation of the variable's purpose and usage context.

Usage Note	This property is for documentation and maintainability, helping developers understand the role of the variable. Reuses the property from Schema.org.

8.4.8.2.4. Property: expects

TABLE 79: Property Definition: act:expects

Property	`act:expects`
IRI	`https://www.spatialwebfoundation.org/ns/hsml/activity#expects`
JSON name	`expects`
Requirement Level	Recommended
Cardinality	0..*
Domain	`act:Variable`
Range	`rdfs:Class`
Definition	A declaration of the expected data type(s) or class(es) for the variable's value.
Usage Note	This property provides a simple, direct way for applications to understand the variable's type without needing to parse a `core:Condition`. The range can be an XSD datatype (e.g., `xsd:string`) or another class (e.g., `core:Agent`). The property may be repeated to allow for union types (e.g., a variable that expects either a `core:Agent` or an `xsd:string`). This is the declaration of intent.

8.4.8.2.5. Property: hasCondition

TABLE 80: Property Definition: core:hasCondition

Property	`core:hasCondition`
IRI	`https://www.spatialwebfoundation.org/ns/hsml/core#hasCondition`
JSON name	`hasCondition`
Requirement Level	Optional
Cardinality	0..*
Domain	`act:Variable`
Range	`core:Condition`

Definition	Associates one or more formal conditions that a variable's bound value must satisfy.
Usage Note	This is the **enforcement mechanism**. While `act:expects` declares the basic type, `core:hasCondition` is used to enforce more complex rules, such as value ranges, string patterns (regex), or conformance to a SHACL shape. A `core:SHACLCondition` can also be used to enforce the `act:expects` declaration.

8.4.9. Class: act:VariableBinding

The class `act:VariableBinding` provides the concrete link between an abstract `act:Variable` in a schema and a specific value in an `act:Activity` instance.

`act:VariableBinding` is the mechanism that makes schemas reusable. It connects the abstract parameter slots defined in the `act:ActivitySchema` to the real-world data and entities used in a particular execution, ensuring that every `act:Activity` is a complete and self-contained record.

Key Requirements

- **Variable Reference**: A `act:VariableBinding` **SHALL** reference exactly one `act:Variable` from the parent activity's schema via the `act:variable` property, using the variable's local identifier.
- **Value Assignment**: A `act:VariableBinding` **SHALL** provide exactly one concrete value (either a literal or a resource) via the standard `rdf:value` property.
- **Context**: A `act:VariableBinding` only exists as part of an `act:Activity`, linked via the `act:hasBinding` property.

8.4.9.1. Class Definition

TABLE 81: Class Definition for act:VariableBinding

RDF Class	`act:VariableBinding`
Is Abstract	No
Definition	A binding that connects a `Variable` to a concrete value (object or literal) in the context of an `Activity`.
Subclass Of	`owl:Thing`
Usage Note	This class is the bridge between the abstract schema and the concrete activity. An `act:Activity` will have one `act:VariableBinding` instance for each parameter it provides.
Rationale	Separates the abstract parameter definition from its concrete value, enabling the "Parameter/Binding Pattern" for maximum schema reusability.

TABLE 82: Properties Summary for act:VariableBinding

Predicate	JSON-LD name	Description	Range	Cardin	Requirement Level
act:variable	variable	The identifier of the act:Variable this binding parameterizes.	xsd:string	1..1	Mandatory
rdf:value	value	The concrete value (IRI or Literal) assigned in the binding.	rdfs:Resource or rdfs:Literal	1..1	Mandatory

8.4.9.2. Properties

This section provides the detailed normative definitions for the properties of the act:VariableBinding class.

8.4.9.2.1. Property: variable

TABLE 83: Property Definition: act:variable

Property	act:variable
IRI	https://www.spatialwebfoundation.org/ns/hsml/activity#variable
JSON name	variable
Requirement Level	Mandatory
Cardinality	1..1
Domain	act:VariableBinding
Range	xsd:string
Definition	Connects a VariableBinding to the Variable it parameterizes by referencing the variable's identifier.
Usage Note	The value of this property SHALL match the schema:identifier of an act:Variable defined in the activity's schema. This provides a consistent, portable binding mechanism.

8.4.9.2.2. Property: value

TABLE 84: Property Definition: rdf:value

Property	rdf:value
IRI	http://www.w3.org/1999/02/22-rdf-syntax-ns#value
JSON name	value

Requirement Level	Mandatory
Cardinality	1..1
Domain	`act:VariableBinding`
Range	`rdfs:Resource` or `rdfs:Literal`
Definition	The concrete value assigned in a `VariableBinding`.
Usage Note	This standard RDF property is used to provide the actual data for a specific activity execution. The value can be a literal (e.g., string, number, boolean) or a URI pointing to another entity. The value provided should be validated against the `core:hasCondition` of the bound `act:Variable`.

9. HSML Governance Module

9.1. Architectural Principles and Design Rationale

This clause explains the design choices behind the HSML Governance Module and how they satisfy IEEE P2874™/D-3.3.1-2025-03's requirements for governable, auditable, and interoperable action across Domains. The principles are informative (non-normative), but they motivate the normative models and constraints defined in subsequent clauses.

9.1.1. The Norm/Policy Separation: Atomic Rules vs Governance Bundles

The foundation of the governance model is the separation between atomic rules and the governance bundles that publish them. `act:ActivitySchema` defines the universal semantics of an action—its roles, inputs, outputs, and pre/post conditions—in a way that is portable and immutable across Domains. By contrast, a `gov:Norm` represents a single deontic rule. Each Norm specifies whether an action or state is Obligatory, Prohibited, or Permitted, and links that modality to explicit machine-executable conditions (`core:Condition`). Norms are intentionally minimal: they state "what rule applies, to whom, and under which condition."

To make those rules effective in practice, authorities issue `gov:Policy` artifacts. A Policy bundles one or more Norms and supplies the governance context that a Norm by itself does not carry. Policies declare scope (which actors, activities, or domains the rules apply to), set validity periods, publish lifecycle state, establish ordering in case of conflicts, and—critically—reference credential profiles that define what types of verifiable credentials are acceptable. This separation allows Norms to remain atomic

and reusable across contexts, while Policies provide the authoritative packaging that determines where and when Norms are in force.

9.1.2. Credentials and Credential Profiles

Verifiable Credentials (VCs) are not embedded in Norms but are instead attached to Agents. Norms may presuppose that certain credentials exist, but it is Policies that enforce credential requirements through `gov:CredentialProfile`. A Credential Profile describes, at the type level, what any acceptable VC must satisfy—its type, issuer trust, subject binding, attribute constraints, proof suite, and freshness requirements. During contract validation, Agents present credential instances, and the validation process checks both their cryptographic proofs and their conformance to the profiles declared by the applicable Policies. This design keeps Policies declarative and reusable, while preserving Agent privacy until execution time.

9.1.3. Deontic Modality and Executable Conditions

The heart of each Norm is its deontic modality—Obligation, Prohibition, or Permission—coupled with one or more executable conditions. A Norm is therefore both semantically clear and operational: it not only states the normative force but also the concrete, machine-checkable predicates under which the rule applies. These conditions are expressed in standards-aligned constraint languages such as SHACL, SPARQL ASK, JSON-Schema, or CEL, ensuring determinism, auditability, and interoperability. Policy-level precedence rules determine how to resolve conflicts when multiple Norms apply at once.

9.1.4. Time-Bound Governance

Policies provide temporal boundaries for governance. They carry `schema:validFrom` and `schema:validThrough` properties to indicate when a bundle of Norms is in force. A Policy outside its validity window must not be considered during contract validation. If no end time is declared, the Policy remains in effect until explicitly revoked. Individual Norms may also include effectivity windows when a rule itself is inherently time-limited, but the general assumption is that time-scoping is managed at the Policy level.

9.1.5. Contracts as the Universal Trigger

Execution of every `act:Activity` is mediated through a `gov:Contract`. The Contract acts as the universal trigger and single enforcement point. It records the intent to act, the participating parties, the validation process, and the resulting lifecycle status. By funnelling all execution through Contracts, the module ensures a tamper-evident audit trail that links the governing Policies and Norms, the conditions that were evaluated, the credentials that were presented, and the decision outcomes. This approach guarantees both consistent enforcement and complete traceability.

9.1.6. Trust Substrate and Evidence

The governance model relies on W3C standards for identity and credentials. Spatial Web Identifiers (DIDs) identify Agents, Domains, and Contracts. Verifiable Credentials

supply cryptographic attestations of authority, qualification, or compliance. Validation always includes proof verification, issuer trust assessment, revocation checks, and freshness evaluation. Implementations are expected to persist minimal verification transcripts so that decisions can be independently re-audited, providing accountability without unnecessary data retention.

9.1.7. Evaluation Flow

The governance evaluation process follows a predictable sequence. First, the system discovers which Policies apply given the Domain, ActivitySchema, actors, and time. It then collects the Norms bundled in those Policies and applies precedence rules to resolve conflicts. Next, the system verifies that the Agent's credentials satisfy the CredentialProfiles declared by the Policies. Once credential gates are passed, the executable conditions associated with the Norms are evaluated against the current state. The combined results yield a decision—permit, deny, or permit with obligations—which is recorded in the Contract along with evidence. If permitted, obligations may be monitored at runtime, and violations may trigger enforcement actions.

9.1.8. Interoperability and Extensibility

The model is designed to be interoperable across heterogeneous Domains. Activities are always referenced by IRIs, making schema usage neutral. Conditions are pluggable: any standards-aligned constraint language can be used so long as it is identifiable by content type. Policies can be composed hierarchically to represent organizational or jurisdictional layers. Evidence is linked but content-agnostic, allowing different proof suites and VC profiles to interoperate.

9.1.9. Security and Privacy

Finally, the governance design incorporates privacy and security considerations. Policies declare only credential types, never instances, limiting disclosure. Contracts bind VC presentations to specific transactions, preventing replay. Selective disclosure and zero-knowledge proofs are preferred when only one attribute is needed. Revocation checks are repeated when contracts extend across expiry or state changes, preventing drift. Together these measures ensure least disclosure, freshness, and resistance to side-channel leakage.

9.2. Normative Classes

This clause provides the normative definitions for all class concepts. It is divided into two parts: classes that are defined as part of this Governance Module, and classes from the HSML Core Module that are normatively used by this module.

The namespace prefix `gov:` refers to `https://www.spatialwebfoundation.org/ns/hsml/governance#/`.

9.2.1. Summary of Governance Module Classes

TABLE 85: Summary of Classes Used in the HSML Governance Module

Class	Description
gov:Contract	The binding agreement that initiates and governs the execution of one or more `act:Activity` instances.
gov:Credential	A tamper-evident, cryptographically verifiable set of claims, as defined by the W3C VC standard, used for authentication and authorization.
gov:CredentialProfile	A reusable bundle of constraints describing what a Verifiable Credential instance MUST satisfy (type, issuer/trust, subject binding, attribute constraints, proof, freshness)
gov:Norm	An atomic deontic rule (Obligation, Prohibition, Permission) governing behavior in a Domain, expressed as one or more executable Conditions.
gov:Policy	A governance artifact issued by an authority, bundling one or more Norms, and declaring their scope, applicability, and lifecycle.
gov:DeonticModality	An enumeration class that defines the set of allowable deontic modalities for Norms (`Obligation`, `Prohibition`, `Permission`).

9.2.2. Class: gov:Contract

The class `gov:Contract` realises the **CONTRACT** concept in IEEE P2874™/D-3.3.1-2025-03, Clause 6.6.4:

> A binding agreement between two or more parties—enforceable by law or internal policy—that governs one or more Activities in the Spatial Web.

`gov:Contract` links the initiating **Domain**, the participating **Agents**, the governed **Activity** (or Activities), and the evolving **ContractStatus** instances that capture its lifecycle.

Key Requirements

- **Identity** Every Contract **SHALL** possess a Spatial Web Identifier (`core:swid`, W3C DID Core-compliant).
- **Initiator** Exactly one `gov:isRequestedBy` **SHALL** reference the **Domain** that issued the request.
- **Acceptance** One or more `gov:isAcceptedBy` references **SHALL** identify the Agent(s) that accept the terms.
- **Fulfilment** One or more `gov:isFulfilledBy` references **SHALL** identify the Agent(s) responsible for execution.
- **Governed Activity** One or more `gov:contractFor` references **SHALL** identify the Activity(ies) the contract governs.
- **Lifecycle** `gov:contractStatus` references **SHALL** record the contract's state
- **Extensibility** Additional clauses, policy links, or monetary terms **MAY** be added via further properties or subclasses without altering these core semantics.

These rules guarantee that every contract is discoverable, auditable, and machine-actionable across Spatial-Web systems.

9.2.2.1. Class Definition

TABLE 86: Class Definition for gov:Contract

RDF Class	`gov:Contract`
Is Abstract	No
Definition	A binding agreement governing the execution of one or more `act:Activity` instances by specific `agt:Agent`s within a `core:Domain` context.
Subclass Of	`core:Entity`
Usage Notes	A `gov:Contract` must carry a SWID and link to its initiating domain, accepting and fulfilling agents, the governed activity, and its lifecycle status. For detailed roles, it uses `core:Participation` records.

TABLE 87: Properties Summary for gov:Contract

Predicate	JSON-LD name	Description	Range	Cardin	Requirement Level
`gov:isRequestedBy`	`requestedBy`	The `core:Domain` that initiated the contract.	`core:Domain`	1..1	Mandatory
`gov:isAcceptedBy`	`acceptedBy`	The `agt:Agent`(s) that accepted the contract.	`agt:Agent`	1..*	Mandatory
`gov:isFulfilledBy`	`fulfilledBy`	The `agt:Agent`(s) responsible for fulfilling the contract.	`agt:Agent`	1..*	Mandatory
`gov:contractFor`	`contractFor`	The `act:Activity` the contract governs.	`act:Activity`	1..*	Mandatory
`gov:contractStatus`	`contractStatus`	The current lifecycle status of the contract.	`xsd:string`	1..1	Mandatory
`gov:hasParticipatic`	`hasParticipatic`	Links to detailed participation records.	`core:Participatic`	0..*	Optional

9.2.2.2. Properties

This section provides the detailed normative definitions for the `gov:Contract` class.

9.2.2.2.1. Property: isRequestedBy

TABLE 88: Property Definition: gov:isRequestedBy

Property	`gov:isRequestedBy`

IRI	`https://www.spatialwebfoundation.org/ns/hsml/governance#isRequestedBy`
JSON name	`requestedBy`
Requirement Level	Mandatory
Cardinality	1..1
Domain	`gov:Contract`
Range	`core:Domain`
Definition	Identifies the `core:Domain` that initiated or requested creation of the contract.
Usage Note	Exactly one initiating `core:Domain` is recorded.

9.2.2.2.2. Property: isAcceptedBy

TABLE 89: Property Definition: gov:isAcceptedBy

Property	`gov:isAcceptedBy`
IRI	`https://www.spatialwebfoundation.org/ns/hsml/governance#isAcceptedBy`
JSON name	`acceptedBy`
Requirement Level	Mandatory
Cardinality	1..*
Domain	`gov:Contract`
Range	`agt:Agent`
Definition	Identifies the `agt:Agent`(s) formally accepting the contract.
Usage Note	Multi-party contracts must list every accepting `agt:Agent`.

9.2.2.2.3. Property: isFulfilledBy

TABLE 90: Property Definition: gov:isFulfilledBy

Property	`gov:isFulfilledBy`
IRI	`https://www.spatialwebfoundation.org/ns/hsml/governance#isFulfilledBy`
JSON name	`fulfilledBy`
Requirement Level	Mandatory

Cardinality	1..*
Domain	gov:Contract
Range	agt:Agent
Definition	Identifies the agt:Agent(s) tasked with fulfilling the contractual obligations.
Usage Note	This is often, but not always, the same agt:Agent(s) as gov:isAcceptedBy.

9.2.2.2.4. Property: contractFor

TABLE 91: Property Definition: gov:contractFor

Property	gov:contractFor
IRI	https://www.spatialwebfoundation.org/ns/hsml/governance#contractFor
JSON name	contractFor
Requirement Level	Mandatory
Cardinality	1..*
Domain	gov:Contract
Range	act:Activity
Definition	Identifies the act:Activity (or Activities) that this contract governs.
Usage Note	This property links the agreement to the specific action(s) to be executed.

9.2.2.2.5. Property: contractStatus

TABLE 92: Property Definition: gov:contractStatus

Property	gov:contractStatus
IRI	https://www.spatialwebfoundation.org/ns/hsml/governance#contractStatus
JSON name	contractStatus
Requirement Level	Mandatory
Cardinality	1..1
Domain	gov:Contract
Range	xsd:string

Definition	The current lifecycle state of the contract. The value **shall** be one of: "Requested", "Executed", "Fulfilled", "Rescinded", or "Breached".
Usage Note	This property provides the current state of the agreement. For a full audit trail, a history of status changes with timestamps should be recorded.

9.2.2.2.6. Property: hasParticipation

TABLE 93: Property Definition: gov:hasParticipation

Property	`gov:hasParticipation`
IRI	`https://www.spatialwebfoundation.org/ns/hsml/governance#hasParticipation`
JSON name	`hasParticipation`
Requirement Level	Optional
Cardinality	0..*
Domain	`gov:Contract`
Range	`core:Participation`
Definition	Links the contract to detailed participation records.
Usage Note	Use for complex contracts to explicitly define agent roles beyond requester/fulfiller.

9.2.3. Class: `gov:Credential`

The class `gov:Credential` realizes the CREDENTIAL concept in IEEE P2874™/D-3.3.1-2025-03, Clause 6.6.3. It specializes the W3C VC Data Model to carry attestations that govern identity, authorization, compliance, and trust across Domains and Activities.

9.2.3.1. Key Requirements (Normative)

1. A `gov:Credential` **shall** be processable as a W3C Verifiable Credential (VC); core VC fields (e.g., `issuer`, `credentialSubject`, `proof`) **shall** be supported.
2. Verification **shall** be two-stage:
   a. Cryptographic — verify `proof` per the VC spec; failure **shall** reject the credential.
   b. Semantic (conditional) — if a schema is discoverable (from policy via `gov:CredentialProfile` and/or from `gov:hasSchema` in the credential), the `credentialSubject` **shall** be validated accordingly; failure **shall** make it semantically invalid for the intended purpose.
3. A credential **need not embed** a schema; policies typically provide schema/constraints via `gov:CredentialProfile`. If present, a schema pointer **shall** use `gov:hasSchema`.

4. Implementations **should** support multiple schema languages (e.g., SHACL, JSON Schema) and select a validator based on the schema's media type and/or RDF type.

9.2.3.2. Class Definition

TABLE 94: Class Definition for gov:Credential

RDF Class	`gov:Credential`
Is Abstract	No
Definition	An Entity representing a permission, attestation, or claim that can be verified or required in the Spatial Web.
Subclass Of	`vc:VerifiableCredential`, `core:Entity`
Usage Note	Schema pointers are optional because policy-linked `gov:CredentialProfile` typically supplies schema/constraints.

9.2.3.3. Properties Summary

TABLE 95: Properties Summary for gov:Credential

Predicate	JSON-LD name	Description	Range	Cardin.	Requirement
`gov:conformsToProfile`	`conformsToProfile`	Declares an intended `gov:CredentialProfile` this credential claims to satisfy (hint for evaluators; policy is authoritative).	`gov:CredentialProfile`	0..*	Optional

9.2.3.4. Properties

9.2.3.4.1. Property: conformsToProfile

TABLE 96: Property Definition: gov:conformsToProfile

Property	`gov:conformsToProfile`
IRI	`https://www.spatialwebfoundation.org/ns/hsml/governance#conformsToProfile`
JSON name	`conformsToProfile`
Requirement Level	Optional
Cardinality	0..*
Domain	`gov:Credential`
Range	`gov:CredentialProfile`

Definition	Identifies a credential profile the credential claims to meet; used as a routing/validation hint.
Usage Note	Policy evaluation is governed by the policy's required gov:CredentialProfile(s), not by this self-assertion.

9.2.3.5. Credential Validation Process

1. Stage 1 — Cryptographic (MUST): Verify `proof` per VC spec; reject on failure.
2. Stage 2 — Semantic (IF schema discoverable): If policy requires a gov:CredentialProfile and/or the credential provides gov:hasSchema, fetch the schema and validate `credentialSubject` using a suitable engine for the media type or RDF type.

9.2.3.6. Requirements for Policy Engines

1. Policies **should** specify credential type/class and constraints via gov:CredentialProfile; engines **shall** fetch and apply referenced schemas.
2. Engines **shall** support gov:hasSchema (generic). gov:hasClaimSchema is processed only as a deprecated alias.

9.2.4. Class: gov:CredentialProfile

The class gov:CredentialProfile bundles the **requirements a Verifiable Credential instance MUST satisfy** to pass a policy's credential gate. It unifies (a) the **credential class/type**, (b) **subject/holder binding rules**, and © **attribute / issuer / trust / proof / freshness** constraints into a single reusable profile.

gov:CredentialProfile is referenced by Policies (and Norms) and evaluated at gov:Contract validation time against presented VC instances.

Key Requirements

- Type Basis A profile **SHALL** specify the acceptable credential class via gov:profileOfCredentialType.
- Conformance Presented VC instances **MUST** conform to all constraints in the profile (shapes, conditions, issuer/trust, status, proof suites, freshness, subject binding).
- Reusability Profiles **SHOULD** be reusable across Policies; Policies reference profiles rather than hard-coding constraints.

9.2.4.1. Class Definition

TABLE 97: Class Definition for gov:CredentialProfile

RDF Class	gov:CredentialProfile
Is Abstract	No

RDF Class	gov:CredentialProfile
Definition	A reusable bundle of constraints describing what a Verifiable Credential instance MUST satisfy (type, issuer/trust, subject binding, attribute constraints, proof, freshness).
Subclass Of	dct:Standard (recommended)
Usage Notes	Profiles may be versioned and governed by a Domain. Use with dct:conformsTo during verification.

TABLE 98: Properties Summary for gov:CredentialProfile

Predicate	JSON-LD name	Description	Range	Card.	Level
gov:profileOfCredentialType	profileOfCredentialType	The base credential class/type this profile constrains.	cred:CredentialType	1..1	Mandatory
gov:credentialShape	credentialShape	SHACL shape(s) the VC instance MUST satisfy (claims structure/content).	sh:NodeShape	0..*	Optional
core:hasCondition	hasCondition	Executable conditions evaluated against VC (and/or subject) claims.	core:Condition	0..*	Optional
gov:acceptableIssuer	acceptableIssuer	Allowlisted issuers whose VCs are accepted for this profile.	agt:Agent or core:Domain	0..*	Optional
gov:trustFramework	trustFramework	Named trust framework governing status & crypto evaluation.	skos:Concept	0..*	Optional
gov:statusPolicy	statusPolicy	Required status (e.g., not Revoked / StatusList2021: valid).	xsd:string	0..1	Optional
gov:issuedWithin	issuedWithin	Max credential age at validation (duration, e.g., P1Y).	xsd:duration	0..1	Optional
gov:requiresSubjectBinding	requiresSubjectBinding	VC subject MUST be bound to the performing Agent's identifier.	xsd:boolean	0..1	Optional
gov:proofSuite	proofSuite	Acceptable cryptographic proof suites (e.g., Ed25519Signature2020).	skos:Concept	0..*	Optional
gov:profileVersion	profileVersion	Version identifier of this profile.	xsd:string	0..1	Optional

9.2.4.2. Properties

9.2.4.2.1. Property: profileOfCredentialType

TABLE 99: Property Definition: gov:profileOfCredentialType

Property	`gov:profileOfCredentialType`
IRI	`https://www.spatialwebfoundation.org/ns/hsml/governance#profileOfCredentialType`
JSON name	`profileOfCredentialType`
Requirement Level	Mandatory
Cardinality	1..1
Domain	`gov:CredentialProfile`
Range	`cred:CredentialType`
Definition	Points to the base credential class that instances MUST instantiate to be eligible under this profile.
Usage Note	The instance's `@type` MUST equal or subclass this type.

9.2.4.2.2. Property: credentialShape

TABLE 100: Property Definition: gov:credentialShape

Property	`gov:credentialShape`
IRI	`https://www.spatialwebfoundation.org/ns/hsml/governance#credentialShape`
JSON name	`credentialShape`
Requirement Level	Optional
Cardinality	0..*
Domain	`gov:CredentialProfile`
Range	`sh:NodeShape`
Definition	SHACL NodeShape(s) that MUST validate true for a presented VC instance.
Usage Note	Use to assert claim presence, formats, enumerations, nested subject constraints, etc.

9.2.4.2.3. Property: hasCondition

TABLE 101: Property Definition: core:hasCondition

Property	`core:hasCondition`
IRI	`https://www.spatialwebfoundation.org/ns/hsml/core#hasCondition`
JSON name	`hasCondition`
Requirement Level	Optional
Cardinality	0..*
Domain	`gov:CredentialProfile`
Range	`core:Condition`
Definition	Machine-executable conditions over VC/subject/environment (e.g., assurance ≥ X, role in org Y).
Usage Note	Reuses HSML Core; express as SHACL rules, SPARQL ASK templates, or CEL expressions.

9.2.4.2.4. Property: acceptableIssuer

TABLE 102: Property Definition: gov:acceptableIssuer

Property	`gov:acceptableIssuer`
IRI	`https://www.spatialwebfoundation.org/ns/hsml/governance#acceptableIssuer`
JSON name	`acceptableIssuer`
Requirement Level	Optional
Cardinality	0..*
Domain	`gov:CredentialProfile`
Range	`agt:Agent` or `core:Domain`
Definition	Whitelist of issuers permitted for credentials conforming to this profile.
Usage Note	Combine with `gov:trustFramework` and revocation checks.

9.2.4.2.5. Property: trustFramework

TABLE 103: Property Definition: gov:trustFramework

Property	`gov:trustFramework`

IRI	`https://www.spatialwebfoundation.org/ns/hsml/governance#trustFramework`
JSON name	`trustFramework`
Requirement Level	Optional
Cardinality	0..*
Domain	`gov:CredentialProfile`
Range	`skos:Concept`
Definition	Named trust framework policy guiding verification and status handling.
Usage Note	Examples: “GovID-EU-eIDAS-High”, “Aviation-FAA-Ops”.

9.2.4.2.6. Property: statusPolicy

TABLE 104: Property Definition: gov:statusPolicy

Property	`gov:statusPolicy`
IRI	`https://www.spatialwebfoundation.org/ns/hsml/governance#statusPolicy`
JSON name	`statusPolicy`
Requirement Level	Optional
Cardinality	0..1
Domain	`gov:CredentialProfile`
Range	`xsd:string`
Definition	Required VC status condition (e.g., “notRevoked”, “StatusList2021:valid”).
Usage Note	Mapped to concrete verifier behavior.

9.2.4.2.7. Property: issuedWithin

TABLE 105: Property Definition: gov:issuedWithin

Property	`gov:issuedWithin`
IRI	`https://www.spatialwebfoundation.org/ns/hsml/governance#issuedWithin`
JSON name	`issuedWithin`
Requirement Level	Optional

Cardinality	0..1
Domain	`gov:CredentialProfile`
Range	`xsd:duration`
Definition	Maximum credential age at validation time.
Usage Note	Evaluated against VC `issuanceDate`; ensure VC not expired.

9.2.4.2.8. Property: requiresSubjectBinding

TABLE 106: Property Definition: gov:requiresSubjectBinding

Property	`gov:requiresSubjectBinding`
IRI	`https://www.spatialwebfoundation.org/ns/hsml/governance#requiresSubjectBinding`
JSON name	`requiresSubjectBinding`
Requirement Level	Optional
Cardinality	0..1
Domain	`gov:CredentialProfile`
Range	`xsd:boolean`
Definition	If true, the VC subject MUST be bound to the performing Agent's identifier at contract time.
Usage Note	Enforce via holder binding or subject DID equality checks.

9.2.4.2.9. Property: proofSuite

TABLE 107: Property Definition: gov:proofSuite

Property	`gov:proofSuite`
IRI	`https://www.spatialwebfoundation.org/ns/hsml/governance#proofSuite`
JSON name	`proofSuite`
Requirement Level	Optional
Cardinality	0..*
Domain	`gov:CredentialProfile`
Range	`skos:Concept`

Definition	Acceptable proof suites for presented VCs (e.g., Ed25519Signature2020, ECDSA-JWS).
Usage Note	Profiles may list multiple acceptable suites for interoperability.

9.2.4.2.10. Property: profileVersion

TABLE 108: Property Definition: gov:profileVersion

Property	`gov:profileVersion`
IRI	`https://www.spatialwebfoundation.org/ns/hsml/governance#profileVersion`
JSON name	`profileVersion`
Requirement Level	Optional
Cardinality	0..1
Domain	`gov:CredentialProfile`
Range	`xsd:string`
Definition	Version identifier of the profile for audit/change control.
Usage Note	Consider semantic versioning; deprecate older profiles via publisher policy.

9.2.5. Class: gov:DeonticModality

The class `gov:DeonticModality` defines the **enumerated values** of deontic force that a `gov:Norm` may express. It provides the controlled vocabulary for `gov:modality` values.

Key Requirements

- **Identity** Every modality value **SHALL** be globally identified by an IRI in the `gov:` namespace.
- **Closed Enumeration** Allowed values are strictly limited to: `gov:Obligation`, `gov:Prohibition`, `gov:Permission`.
- **Usage** Every `gov:Norm` **MUST** reference exactly one `gov:DeonticModality` via `gov:modality`.

9.2.5.1. Class Definition

TABLE 109: Class Definition for gov:DeonticModality

RDF Class	`gov:DeonticModality`
Is Abstract	Yes (enumeration)

RDF Class	gov:DeonticModality
Definition	An enumeration class for deontic modalities representing the normative force of a Norm.
Subclass Of	skos:Concept (optional alignment)
Usage Notes	Used only as the range of gov:modality. Instances are controlled vocabulary individuals.

9.2.5.2. Individuals

TABLE 110: Enumeration Values of gov:DeonticModality

Individual	Description
gov:Obligation	A Norm requiring that an action **must** be performed or a condition **must** hold.
gov:Prohibition	A Norm requiring that an action **must not** be performed or a condition **must not** hold.
gov:Permission	A Norm indicating that an action **may** be performed or a condition **may** hold (neither required nor forbidden).

9.2.6. Class: gov:Norm

The class gov:Norm realizes the **NORM** concept in IEEE P2874™/D-3.3.1-2025-03, Clause 6.6.4:

> An atomic deontic rule—Obligation, Prohibition, or Permission—governing behavior in a Domain and expressed via one or more evaluable Conditions.

A Norm is the **atomic rule unit**: it specifies what modality (obligation, prohibition, permission) applies to which targets, and under which conditions. It does **not** carry issuer, validity, credential gates, or precedence; those are modeled at the gov:Policy level. Policies must reference one or more Norms via gov:hasNorm.

9.2.6.1. Class Definition

TABLE 111: Class Definition for gov:Norm

RDF Class	gov:Norm
Is Abstract	No
Definition	An atomic deontic rule (Obligation/Prohibition/Permission) expressed by executable conditions and applied to specific targets.
Subclass Of	core:Entity
Usage Notes	Norms define one rule. Policies package and govern them.

9.2.6.2. Key Requirements (Normative)

1. A gov:Norm **shall** declare exactly one gov:modality (Obligation, Prohibition, Permission).
2. A gov:Norm **shall** specify one or more governed targets via gov:appliesTo.
3. A gov:Norm **shall** include one or more core:hasCondition that operationalize applicability.
4. A gov:Norm **may** declare enforcement actions via gov:onViolation.
5. A gov:Norm **may** include an intra-policy ordering hint via gov:priority.
6. A gov:Policy **shall** reference one or more gov:Norm when publishing governance bundles.

9.2.6.3. Properties Summary

TABLE 112: Properties Summary for gov:Norm

Predicate	JSON-LD name	Description	Range	Cardin.	Requirement
gov:appliesTo	appliesTo	Targets governed by the norm (agents, activities, domains, or role classes).	core:Entity or rdfs:Class	1..*	Mandatory
core:hasCondition	hasCondition	Executable conditions for applicability/evaluation.	core:Condition	1..*	Mandatory
gov:modality	modality	Deontic modality of the rule (Obligation, Prohibition, Permission).	gov:DeonticModality	1..1	Mandatory
gov:onViolation	onViolation	Enforcement action(s) if violated.	gov:EnforcementAction	0..*	Optional
gov:priority	priority	Resolution priority within a policy bundle.	xsd:integer	0..1	Optional

9.2.6.4. Properties

9.2.6.4.1. Property: modality

TABLE 113: Property Definition: gov:modality

Property	gov:modality
IRI	https://www.spatialwebfoundation.org/ns/hsml/governance#modality
JSON name	modality
Requirement Level	Mandatory
Cardinality	1..1

Domain	gov:Norm
Range	gov:DeonticModality
Definition	Declares the deontic force of the norm.
Usage Note	Allowed values: gov:Obligation, gov:Prohibition, gov:Permission.

9.2.7. Class: gov:Policy

The class gov:Policy is a governance artifact issued by an authority to **declare scope**, **bundle Norms**, and **gate execution** of Activities via credential requirements. A Policy does not itself execute rules; rather, it references executable core:Condition`s (directly or via `gov:Norm) and **type-level** credential requirements expressed as gov:CredentialProfile. Policy validity is time-scoped using schema:validFrom and schema:validThrough.

Design Notes

- **Bundled Norms** Policies collect one or more gov:Norm (Obligation/Prohibition/Permission) that apply within the policy's declared scope.
- **Credential Gating (Type-level)** Policies reference one or more reusable gov:CredentialProfile via gov:hasCredentialRequirement. Each profile specifies an allowed credential **type/class** and the constraints that any presented **credential instance** must satisfy at gov:Contract validation time.
- **Conditions Reuse** Policies MAY also include additional core:hasCondition for policy-level applicability or evaluation (e.g., jurisdictional, temporal, or role constraints) without redefining the Condition class.

9.2.7.1. Class Definition

TABLE 114: Class Definition for gov:Policy

RDF Class	gov:Policy
Is Abstract	No
Definition	A governance artifact that declares scope, bundles one or more Norms, and specifies credential profiles that authoritatively gate Activity execution.
Subclass Of	core:Entity
Usage Notes	Policies are time-scoped with schema:validFrom/schema:validThrough. Credential gates reference gov:CredentialProfile (type-level). Instance-level credential verification occurs during gov:Contract validation.

TABLE 115: Properties Summary for gov:Policy

Predicate	JSON-LD name	Description	Range	Cardin	Requirement
schema:description	rationale	Human-readable rationale/summary.	xsd:string	0..1	Optional
schema:creator	issuedBy	Issuing authority (Domain or Agent) responsible for the policy.	core:Domain or agt:Agent	1..1	Mandatory
schema:validFrom	validFrom	Start of the policy's validity window (inclusive).	xsd:dateTime	1..1	Mandatory
schema:validThrough	validThrough	End of the policy's validity window (exclusive). Omit for open-ended.	xsd:dateTime	0..1	Recommended
gov:appliesToActivitySchema	appliesToActivitySchema	Activity schema(s) governed by this policy.	act:ActivitySchema	1..*	Mandatory
gov:appliesToDomain	appliesToDomain	Domain(s) (places/orgs/contexts) where the policy applies.	core:Domain	0..*	Optional
gov:appliesToActorClass	appliesToActorClass	Actor/role classes targeted (e.g., Pilot, Contractor).	rdfs:Class	0..*	Optional
gov:hasNorm	hasNorm	Bundled atomic deontic rules governed by this policy.	gov:Norm	1..*	Mandatory
core:hasCondition	hasCondition	Additional executable applicability/evaluation conditions.	core:Condition	0..*	Optional
gov:hasCredentialRequirement	hasCredentialRequirement	Type-level credential gate(s) expressed as reusable profiles.	gov:CredentialProfile	0..*	Optional
gov:precedence	precedence	Policy priority for conflict resolution (higher wins).	xsd:integer	0..1	Optional
gov:policyStatus	policyStatus	Lifecycle status (e.g., Draft, Active, Suspended, Retired).	xsd:string	0..1	Optional
schema:version	version	Policy version identifier.	xsd:string	0..1	Optional
schema:spatialCoverage	jurisdiction	Geographic or legal jurisdiction in scope.	schema:Place or skos:Concept	0..*	Optional
gov:relatedPolicy	relatedPolicy	Links to superseding/subordinate/peer policies.	gov:Policy	0..*	Optional

9.2.7.2. Properties

9.2.7.2.1. Property: description

TABLE 116: Property Definition: schema:description

Property	`schema:description`
IRI	`https://schema.org/description`
JSON name	`rationale`
Requirement Level	Optional
Cardinality	0..1
Domain	`gov:Policy`
Range	`xsd:string`
Definition	Human-readable summary, rationale, or notes.
Usage Note	Non-normative; do not encode executable constraints here.

9.2.7.2.2. Property: issuedBy

TABLE 117: Property Definition: schema:creator

Property	`schema:creator`
IRI	`https://schema.org/creator`
JSON name	`issuedBy`
Requirement Level	Mandatory
Cardinality	1..1
Domain	`gov:Policy`
Range	`core:Domain` or `agt:Agent`
Definition	Identifies the authority that authors and promulgates the policy.
Usage Note	Prefer the controlling `core:Domain` when the issuer is an organization; use an Agent for individual signatories.

9.2.7.2.3. Property: validFrom

TABLE 118: Property Definition: schema:validFrom

Property	`schema:validFrom`
IRI	`https://schema.org/validFrom`
JSON name	`validFrom`
Requirement Level	Mandatory
Cardinality	1..1
Domain	`gov:Policy`
Range	`xsd:dateTime`
Definition	Start timestamp when the policy becomes applicable.
Usage Note	Evaluators MUST ignore a policy before this timestamp.

9.2.7.2.4. Property: validThrough

TABLE 119: Property Definition: schema:validThrough

Property	`schema:validThrough`
IRI	`https://schema.org/validThrough`
JSON name	`validThrough`
Requirement Level	Recommended
Cardinality	0..1
Domain	`gov:Policy`
Range	`xsd:dateTime`
Definition	End timestamp (exclusive) after which the policy is no longer applicable.
Usage Note	Omit for open-ended; revocation/suspension should set `gov:policyStatus`.

9.2.7.2.5. Property: appliesToActivitySchema

TABLE 120: Property Definition: gov:appliesToActivitySchema

Property	`gov:appliesToActivitySchema`

IRI	`https://www.spatialwebfoundation.org/ns/hsml/governance#appliesToActivitySchema`
JSON name	`appliesToActivitySchema`
Requirement Level	Mandatory
Cardinality	1..*
Domain	`gov:Policy`
Range	`act:ActivitySchema`
Definition	Declares the Activity schema(s) governed by the policy.
Usage Note	Use IRIs of globally reusable schemas to enable cross-domain interoperability.

9.2.7.2.6. Property: appliesToDomain

TABLE 121: Property Definition: gov:appliesToDomain

Property	`gov:appliesToDomain`
IRI	`https://www.spatialwebfoundation.org/ns/hsml/governance#appliesToDomain`
JSON name	`appliesToDomain`
Requirement Level	Optional
Cardinality	0..*
Domain	`gov:Policy`
Range	`core:Domain`
Definition	Limits applicability to one or more Domains (e.g., sites, org units).
Usage Note	If omitted, default scope is the issuer's Domain and its sub-domains (implementation-defined).

9.2.7.2.7. Property: appliesToActorClass

TABLE 122: Property Definition: gov:appliesToActorClass

Property	`gov:appliesToActorClass`
IRI	`https://www.spatialwebfoundation.org/ns/hsml/governance#appliesToActorClass`
JSON name	`appliesToActorClass`
Requirement Level	Optional

Cardinality	0..*
Domain	gov:Policy
Range	rdfs:Class
Definition	Targets classes/roles of actors (e.g., org:Role, agt:Pilot).
Usage Note	Pair with Norm conditions for precise targeting.

9.2.7.2.8. Property: hasNorm

TABLE 123: Property Definition: gov:hasNorm

Property	gov:hasNorm
IRI	https://www.spatialwebfoundation.org/ns/hsml/governance#hasNorm
JSON name	hasNorm
Requirement Level	Mandatory
Cardinality	1..*
Domain	gov:Policy
Range	gov:Norm
Definition	Includes the atomic deontic rules governed by the policy.
Usage Note	Each Norm declares gov:deonticModality and one or more executable core:Condition.

9.2.7.2.9. Property: hasCondition

TABLE 124: Property Definition: core:hasCondition

Property	core:hasCondition
IRI	https://www.spatialwebfoundation.org/ns/hsml/core#hasCondition
JSON name	hasCondition
Requirement Level	Optional
Cardinality	0..*
Domain	gov:Policy
Range	core:Condition

Definition	Executable constraints for applicability/evaluation at policy level.
Usage Note	Reuse HSML Core. Express with SHACL/ASK/CEL and record evaluation artifacts during contract validation.

9.2.7.2.10. Property: hasCredentialRequirement

TABLE 125: Property Definition: gov:hasCredentialRequirement

Property	`gov:hasCredentialRequirement`
IRI	`https://www.spatialwebfoundation.org/ns/hsml/governance#hasCredentialRequirement`
JSON name	`hasCredentialRequirement`
Requirement Level	Optional
Cardinality	0..*
Domain	`gov:Policy`
Range	`gov:CredentialProfile`
Definition	References reusable credential profiles that type-level define acceptable credential classes and constraints.
Usage Note	Instance-level verification occurs at `gov:Contract` time by checking presented VCs conform to the referenced `gov:CredentialProfile`(s) (type match, issuer/trust, status, proof suite, freshness, subject binding, shapes/conditions).

9.2.7.2.11. Property: precedence

TABLE 126: Property Definition: gov:precedence

Property	`gov:precedence`
IRI	`https://www.spatialwebfoundation.org/ns/hsml/governance#precedence`
JSON name	`precedence`
Requirement Level	Optional
Cardinality	0..1
Domain	`gov:Policy`
Range	`xsd:integer`
Definition	Numeric priority used in conflict resolution across applicable policies.

Usage Note	Higher values override lower; tie-break by modality precedence if needed.

9.2.7.2.12. Property: policyStatus

TABLE 127: Property Definition: gov:policyStatus

Property	`gov:policyStatus`
IRI	`https://www.spatialwebfoundation.org/ns/hsml/governance#policyStatus`
JSON name	`policyStatus`
Requirement Level	Optional
Cardinality	0..1
Domain	`gov:Policy`
Range	`xsd:string`
Definition	Current lifecycle state (e.g., Draft, Active, Suspended, Retired).
Usage Note	Evaluators SHOULD ignore policies not in an “Active”-like state.

9.2.7.2.13. Property: version

TABLE 128: Property Definition: schema:version

Property	`schema:version`
IRI	`https://schema.org/version`
JSON name	`version`
Requirement Level	Optional
Cardinality	0..1
Domain	`gov:Policy`
Range	`xsd:string`
Definition	Version label for change control and auditability.
Usage Note	Use semantic versioning where practical.

9.2.7.2.14. Property: jurisdiction

TABLE 129: Property Definition: schema:spatialCoverage

Property	`schema:spatialCoverage`
IRI	`https://schema.org/spatialCoverage`
JSON name	`jurisdiction`
Requirement Level	Optional
Cardinality	0..*
Domain	`gov:Policy`
Range	`schema:Place` or `skos:Concept`
Definition	Geographic or legal area covered by the policy.
Usage Note	May reference controlled vocabularies for regions/jurisdictions.

9.2.7.2.15. Property: relatedPolicy

TABLE 130: Property Definition: gov:relatedPolicy

Property	`gov:relatedPolicy`
IRI	`https://www.spatialwebfoundation.org/ns/hsml/governance#relatedPolicy`
JSON name	`relatedPolicy`
Requirement Level	Optional
Cardinality	0..*
Domain	`gov:Policy`
Range	`gov:Policy`
Definition	Links to superseding, superseded, parent, or child policies.
Usage Note	Use `gov:relatedPolicy` with subproperties if finer relation typing is required.

10. HSML Agent Module

10.1. Architectural Principles and Design Rationale

This clause describes the architectural principles underlying the HSML Agent Module. These principles are *informative* and not required for conformance; however, understanding them is recommended to ensure robust and correct implementations.

10.1.1. The Goal-Directed Actor Pattern: Defining Purpose

A fundamental principle of the Agent Module is that all autonomous actions are purpose-driven. An agent doesn't simply act; it acts to achieve an objective. This is realized through a clear separation between the actor and its purpose:

- `agt:Agent` — The actor itself. An autonomous entity capable of perception, decision-making, and action.
- `agt:Goal` — A declarative, self-contained entity that represents the desired state or objective the agent seeks to achieve.

This separation is the cornerstone of explainable AI and governable autonomy in the Spatial Web. By making an agent's `Goal` an explicit, inspectable entity linked via the mandatory `agt:hasGoal` property, the model ensures that the "why" behind an agent's behavior is always a first-class citizen. This allows an orchestration engine or auditor to understand an agent's intent without needing to reverse-engineer its internal logic. It provides a clear, declarative basis for authorizing agent actions—if the goal is permissible within a domain, the agent's subsequent actions can be evaluated against it.

10.1.2. The Capability Model: Separating Potential from Action

Complementing the goal-directed pattern is the distinction between an agent's potential to act and its actual performance of an action. This is achieved by linking the agent to the `act:ActivitySchema` rather than to specific `act:Activity` instances:

- `agt:Agent` — The actor.
- `act:ActivitySchema` — A reusable template defining a *type* of action an agent is capable of performing.
- `agt:canPerform` — The property linking an `Agent` to the `act:ActivitySchema` instances that represent its skills or functions.

This design decouples the agent's intrinsic abilities from its operational history. The `agt:canPerform` property defines the agent's skill set, which is a relatively static and verifiable aspect of its identity. This allows a Domain Authority to grant credentials based on a clear, auditable list of an agent's capabilities. It ensures that governance is applied to what an agent *can do* in principle, providing a stable foundation for trust and permissioning. The agent's actual execution of these capabilities is then recorded as

separate `act:Activity` instances, creating a clean and auditable separation between an agent's potential and its performance.

10.1.3. The Specialization Pattern: Tailoring Agents and Goals

A key architectural principle is that the `agt:Agent` and `agt:Goal` classes are designed as extensible foundations. This allows the framework to support a wide variety of agent architectures—such as Simple Reflex, Goal-based, Deliberative (BDI), or LLM-based Agents—without being overly prescriptive. The primary mechanism for this is the specialization of the base `agt:Goal` class, as the way an agent describes its goals is fundamental to its nature.

This enables the creation of specific `Goal` subclasses that align with different agent behaviors:

- `AchievementGoal`:: A goal to bring about a specific state of the world. Once the state is reached, the goal is considered achieved and is complete. For example, "Deliver a package to a specific address."
- `MaintenanceGoal`:: A goal to keep a specific condition continuously true over time. This type of goal persists and is never truly "complete." For example, "Keep the server uptime above 99.9%."
- `PerformingGoal`:: A goal where success is defined by the execution of an action itself, regardless of the resulting state. For example, "Perform a system diagnostic scan every 24 hours."
- `QueryGoal`:: A goal whose aim is to acquire information, to know the true value of a proposition, or to otherwise reduce uncertainty before planning or acting. For example, "Determine the current traffic conditions on the planned route."

By defining these and other goal specializations (like Hard vs. Soft Goals with preference models), the architecture allows for a rich and precise description of agent behavior. A sophisticated Deliberative Agent might pursue complex `AchievementGoal`s, while a simpler monitoring agent would be concerned with a `MaintenanceGoal`. This provides a flexible and future-proof framework that can adapt to new agent designs by simply introducing new, well-defined subclasses of `agt:Goal`.

10.1.4. The Embodiment Pattern: Separating Agency from Substrate

IEEE P2874™/D-3.3.1-2025-03, Clause 6.3.2.1.7 defines a `core:Thing` as a type of DOMAIN that:

> 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.

From this definition, HSML Core declares `agt:Agent` and `core:Thing` to be disjoint classes: an individual cannot simultaneously be a Thing and an Agent.

At the same time, many agents in the Spatial Web are **embodied**—for example, a human body, a humanoid robot, or a connected device that an agent inhabits. To support this without violating the disjointness constraint, the Agent Module introduces the **embodiment relation**:

- `agt:embodiedIn` — links an `agt:Agent` to the `core:Thing` that serves as its embodiment.
- `agt:embodiedBy` — the inverse, linking a `core:Thing` to the `agt:Agent` it embodies.

This pattern allows the ontology to represent:

- **Embodied agents** (e.g., humans, robots) as agents tied to a Thing that provides their physical or digital substrate.
- **Disembodied agents** (e.g., cloud services, software agents) as agents without any embodiment relation.

Principle: By separating agency (`agt:Agent`) from substrate (`core:Thing`) and linking them only through embodiment, HSML upholds the disjointness mandated by P2874 and avoids Cartesian dualism, while enabling a consistent way to model both embodied and disembodied agents.

10.2. Normative Classes

This clause provides the normative definitions for all class concepts within the HSML Agent Module. Each class is detailed in a table that specifies its URI, description, JSON-LD context name, usage notes, and relationship to other classes.

The namespace prefix `agt:` refers to `https://www.spatialwebfoundation.org/ns/hsml/agent#`.

10.2.1. Summary of Normative Classes

TABLE 131: Summary of HSML Agent Module Classes

Class	Description
agt:Agent	An autonomous entity capable of perceiving, deciding, and performing Activities to achieve its goals.
agt-Person	A human person, modeled as a special type of `agt:Agent` with a self-sovereign identity.
agt:Goal	A state or objective that an Agent aims to achieve through the performance of Activities.

10.2.2. Class: agt:Agent

The class `agt:Agent` realises the **AGENT** concept in IEEE P2874™/D-3.3.1-2025-03, Clause 6.6.3:

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

`agt:Agent` represents an autonomous entity capable of perceiving its environment, making decisions, and enacting `act:Activity` instances in pursuit of explicitly declared goals. An Agent may represent a person, robot, AI system, or other autonomous entity.

Key Requirements

- **Identity**:: Every `agt:Agent` **SHALL** possess a Spatial Web Identifier (`core:swid`, W3C DID Core–compliant).
- **Goal-Directed**:: An `agt:Agent` **SHALL** be linked to one or more objectives via `agt:hasGoal`.
- **Capability**:: An `agt:Agent` **SHALL** be linked to the `act:ActivitySchema` definitions it can perform via `agt:canPerform`.
- **Embodiment (when applicable)**:: If an Agent acts through a physical or digital substrate, it **SHOULD** indicate that substrate via `agt:embodiedIn` to a `core:Thing`. The inverse relation `agt:embodiedBy` links a `core:Thing` back to the Agent it embodies. Absence of `agt:embodiedIn` denotes a disembodied Agent.

10.2.2.1. Class Definition

TABLE 132: Class Definition for agt:Agent

RDF Class	`agt:Agent`
Is Abstract	No
Definition	An autonomous entity capable of perceiving, deciding, and performing Activities to achieve its goals.
Subclass Of	`core:Domain`
Disjoint With	`core:Thing` // per P2874 Thing DOMAIN: bounded items **without agency**
Usage Note	Agents are the actors in the Spatial Web. They declare goals, obtain authorization (e.g., via `gov:Contract`), and perform `act:Activity` instances.
Rationale	Provides the normative model for autonomous actors in the Spatial Web, supporting goal-directed behavior, governed interactions, and (when relevant) explicit embodiment without conflating agency with substrate.

TABLE 133: Properties Summary for agt:Agent

Predicate	JSON-LD name	Description	Range	Cardin	Requirement Level
`agt:hasGoal`	`hasGoal`	Links the Agent to one or more objectives it seeks to achieve.	`agt:Goal`	1..*	Mandatory

Predicate	JSON-LD name	Description	Range	Cardin	Requirement Level
agt:canPerform	canPerform	Links the Agent to the schemas for Activities it can perform.	act:ActivitySchema	1..*	Mandatory
agt:embodiedIn	embodiedIn	Indicates the core:Thing that serves as the Agent's physical or digital substrate.	core:Thing	0..1	Recommended (when embodied)
agt:embodiedBy	embodiedBy	Inverse of agt:embodiedIn; links a core:Thing back to the Agent it embodies.	agt:Agent	0..1	Recommended (when embodied)

10.2.2.2. Properties

This clause provides the detailed normative definitions for the properties of the agt:Agent class.

10.2.2.2.1. Property: hasGoal

TABLE 134: Property Definition: agt:hasGoal

Property	agt:hasGoal
IRI	https://www.spatialwebfoundation.org/ns/hsml/agent#hasGoal
JSON name	hasGoal
Requirement Level	Mandatory
Cardinality	1..*
Domain	agt:Agent
Range	agt:Goal
Definition	Links an Agent to one or more goals that it aims to fulfill through its Activities.
Usage Note	Goals are explicit, inspectable objects enabling explainable and governable autonomy; they may be specialized (e.g., Achievement, Maintenance) per the Agent's design.

10.2.2.2.2. Property: canPerform

TABLE 135: Property Definition: agt:canPerform

Property	agt:canPerform
IRI	https://www.spatialwebfoundation.org/ns/hsml/agent#canPerform
JSON name	canPerform

Requirement Level	Mandatory
Cardinality	1..*
Domain	`agt:Agent`
Range	`act:ActivitySchema`
Definition	Identifies the types of Activities the Agent is capable of performing.
Usage Note	Declares an Agent's skills as reusable templates (`act:ActivitySchema`). Actual executions are captured as `act:Activity` instances.

10.2.2.2.3. Property: embodiedIn

TABLE 136: Property Definition: agt:embodiedIn

Property	`agt:embodiedIn`
IRI	`https://www.spatialwebfoundation.org/ns/hsml/agent#embodiedIn`
JSON name	`embodiedIn`
Requirement Level	Recommended (when embodied)
Cardinality	0..1 (atemporal graphs; temporal histories may be represented via Embodiment records)
Domain	`agt:Agent`
Range	`core:Thing`
Definition	Links an Agent to the `core:Thing` that serves as its physical or digital substrate.
Usage Note	Preserves the P2874 disjointness between `agt:Agent` and `core:Thing` (Thing DOMAIN: bounded items without agency; see §6.3.2.1.7). Use absence of this property to denote disembodied Agents (e.g., cloud services). For time-varying embodiment, model histories using time-bounded Embodiment records and derive the current substrate.

10.2.2.2.4. Property: embodiedBy

TABLE 137: Property Definition: agt:embodiedBy

Property	`agt:embodiedBy`
IRI	`https://www.spatialwebfoundation.org/ns/hsml/agent#embodiedBy`
JSON name	`embodiedBy`

Requirement Level	**Recommended** (when embodied)
Cardinality	0..1
Domain	`core:Thing`
Range	`agt:Agent`
Definition	Inverse of `agt:embodiedIn`; links a `core:Thing` back to the Agent it embodies.
Usage Note	This property allows implementers to navigate from the physical or digital substrate (`core:Thing`) to the agentive entity it supports. It complements `agt:embodiedIn` and maintains symmetry in embodiment modeling.

10.2.3. Class: agt:Person

The class `agt:Person` realises the **PERSON** concept in IEEE P2874™/D-3.3.1-2025-03, Clause 6.3.2.1.6, a special subtype of `agt:Agent` that maintains a self-sovereign identity.

> 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.

`agt:Person` represents a human individual in the Spatial Web. While it inherits all the goal-directed and capability-driven characteristics of an `agt:Agent`, its primary distinction is its intrinsic link to a self-sovereign identity, ensuring individual control over personal data and interactions.

Key Requirements

- **Inheritance**: An `agt:Person` **SHALL** inherit all requirements from `agt:Agent`, including having a `core:swid`, `agt:hasGoal`, and `agt:hasCapability`.
- **Self-Sovereignty**: The `core:swid` of an `agt:Person` **SHALL** represent a self-sovereign identity, giving the individual ultimate control over their digital presence and credentials.
- **Personal Attributes**: An `agt:Person` **SHOULD** use properties from well-known vocabularies like `schema.org` to describe personal attributes for interoperability.

10.2.3.1. Class Definition

TABLE 138: Class Definition for agt:Person

RDF Class	`agt:Person`
Is Abstract	No
Definition	A human person, modeled as a special type of `agt:Agent` with a self-sovereign identity.

RDF Class	agt:Person
Subclass Of	agt:Agent
Usage Note	Represents human users who can initiate contracts and perform activities. The management of its identity and credentials SHALL adhere to the principles of self-sovereignty.
Rationale	Provides a specific class for human actors, distinguishing them from autonomous AI or robotic agents and ensuring their rights and privacy are structurally represented.

TABLE 139: Properties Summary for agt:Person

Predicate	JSON-LD name	Description	Range	Cardin.	Requirement Level
schema:givenName	givenName	The given name (first name) of the person.	xsd:string	0..1	Recommended
schema:familyName	familyName	The family name (last name) of the person.	xsd:string	0..1	Recommended
schema:email	email	An email address for the person.	xsd:string	0..*	Optional

10.2.3.2. Properties

This section provides the detailed normative definitions for properties commonly used with the agt:Person class. Note that this class also inherits all properties from agt:Agent.

10.2.3.2.1. Property: givenName

TABLE 140: Property Definition: schema:givenName

Property	schema:givenName
IRI	https://schema.org/givenName
JSON name	givenName
Requirement Level	Recommended
Cardinality	0..1
Domain	agt:Person
Range	xsd:string
Definition	The given name of the person.
Usage Note	Reuses the property from Schema.org for interoperability in representing personal names.

10.2.3.2.2. Property: familyName

TABLE 141: Property Definition: schema:familyName

Property	`schema:familyName`
IRI	`https://schema.org/familyName`
JSON name	`familyName`
Requirement Level	Recommended
Cardinality	0..1
Domain	`agt:Person`
Range	`xsd:string`
Definition	The family name of the person.
Usage Note	Reuses the property from Schema.org for interoperability in representing personal names.

10.2.3.2.3. Property: email

TABLE 142: Property Definition: schema:email

Property	`schema:email`
IRI	`https://schema.org/email`
JSON name	`email`
Requirement Level	Optional
Cardinality	0..*
Domain	`agt:Person`
Range	`xsd:string`
Definition	An email address for the person.
Usage Note	Reuses the property from Schema.org for contact information. Multiple email addresses are permissible.

10.2.4. Class: core:Organization

The class agt:Organization realises the ORGANIZATION DOMAIN concept in IEEE P2874™/D-3.3.1-2025-03, Clause 6.6.3:

> An ORGANIZATION is a DOMAIN representing a group of Agents operating under shared governance, norms, or objectives within the Spatial Web.

cor:Organization represents collective actors—such as companies, institutions, or public agencies—that initiate, govern, and coordinate Activities, issue Contracts, and manage subordinate Domains, Agents, and Things.

10.2.4.1. Class Definition

TABLE 143: Class Definition for agt:Organization

RDF Class	`agt:Organization`
Is Abstract	No
Definition	A collective group comprising Agents and/or Person under common governance, capable of issuing Contracts, Credentials, and norms.
Subclass Of	agt:Agent
Usage Note	Organizations model collective entities that issue norms, govern Agents, and manage subordinate domains.
Rationale	Provides the framework for representing legal entities, institutions, or other collective actors essential to polycentric governance and domain hierarchy in the Spatial Web.

10.2.5. Class: agt:Goal

The class `agt:Goal` realizes the concept of an objective that an `agt:Agent` is motivated to achieve. A Goal represents a state or objective that an Agent seeks to bring about through its activities.

It can be instantiated directly to represent a general-purpose goal or serve as a parent class for more specialized goal types (e.g., `AchievementGoal`, `MaintenanceGoal`, TBD). Every `agt:Agent` is required to be linked to one `agt:Goal`, making this concept fundamental to defining goal-directed behavior in the Spatial Web.

10.2.5.1. Class Definition

TABLE 144: Class Definition for agt:Goal

RDF Class	`agt:Goal`
Is Abstract	No
Definition	A state or objective that an Agent aims to achieve through the performance of Activities.
Subclass Of	Not specified in the provided text.
Usage Note	This class can be instantiated directly for general objectives. An LLM-based agent could use the `description` property for task planning.

RDF Class	`agt:Goal`
Rationale	Provides a flexible, instantiable class for representing the objectives that drive autonomous, goal-directed actions in the Spatial Web.

10.2.5.2. Properties

This section provides the detailed normative definitions for the properties of the `agt:Goal` class.

10.2.5.2.1. Property: description

TABLE 145: Property Definition: schema:description

Property	`schema:description`
IRI	`http://schema.org/description`
JSON name	`description`
Requirement Level	Mandatory
Cardinality	1..1
Domain	`agt:Goal`
Range	`xsd:string`
Definition	A human-readable text description of the objective the Agent seeks to achieve.
Usage Note	This value should be a clear, unambiguous string that explains the goal.

10.2.5.2.2. Property: hasSubGoal

TABLE 146: Property Definition: agt:hasSubGoal

Property	`agt:hasSubGoal`
IRI	`https://www.spatialwebfoundation.org/ns/hsml/agent#hasSubGoal`
JSON name	`subGoal`
Requirement Level	Optional
Cardinality	`0..*` (zero to many)
Domain	`agt:Goal`
Range	`agt:Goal`
Definition	Links a Goal to one or more subordinate Goals that contribute to the fulfillment of the parent Goal.

Usage Note	This property enables the creation of goal trees or hierarchies (hierarchical goal decomposition), which is essential for complex planning.

11. HSML Communication Module

The HSML Communication Module realizes the CHANNEL concept of IEEE P2874™/D-3.3.1-2025-03, Clause 6.6.6, providing a semantic framework for modeling communication contexts and message exchange in the Spatial Web.

Where the Governance Module addresses rules and the Activity Module defines purposeful processes, the Communication Module focuses on how entities interact during the execution of Activities. It provides a minimal but extensible set of classes to represent Channels, Messages, and Subscriptions in a way that is compatible with both the Hyperspace Transaction Protocol (HSTP) and external communication systems.

The design follows three guiding intentions:

- To distinguish ephemeral communication contexts (Channels) from persistent identity contexts (Domains).
- To allow semantic projection of messages when provenance, traceability, or validation are required, without redefining HSTP transport.
- To ensure that communication remains Activity-linked, keeping transient exchanges grounded in HSML's enduring models of entities and processes.

The Communication Module thereby acts as the "conversation layer" of HSML: lightweight enough to support ad-hoc collaboration, yet formally defined so that message flows can participate in governance, provenance, and discovery across the Spatial Web.

11.1. Architectural Principles and Design Rationale

This clause explains the design choices behind the HSML Communication Module and how they satisfy IEEE P2874™/D-3.3.1-2025-03's requirements for Channels and Message exchange as described in §6.6.6. The principles are informative (non-normative) but motivate the normative class and property definitions introduced later.

11.1.1. Channels as Ephemeral Interaction Contexts

A core principle is that Channels are not Domains. While Domains represent enduring identity-bearing contexts (geographic, organizational, or conceptual), Channels are ad-hoc and transient groupings of HSML Entities around a purpose or Activity. P2874 defines a Channel as "a stream of HSML ENTITIES that are related to an ACTIVITY of

a specific context that does not itself warrant a DOMAIN or hierarchy." This design ensures that Channels do not alter the permanent domain hierarchy but still allow session-like coordination.

- Channels are modeled as subclass of `core:Entity` but declared **disjoint from** `core:Domain`.
- Membership is flexible, but typically they are Agent, Person entities.
- Sub-channels allow hierarchical scoping of collaborative contexts without redefining domain hierarchies.

11.1.2. Messages as Optional Semantic Projections

The Communication Module distinguishes **wire messages** (defined by the Hyperspace Transaction Protocol, HSTP) from **semantic message entities**. HSTP envelopes move bytes; Channels may choose to **project messages** as HSML `comm:Message` entities when semantic traceability is required (e.g., for provenance, policy, or analytics). This duality prevents duplication of concepts:

- At minimum, Channel membership can simply reference Agents and Activities, with message exchange implicit in HSTP.
- When auditing, governance, or discovery are required, each HSTP envelope may be projected into a `comm:Message` entity with semantic annotations (sender, media type, content schema, relation to Channel).
- This pattern aligns with W3C PROV-O's distinction between events (Activities/Agents) and artifacts (Entities).

11.1.3. Separation of Concerns: HSTP vs HSML

The Communication Module does **not redefine transport**. HSTP specifies the abstract message envelope, headers, and bindings to HTTP, MQTT, QUIC, etc. The Communication Module only defines how such transported payloads are contextualized in HSML Channels. This ensures:

- **No duplication** of protocol details. Media types, signatures, and routing remain in HSTP.
- **Semantic overlay** only when needed: Channels can record provenance of what was exchanged, not how the bytes were framed.
- **Extensibility**: new bindings (e.g., WebRTC, QUIC streams) require no changes to HSML—Channels remain abstract contexts.

11.1.4. Activity-Linked Communication

Channels are always **linked to Activities**. This supports use cases such as:

- Real-time coordination of an Activity (e.g., multiple agents working on a shared task).

- Streaming sensor data into a Channel associated with a monitoring Activity.
- Collaborative annotation or decision-making during an Activity lifecycle.

The `comm:forActivity` property ensures that Channels carry explicit purpose, grounding otherwise transient message streams in the enduring Activity model of HSML.

11.1.5. Governance Delegation

Policies and credential checks are not embedded directly in Channels. Instead:

- Domain-level governance defines who may create or join Channels.
- Channels may include optional hints (e.g., `comm:allowedAgent`) but formal credential gates and policy enforcement remain in the Governance Module.
- This simplifies the Channel model while ensuring consistent enforcement across Activities, Domains, and Channels.

11.1.6. Interoperability and Extensibility

The design follows Semantic Web and Internet principles:

- Media type declarations in HSTP headers allow arbitrary payloads (JSON-LD, SHACL instance data, binary media).
- `comm:Message` entities can reference a `comm:contentSchema` (SHACL or JSON Schema) for validation, similar to how HTTP uses `Content-Type` with a `profile` parameter or `Link rel=describedby`.
- Sub-channel structures resemble chat rooms or topic hierarchies in existing systems (MQTT, XMPP), but retain formal semantics.
- Alignments with schema.org (`schema:Message`, `schema:CommunicateAction`) are possible for lightweight web interoperability.

11.1.7. Summary

The Communication Module provides a lightweight, semantically grounded way to model Channels and Messages without duplicating HSTP transport concerns or Domain governance rules. It supports ephemeral, Activity-linked collaboration while leaving transport framing to HSTP and policy enforcement to the Governance Module. This separation yields clarity, reuse, and flexibility across diverse use cases, from ad-hoc collaboration to persistent provenance trails.

11.2. Normative Classes

This clause provides the normative definitions for the classes of the Communication Module.

11.2.1. Summary of Communication Module Classes

TABLE 147: Summary of HSML Communication Module Classes

Class	Description
comm:Channel	Ephemeral, non-hierarchical, Domain-hosted context for grouping Entities and exchanging Messages around Activities.
comm:Message	Optional semantic description of a communicative artifact exchanged via HSTP. Used when provenance, validation, or audit are needed.

11.2.2. Class: `comm:Channel`

The `comm:Channel` class realizes the CHANNEL concept as defined in the IEEE P2e874 draft standard. As a central element of the communications (comm) module, it provides a contextual container that links participants, data, and messages around specific Activities without forming part of the permanent domain hierarchy. This enables ad-hoc, session-based, or otherwise transient coordination and monitoring.

This class is a subclass of `core:Entity`, inheriting a `core:swid` as its unique identifier.

11.2.2.1. Key Requirements & Design Principles

- A `comm:Channel` **shall link** to at least one `act:Activity` it supports.
- A `comm:Channel` **shall be disjoint** from `core:Domain`, as it represents a non-hierarchical, transient grouping.
- A `comm:Channel` **shall include** one or more participants via the `core:hasParticipant` property.
- Parent-child relationships between channels **shall be modeled** using the inverse properties `comm:hasSubChannel` and `comm:subChannelOf`.
- Governance and access control **are intentionally delegated** to the Governance Module and are not embedded properties of a Channel.

11.2.2.2. Class Definition

TABLE 148: Class Definition for comm:Channel

RDF Class	`comm:Channel`
Is Abstract	No
Definition	A contextual, non-hierarchical grouping of entities associated with a specific Activity or purpose, for coordinating transient communications.
Subclass Of	`core:Entity`
Usage Note	Channels are for transient, ad-hoc collaboration; they do not define domain boundaries or permanent hierarchies. The `core` namespace refers to a separate module defining foundational, cross-cutting properties.

Rationale	Provides a lightweight mechanism for coordinating information and participants. Access control is delegated to the Governance Module; Channels do not embed their own access control lists (ACLs).

11.2.2.3. Properties Summary

TABLE 149: Properties Summary for comm:Channel

Predicate	JSON(-LD) Name	Description	Cardinality
rdf:type	`@type`	Declares the resource as an instance of `comm:Channel`.	1..n
core:swid	`swid`	The Spatial Web Identifier (SWID) inherited from `core:Entity`.	1
core:has Participant	`hasParticipant`	Identifies the entities participating in the Channel.	1..n
comm:for Activity	`forActivity`	Links the Channel to the Activity it supports.	1..n
comm:has SubChannel	`hasSubChannel`	Links to a nested sub-channel.	0..n
comm:sub ChannelOf	`subChannelOf`	Links to the parent channel.	0..1

11.2.2.4. Property Details

11.2.2.4.1. Property: `core:hasParticipant`

TABLE 150: Property Definition: core:hasParticipant

Property	`core:hasParticipant`
IRI	`https://schema.spatialwebfoundation.org/core#hasParticipant`
JSON Name	`hasParticipant`
Requirement Level	Mandatory
Cardinality	1..n
Domain	`comm:Channel`
Range	`core:Entity`
Definition	Links the Channel to its participants (Agents, Things, or other Entities).
Usage Note	A Channel must have at least one participant to be meaningful.

11.2.2.4.2. Property: `comm:forActivity`

TABLE 151: Property Definition: comm:forActivity

Property	`comm:forActivity`
IRI	`https://schema.spatialwebfoundation.org/comm#forActivity`
JSON Name	`forActivity`
Requirement Level	Mandatory
Cardinality	1..n
Range	`act:Activity`
Definition	Associates the Channel with one or more Activities it supports or relates to.
Usage Note	Channels provide the necessary communication and data context for their referenced Activities.

11.2.2.4.3. Property: `comm:hasSubChannel`

TABLE 152: Property Definition: comm:hasSubChannel

Property	`comm:hasSubChannel`
IRI	`https://schema.spatialwebfoundation.org/comm#hasSubChannel`
JSON Name	`hasSubChannel`
Requirement Level	Optional
Cardinality	0..n
Range	`comm:Channel`
Inverse Property	`comm:subChannelOf`
Definition	Links the Channel to its sub-channels for hierarchical structuring of information streams.
Usage Note	This property enables efficient downward traversal of the Channel hierarchy (from parent to children).

11.2.2.4.4. Property: `subChannelOf`

TABLE 153: Property Definition: comm:subChannelOf

Property	`comm:subChannelOf`

IRI	`https://schema.spatialwebfoundation.org/comm#subChannelOf`
JSON Name	`subChannelOf`
Requirement Level	Optional
Cardinality	0..1
Range	`comm:Channel`
Inverse Property	`comm:hasSubChannel`
Definition	Links a sub-channel to its parent Channel.
Usage Note	This property allows for efficient upward traversal of the Channel hierarchy. The `0..1` cardinality enforces a strict tree structure, preventing a single channel from having multiple parents.

11.2.2.5. Example

FIGURE 6: Example of a Channel with a Sub-Channel using DIDs

```
{
  "@context": "http://spatialwebfoundation.org/context/
hsml.jsonld",
  "@id": "did:swid:channel:metro-hospital-drone-ops",
  "@type": "Channel",
  "name": "Metro Hospital Drone Operations",
  "description": "Coordination channel for all emergency
medical supply deliveries in the downtown metro area.",
  "swid": "did:swid:channel:metro-hospital-drone-ops",
  "forActivity": "did:swid:activity:med-delivery-ops",
  "hasParticipant": [
    "did:swid:agent:drone-7",
    "did:swid:agent:ops-dashboard"
  ],
  "hasSubChannel": [
    {
      "@id": "did:swid:channel:drone-7-telemetry",
      "@type": "Channel",
      "name": "Drone 7 - Flight Telemetry",
      "description": "Real-time flight data, battery
status, and payload vitals for Drone 7.",
      "swid": "did:swid:channel:drone-7-telemetry",
      "forActivity": "did:swid:activity:med-delivery-ops",
      "hasParticipant": [
        "did:swid:agent:drone-7"
      ],
      "subChannelOf": "did:swid:channel:metro-hospital-
drone-ops"
    }
  ]
```

```
    }
```

11.2.3. Class: comm:Message

comm:Message models an optional semantic projection of a transported envelope (per HSTP) into HSML. It is used to persist provenance, governance, validation, discovery, and correlation of communications that occur within a chan:Channel and concern an act:Activity. Transport framing, headers, and bindings remain the responsibility of HSTP; comm:Message captures the who/what/when/why at the semantic layer.

Messages are not required for all exchanges. Implementations materialize comm:Message only when traceability or auditability is needed.

Key Requirements

1. A comm:Message shall be associated with exactly one chan:Channel via comm:inChannel.
2. A comm:Message shall be linked to at least one act:Activity via comm:aboutActivity.
3. A comm:Message shall identify at least one comm:sender of type agt:Agent.
4. A comm:Message shall record a generation timestamp (e.g., prov:generatedAtTime).
5. A comm:Message should declare comm:mediaType and one or more comm:contentSchema to enable validation/routing.
6. A comm:Message may include integrity (comm:contentHash) and ordering (comm:sequenceNumber) metadata, and may correlate to other messages (comm:correlatesWith).

11.2.3.1. Class Definition

TABLE 154: Class Definition for comm:Message

RDF Class	comm:Message
Is Abstract	No
Definition	Semantic record of a communicative artifact exchanged within a Channel and about an Activity; optional overlay on HSTP transport.
Subclass Of	core:Concept
JSON-LD Term	“Message”: “comm:Message”
Usage Notes	Use to capture provenance (who/when), integrity (hash/sequence), typing (media/profile), and correlation (threads, request/response). Payload may be stored inline or referenced by immutable link.

11.2.3.2. Properties Summary

TABLE 155: Properties Summary for comm:Message

Predicate	JSON-LD name	Description	Range	Cardin	Requirement
comm:in Channel	inChannel	Channel carrying this message (context).	chan:Channel	1..1	Mandatory
comm:about Activity	aboutActivity	Activity that this message concerns.	act:Activity	1..*	Mandatory
comm:sender	sender	Author/emitter of the message.	agt:Agent	1..*	Mandatory
comm: recipient	recipient	Intended audience (Agents or Channels).	agt:Agent or chan:Channel	0..*	Optional
comm:media Type	mediaType	IANA media type (align with HSTP header).	xsd:anyURI	0..1	Recommended
comm: content Schema	content Schema	Schema/profile describing payload (SHACL, JSON Schema, etc.).	xsd:anyURI	0..*	Recommended
comm: content	content	Embedded payload or immutable link to content.	rdf:lang String or xsd: string or xsd: base64Binary or xsd:anyURI	0..1	Optional
comm: contentHash	contentHash	Integrity hash (e.g., multihash) of payload.	xsd:string	0..1	Optional
comm: sequence Number	sequence Number	Monotonic sequence number within the Channel.	xsd:integer	0..1	Optional
comm: correlates With	correlates With	Correlation to another message (threading, request/ response).	comm: Message	0..*	Optional
prov: generated AtTime	generated AtTime	UTC timestamp when produced.	xsd:dateTime	1..1	Mandatory
prov:was AttributedTo	wasAttributed To	Attribution of authorship (often same as comm: sender).	agt:Agent	1..*	Mandatory

11.2.3.3. Properties

11.2.3.3.1. Property: inChannel

TABLE 156: Property Definition: comm:inChannel

Property	comm:inChannel

IRI	`https://www.spatialwebfoundation.org/ns/hsml/comm#inChannel`
JSON name	inChannel
Requirement Level	Mandatory
Cardinality	1..1
Domain	comm:Message
Range	chan:Channel
Definition	Binds the message to its carrying Channel (context).
Usage Note	Enables ordered archival, replay, and governance scoping per Channel.

11.2.3.3.2. Property: aboutActivity

TABLE 157: Property Definition: comm:aboutActivity

Property	comm:aboutActivity
IRI	`https://www.spatialwebfoundation.org/ns/hsml/comm#aboutActivity`
JSON name	aboutActivity
Requirement Level	Mandatory
Cardinality	1..*
Domain	comm:Message
Range	act:Activity
Definition	Identifies the Activity that the message concerns.
Usage Note	Grounds transient communication in enduring Activity provenance.

11.2.3.3.3. Property: sender

TABLE 158: Property Definition: comm:sender

Property	comm:sender
IRI	`https://www.spatialwebfoundation.org/ns/hsml/comm#sender`
JSON name	sender
Requirement Level	Mandatory

Cardinality	1..*
Domain	comm:Message
Range	agent:Agent
Definition	Agent that authored or emitted the message.
Usage Note	Often mirrored with prov:wasAttributedTo for PROV alignment.

11.2.3.3.4. Property: recipient

TABLE 159: Property Definition: comm:recipient

Property	comm:recipient
IRI	`https://www.spatialwebfoundation.org/ns/hsml/comm#recipient`
JSON name	recipient
Requirement Level	Optional
Cardinality	0..*
Domain	comm:Message
Range	agt:Agent or chan:Channel
Definition	Intended audience of the message.
Usage Note	Use multiple values for broadcast/fan-out. Omit when Channel audience suffices.

11.2.3.3.5. Property: mediaType

TABLE 160: Property Definition: comm:mediaType

Property	comm:mediaType
IRI	`https://www.spatialwebfoundation.org/ns/hsml/comm#mediaType`
JSON name	mediaType
Requirement Level	Recommended
Cardinality	0..1
Domain	comm:Message
Range	xsd:anyURI

Definition	IANA media type of the payload (align with HSTP).
Usage Note	Use IRI form for media types (e.g., `https://iana.org/assignments/media-types/application/json`).

11.2.3.3.6. Property: contentSchema

TABLE 161: Property Definition: comm:contentSchema

Property	comm:contentSchema
IRI	`https://www.spatialwebfoundation.org/ns/hsml/comm#contentSchema`
JSON name	contentSchema
Requirement Level	Recommended
Cardinality	0..*
Domain	comm:Message
Range	xsd:anyURI
Definition	Schema/profile describing payload (e.g., SHACL shape IRI, JSON Schema URL).
Usage Note	Enables validation and content negotiation by profile.

11.2.3.3.7. Property: content

TABLE 162: Property Definition: comm:content

Property	comm:content
IRI	`https://www.spatialwebfoundation.org/ns/hsml/comm#content`
JSON name	content
Requirement Level	Optional
Cardinality	0..1
Domain	comm:Message
Range	rdf:langString or xsd:string or xsd:base64Binary or xsd:anyURI
Definition	The payload itself (inline text/binary) or a canonical, immutable link to it.
Usage Note	Prefer immutable links plus comm:contentHash for large or sensitive payloads.

11.2.3.3.8. Property: contentHash

TABLE 163: Property Definition: comm:contentHash

Property	comm:contentHash
IRI	`https://www.spatialwebfoundation.org/ns/hsml/comm#contentHash`
JSON name	contentHash
Requirement Level	Optional
Cardinality	0..1
Domain	comm:Message
Range	xsd:string
Definition	Integrity hash of the payload (e.g., multihash, SHA-256).
Usage Note	When comm:content is a link, the hash ensures immutability/verifiability.

11.2.3.3.9. Property: sequenceNumber

TABLE 164: Property Definition: comm:sequenceNumber

Property	comm:sequenceNumber
IRI	`https://www.spatialwebfoundation.org/ns/hsml/comm#sequenceNumber`
JSON name	sequenceNumber
Requirement Level	Optional
Cardinality	0..1
Domain	comm:Message
Range	xsd:integer
Definition	Monotonic ordering value relative to the Channel.
Usage Note	Useful for replay cursors and gap detection.

11.2.3.3.10. Property: correlatesWith

TABLE 165: Property Definition: comm:correlatesWith

Property	comm:correlatesWith

IRI	`https://www.spatialwebfoundation.org/ns/hsml/comm#correlatesWith`
JSON name	correlatesWith
Requirement Level	Optional
Cardinality	0..*
Domain	comm:Message
Range	comm:Message
Definition	Links to related messages (e.g., request/response, thread, saga).
Usage Note	Use multiple values to express multi-message conversations or branches.

11.2.3.3.11. Property: prov:generatedAtTime

TABLE 166: Property Definition: prov:generatedAtTime

Property	prov:generatedAtTime
IRI	`http://www.w3.org/ns/prov#generatedAtTime`
JSON name	generatedAtTime
Requirement Level	Mandatory
Cardinality	1..1
Domain	comm:Message
Range	xsd:dateTime
Definition	UTC timestamp when the message was produced.
Usage Note	Use Z-suffixed times or explicit offset; recommend millisecond precision.

11.2.3.3.12. Property: prov:wasAttributedTo

TABLE 167: Property Definition: prov:wasAttributedTo

Property	prov:wasAttributedTo
IRI	`http://www.w3.org/ns/prov#wasAttributedTo`
JSON name	wasAttributedTo
Requirement Level	Mandatory

Cardinality	1..*
Domain	comm:Message
Range	agt:Agent
Definition	Attribution of authorship/agency for the message.
Usage Note	Often same individual(s) as comm:sender; keep both for PROV/ tooling compatibility.

12. HSML Hyperspace Module

12.1. Introduction

The Hyperspace Module defines the structural foundation for representing spatial relationships in HSML. It realizes the HYPERSPACE concept of IEEE P2874™/D-3.3.1-2025-03, Clause 6.2.1, which defines a hyperspace as:

> A set whose elements are related by a formal notion of path, satisfying identity and composition laws. Paths may be abstract, as long as they can be traversed in a fashion akin to the paths between points in familiar spaces.

This abstract definition is intentionally broad. It allows HSML to treat a wide range of structures— geographic coordinates, social networks, organizational hierarchies, logical states, numeric values, or semantic concepts— under one unifying abstraction. Hyperspaces ensure that Domains are not just collections of entities, but **structured environments** in which relationships such as adjacency, connectivity, reachability, and composition can be explicitly represented and navigated.

Crucially, Hyperspaces in HSML are **made operational by explicit mappings**:

- **Elements** → classes or datatypes (e.g., `geo:Geometry`, `cell:Cell`, `xsd:integer`).
- **Arrows** (atomic steps) → RDF properties or edge classes (e.g., `graph:edge`, `cell:adjacentTo`).
- **Paths** (compositions) → explicit path resources (e.g., `graph:Route`, `cell:CellChain`) or SPARQL property paths.
- **Operations** → instances of `hspace:Operation` bound to these mappings, validated via SHACL profiles.

Through these mappings, navigation (neighbors, reachability, path composition) and operations (distance, similarity, routing) are not hard-coded into the ontology, but arise

from **declared structures** that can be validated, extended, and executed. This makes the Hyperspace Module both **abstractly universal** and **practically concrete**.

Because the Spatial Web encompasses diverse domains, the Hyperspace Module is **modular by design**. The core module defines only the minimum semantics common to **all** Hyperspaces: elements, arrows, paths, and universal properties. Specializations provide richer semantics:

- GraphSpace — connectivity and networks.
- CellularSpace — grids and tessellations.
- VectorSpace — coordinate systems and geometries.
- MetricSpace — distance and similarity.
- Datatype Hyperspaces — value domains such as numbers, strings, colors, or tensors.

This modular structure allows implementers to import only what they need while preserving interoperability. Namespaces mirror this pattern: the core vocabulary resides in the `hyperspace#` namespace, while each specialization occupies its own sub-namespace under `hyperspace/`.

In this way, the Hyperspace Module provides both a **universal foundation** and a **scalable framework for extension**, making it a cornerstone of HSML and of the Spatial Web as a whole.

12.1.1. Navigation by Mapping

Navigation in a Domain's Hyperspace is not hard-coded; it is **achieved by mapping abstract constructs to RDF structures**:

- Elements
  - Mapped to an RDF class (e.g., `graph:Node`, `cell:Cell`) or a datatype (e.g., `geosparql:wktLiteral`, `tensor:ArrayLiteral`).
  - Optionally bound via a `hyperspace:spatialProperty` (e.g., `geo:hasGeometry`, `hspace:cell`) to point to the actual value.
- Arrows (atomic steps)
  - Mapped to an RDF property (e.g., `graph:edge`, `cell:adjacentTo`) connecting valid element instances.
  - Alternatively represented as a reified edge class with `hspace:source` and `hspace:target`, or as RDF-star annotated triples for weighted/labeled edges.
- Paths (compositions)
  - **Implicit:** expressed through SPARQL property paths over the declared arrow property (e.g., `(graph:edge)+` for reachability).
  - **Explicit:** represented as RDF resources (e.g., `graph:Route`, `cell:CellChain`) with ordered `hspace:step`, `hspace:startsAt`, and `hspace:endsAt` properties.

These mappings allow core navigation queries such as: - **Neighbors:** `?a hspace:hasArrowType ?b` - **Reachability:** `ASK { ?a ( ?arrow )+ ?b }` - **Path Extraction:** select explicit path resources linking two elements.

Thus, navigation is universally defined but concretely realized through the mapping pattern chosen for each Hyperspace specialization.

12.1.2. Design Decision: Paths with Literal Elements (Generalized)

In some Hyperspaces, `hspace:hasElementType` is a **datatype** (e.g., `xsd:string`, JSON literals, tensors, WKT). Because RDF literals cannot be subjects, arrows and paths **CANNOT** be expressed as direct triples between literals. This decision specifies **general, profile-able mapping patterns** and properties that work for **any** element kind (class- or datatype-based) and **any** path representation. (We include a `geo:Geometry` example purely illustratively.)

12.1.2.1. Normative Principles

P1 — No literal subjects	Arrows/paths SHALL NOT rely on triples requiring a literal subject.
P2 — Arrow-driven navigation	Navigation semantics (neighbors, reachability, composition) SHALL be derived from the Hyperspace's **arrow mapping** (predicate edge or reified edge), not from any serialized path payload.
P3 — Two interoperable mappings	Profiles MAY choose either **Value-Node** (recommended) or **Literal-End** mappings. Both are first-class in HSML; the choice MUST be advertised by the Hyperspace's mapping properties.
P4 — Path resource portability	Paths SHOULD be first-class resources (subclasses of `hspace:Path`) so implementations can attach metadata (cost, provenance) and validate steps with SHACL— independent of element representation.

12.1.2.2. Patterns

Pattern L1 — Value-Node (RECOMMENDED)	Materialize each element as a **resource node** (instances of a class declared by `hspace:hasElementType`), and carry the raw value via a datatype property (`hspace:elementValue` or a domain-standard property). Arrows are normal object properties (`hspace:arrowProperty`) or reified edge instances (`hspace:arrowClass` with `hspace:arrowSource` / `hspace:arrowTarget`). Paths use `hspace:startsAt` / `hspace:endsAt` and optional `hspace:step`.
Pattern L2 — Literal-End (SUPPORTED)	Keep elements as **literals** (i.e., `hspace:hasElementType` is a datatype). Represent arrows as **reified edge resources** with **literal endpoints** (`hspace:arrowSourceValue`, `hspace:arrowTargetValue`). Represent paths as **resources** whose endpoints/steps are **literal-valued** (`hspace:startsAtValue`, `hspace:endsAtValue`, `hspace:stepList` or `hspace:pathLiteral`).

NOTE L1 enables property-path traversals and richer per-element metadata; L2 avoids node materialization at the cost of reified navigation. Choose per data-volume, query needs, and tooling.

12.1.3. Separation of Domain and Hyperspace

Domain provides identity and contextual scope. Hyperspace attached to a Domain defines how its entities relate. This separation allows the same Domain to be interpreted under different logics (graph, metric, cellular, temporal) without altering identity.

12.1.4. Universal Operations

A small algebra applies to all Hyperspaces:

- Identity — every element is reachable from itself.
- Reachability — test existence of a path between elements.
- Path Composition — concatenate two compatible paths.
- Subspace Formation — restrict a Hyperspace to a subset of elements and induced arrows.

Specialized Hyperspaces extend this with richer operations (e.g., shortest path, similarity metrics).

12.1.5. Modularity and Namespaces

Namespaces follow a predictable hierarchy:

- Core: `https://www.spatialwebfoundation.org/ns/hsml/hyperspace#`
- GraphSpace: `https://www.spatialwebfoundation.org/ns/hsml/hyperspace/graph#`
- CellularSpace: `https://www.spatialwebfoundation.org/ns/hsml/hyperspace/cell#`
- VectorSpace: `https://www.spatialwebfoundation.org/ns/hsml/hyperspace/vector#`
- MetricSpace: `https://www.spatialwebfoundation.org/ns/hsml/hyperspace/metric#`
- Datatype Hyperspaces: `https://www.spatialwebfoundation.org/ns/hsml/hyperspace/datatype#`

This structure ensures clarity, modularity, and extensibility.

By organizing namespaces in this way, several goals are achieved:

- Clarity — It is immediately clear whether a term belongs to the core Hyperspace abstraction or a specialized extension.

- Modularity — Implementers can import only the extensions they need, keeping systems lightweight.
- Extensibility — New families of Hyperspaces (e.g., probabilistic space, tensor spaces, state-machine spaces) can be introduced simply by assigning them new sub-namespaces, without disrupting existing definitions.
- Best Practices — This mirrors established approaches in ontology engineering, where namespaces are stable, descriptive, and composable.

In effect, the namespace design mirrors the architecture of Hyperspaces themselves: a simple core scaffold that can be specialized into many forms, each with its own dedicated space but all interoperable under a common root.

12.1.6. Hyperspace of Hyperspaces

A Hyperspace is itself an Entity and may serve as an element within another Hyperspace. This enables Hyperspaces of Hyperspaces, supporting higher-order composition:

- Systems-of-Systems — city networks combined into a national network.
- Federations — regional grids aggregated into a global monitoring system.
- Holarchies — nested Hyperspaces reflecting P2874's holonic design principles.

This higher-order capability is essential for modeling federated and polycentric structures in the Spatial Web.

12.1.7. Time as an Extension

Temporal semantics are not universal and are therefore modeled as extensions. Arrows and paths may carry temporal annotations (`time:validDuring`, `time:hasDuration`) using OWL-Time. Profiles may define spatio-temporal Hyperspaces when time is central to navigation and reasoning.

12.1.8. Identity and Governance

Every Hyperspace is identified by a Spatial Web Identifier (SWID) conformant with W3C DID Core. This ensures resolvability and governance. While governance logic is external, the identifier anchors policies, credentials, and trust enforcement.

12.1.9. Validation Through Profiles

Constraints are expressed via SHACL profiles, not fixed in OWL. Profiles may restrict element types, adjacency properties, or valid transitions, providing rigor in specific deployments while preserving generality in the core.

Summary:

The Hyperspace Module defines elements, arrows, paths, and operations as a minimal universal abstraction. By mapping these to RDF constructs, navigation and reasoning are enabled consistently across all domains. SHACL profiles enforce structural integrity,

while modular namespaces and higher-order composition provide extensibility. Together, these design decisions make the Hyperspace Module a cornerstone of HSML and the Spatial Web.

12.2. Normative Classes

This clause provides the normative definitions for the classes of the Hyperspace Module.

12.2.1. Summary of Hyperspace Module Classes

TABLE 168: Summary of Hyperspace Module Classes

Class	Description
hspace:Hyperspace	Domain-attached structural abstraction that declares element, arrow, and path types and optional mappings for navigation and operations.
hspace:Path	First-class representation of composed paths (finite compositions of arrows); may carry endpoints, ordered steps, and serialized path values.
hspace:Operation	Declarative operation bound to a Hyperspace (e.g., reachability, routing, metric evaluation), referencing the mappings it consumes.
hspace:HyperspaceOfHyperspace	Higher-order space whose elements are themselves Hyperspaces; supports federation, holarchies, and systems-of-systems.

12.2.2. Class: hspace:Hyperspace

The class hspace:Hyperspace realises the HYPERSPACE concept in IEEE P2874™/D-3.3.1-2025-03, Clause 6.6.3 and Hyperspace Modeling principles:

> A HYPERSPACE is a spatial structure that specifies relationships among elements (points) in a DOMAIN, including notions such as adjacency, distance, connectivity, or metric, enabling spatial reasoning and operations within the Spatial Web.

hspace:Hyperspace provides the formal structure for expressing the spatial logic that governs how entities in a Domain relate to each other. It generalizes topology, metric spaces, graphs, cellular grids, vector spaces, and datatype spaces into a unified model, supporting composable and navigable relationships across Domains.

This specification separates:

- Hyperspace-level properties — what the space is and how navigation is driven (element type, arrow type, path type, optional edge predicate).
- Element-class properties — properties used on the element instances (when elements are resources).
- Path-class properties — properties used on path instances (explicit paths), including variants for literal-based elements.

12.2.2.1. Class Definition

TABLE 169: Class Definition for hspace:Hyperspace

RDF Class	`hspace:Hyperspace`
Is Abstract	No
Definition	A spatial structure attached to a Domain that defines relationships among its elements, supporting spatial reasoning, navigation, and operations.
Subclass Of	hspace:Entity
Usage Note	Hyperspaces specify how elements in a Domain relate (e.g., adjacency, distance) and drive spatial queries, validation, and tooling.
Rationale	Provides a formal, flexible mechanism to encode spatial structure (graph, cellular, vector, metric, datatype) that underpins Spatial Web reasoning.

12.2.2.2. Hyperspace Properties (Summary)

TABLE 170: Properties Summary for hspace:Hyperspace

Predicate	JSON(-LD) name	Description	Cardinality
rdf:type	@type	Declares the resource as an instance of `hspace:Hyperspace`.	1..n
core:swid	swid	Spatial Web Identifier conformant with W3C DID Core.	1
hspace:hasElementType	hasElementType	Type of elements (class or datatype) represented in the Hyperspace.	1
hspace:hasArrowType	hasArrowType	Type of atomic one-step relations (“arrows”) between elements.	1
hspace:hasPathType	hasPathType	Type(s) of composed paths recognised in the Hyperspace.	0..n
hspace:arrowProperty	arrowProperty	(Optional) RDF predicate used for atomic steps (direct edges).	0..1
hspace:hasOperation	hasOperation	Declares supported operations or transformations for the Hyperspace.	0..n

12.2.2.2.1. Property: rdf:type

TABLE 171: Property Definition: rdf:type

Property	rdf:type
IRI	`http://www.w3.org/1999/02/22-rdf-syntax-ns#type`
JSON name	@type
Requirement Level	Mandatory

Cardinality	1..n
Domain	hspace:Hyperspace
Range	rdfs:Class
Definition	Declares the resource as an instance of subclass of `hspace:Hyperspace`.

12.2.2.2.2. Property: hasElementType

TABLE 172: Property Definition: hspace:hasElementType

Property	hspace:hasElementType
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace#hasElementType`
JSON name	hasElementType
Requirement Level	Mandatory
Cardinality	1
Domain	hspace:Hyperspace
Range	rdfs:Class or datatype IRI
Definition	Identifies the type of elements (points) comprising the Hyperspace.
Usage Note	Examples: `geo:Geometry`, `hspace:Cell`, `xsd:string`, `geo:wktLiteral`.

12.2.2.2.3. Property: hasArrowType

TABLE 173: Property Definition: hspace:hasArrowType

Property	hspace:hasArrowType
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace#hasArrowType`
JSON name	hasArrowType
Requirement Level	Mandatory
Cardinality	1
Domain	hspace:Hyperspace
Range	owl:ObjectProperty IRI or rdfs:Class
Definition	Identifies the atomic one-step relation (“arrow”) connecting elements.

Usage Note	Use an object property IRI for direct edges (e.g., `ex:connect`). If using reified edges, `hasArrowType` MAY point to the edge class (defined outside this section).

12.2.2.2.4. Property: hasPathType

TABLE 174: Property Definition: hspace:hasPathType

Property	hspace:hasPathType
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace#hasPathType`
JSON name	hasPathType
Requirement Level	Optional
Cardinality	0..n
Domain	hspace:Hyperspace
Range	rdfs:Class or datatype IRI
Definition	Identifies the type(s) of composed paths (finite compositions of arrows) recognised in the Hyperspace.
Usage Note	Examples: `hspace:Path`, `ex:Route`, `vector:LineString`, `geo:wktLiteral` (LINESTRING).

12.2.2.2.5. Property: arrowProperty

TABLE 175: Property Definition: hspace:arrowProperty

Property	hspace:arrowProperty
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace#arrowProperty`
JSON name	arrowProperty
Requirement Level	Optional
Cardinality	0..1
Domain	hspace:Hyperspace
Range	owl:ObjectProperty IRI
Definition	Declares the RDF predicate used to encode atomic steps (arrows) as direct edges.
Usage Note	Enables reachability via SPARQL property paths, e.g., `( ?arrow )`.

12.2.2.2.6. Property: hasOperation

TABLE 176: Property Definition: hspace:hasOperation

Property	hspace:hasOperation
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace#hasOperation`
JSON name	hasOperation
Requirement Level	Optional
Cardinality	0..n
Domain	hspace:Hyperspace
Range	hspace:Operation
Definition	Declares supported operations (e.g., reachability, routing, subspace extraction, metric evaluation).

12.2.3. Element-Class Properties

These properties are used on element instances (when `hspace:hasElementType` is a class). They are not properties of the `hspace:Hyperspace` resource itself.

12.2.3.1. Summary

TABLE 177: Properties Summary for Element-Class

Predicate	JSON(-LD) name	Description	Cardinality
hspace:elementValue	elementValue	Carries the element's literal value on the element node (when applicable).	0..1

12.2.3.1.1. Property: elementValue

TABLE 178: Property Definition: hspace:elementValue

Property	hspace:elementValue
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace#elementValue`
JSON name	elementValue
Requirement Level	Optional
Cardinality	0..1
Domain	Class named by `hspace:hasElementType` (when that range is a class)

Range	rdfs:Literal (typed per profile, e.g., geo:wktLiteral, xsd:string)
Definition	Stores a literal value on an element node, enabling arrows between resources while retaining the raw value.

12.2.4. Path-Class Properties

These properties are used **on path instances** (i.e., resources of the class named by hspace:hasPathType when that range is a class). They are not properties of the hspace:Hyperspace resource itself.

12.2.4.1. Summary

TABLE 179: Properties Summary for Path-Class

Predicate	JSON(-LD) name	Description	Cardinality
hspace:startsAt	startsAt	Links a path to its start **element node** (resource-based elements).	0..1
hspace:endsAt	endsAt	Links a path to its end **element node** (resource-based elements).	0..1
hspace:pathStep	pathStep	Ordered steps of a path (elements/edges/step-nodes per profile).	0..1
hspace:onPath	onPath	Membership assertion that an element node lies on the path.	0..1
hspace:startsAtValue	startsAtValue	Start **literal** of the path (literal-based elements).	0..1
hspace:endsAtValue	endsAtValue	End **literal** of the path (literal-based elements).	0..1
hspace:stepList	stepList	rdf:List of ordered **literal** elements (literal-based elements).	0..1
hspace:pathValue	pathValue	Serialized path payload (e.g., LineString, JSON array/polyline).	0..1

12.2.4.1.1. Property: startsAt

TABLE 180: Property Definition: hspace:startsAt

Property	hspace:startsAt
IRI	https://www.spatialwebfoundation.org/ns/hsml/hyperspace#startsAt
JSON name	startsAt
Requirement Level	Optional
Cardinality	0..1

Domain	Class named by `hspace:hasPathType` (when that range is a class)
Range	Element class named by `hspace:hasElementType` (when that range is a class)
Definition	Links a path resource to its start **element node** (resource-based elements).

12.2.4.1.2. Property: endsAt

TABLE 181: Property Definition: hspace:endsAt

Property	hspace:endsAt
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace#endsAt`
JSON name	endsAt
Requirement Level	Optional
Cardinality	0..1
Domain	Class named by `hspace:hasPathType` (when that range is a class)
Range	Element class named by `hspace:hasElementType` (when that range is a class)
Definition	Links a path resource to its end **element node** (resource-based elements).

12.2.4.1.3. Property: pathStep

TABLE 182: Property Definition: hspace:pathStep

Property	hspace:pathStep
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace#pathStep`
JSON name	pathStep
Requirement Level	Optional
Cardinality	0..1
Domain	Class named by `hspace:hasPathType` (when that range is a class)
Range	owl:ObjectProperty IRI
Definition	Ordered property listing the steps of a path. Steps MAY reference elements, edges, or step nodes per profile.

12.2.4.1.4. Property: onPath

TABLE 183: Property Definition: hspace:onPath

Property	hspace:onPath
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace#onPath`
JSON name	onPath
Requirement Level	Optional
Cardinality	0..1
Domain	Class named by `hspace:hasPathType` (when that range is a class)
Range	Element class named by `hspace:hasElementType` (when that range is a class)
Definition	Indicates that an element node lies on this explicit path.

12.2.4.1.5. Property: startsAtValue

TABLE 184: Property Definition: hspace:startsAtValue

Property	hspace:startsAtValue
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace#startsAtValue`
JSON name	startsAtValue
Requirement Level	Optional
Cardinality	0..1
Domain	Class named by `hspace:hasPathType` (when that range is a class)
Range	rdfs:Literal (typed with the datatype named by `hspace:hasElementType` when it is a datatype)
Definition	Records the start literal of the path when elements are literals.

12.2.4.1.6. Property: endsAtValue

TABLE 185: Property Definition: hspace:endsAtValue

Property	hspace:endsAtValue
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace#endsAtValue`

JSON name	endsAtValue
Requirement Level	Optional
Cardinality	0..1
Domain	Class named by `hspace:hasPathType` (when that range is a class)
Range	rdfs:Literal (typed with the datatype named by `hspace:hasElementType` when it is a datatype)
Definition	Records the **end literal** of the path when elements are literals.

12.2.4.1.7. Property: stepList

TABLE 186: Property Definition: hspace:stepList

Property	hspace:stepList
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace#stepList`
JSON name	stepList
Requirement Level	Optional
Cardinality	0..1
Domain	Class named by `hspace:hasPathType` (when that range is a class)
Range	rdf:List
Definition	Points to an RDF Collection whose items are the ordered **literal elements** constituting the path (used when elements are literals).

12.2.4.1.8. Property: pathValue

TABLE 187: Property Definition: hspace:pathValue

Property	hspace:pathValue
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace#pathValue`
JSON name	pathValue
Requirement Level	Optional
Cardinality	0..1
Domain	Class named by `hspace:hasPathType` (when that range is a class)

Range	rdfs:Literal
Definition	Serialized path payload for visualization or exchange (e.g., WKT/GeoJSON LineString, JSON array/polyline).

12.2.5. Class: hspace:Path

The class `hspace:Path` represents a **composed path**: a finite composition of arrows in a given Hyperspace. It provides an identifiable resource on which systems can attach metadata, validate step coherence, and (optionally) serialize a concrete realization (e.g., a LineString or JSON sequence), without altering the core arrow-based semantics.

12.2.5.1. Class Definition

TABLE 188: Class Definition for hspace:Path

RDF Class	`hspace:Path`
Is Abstract	No
Definition	A first-class representation of a composed path (finite sequence of arrows) within a Hyperspace.
Subclass Of	hspace:Entity
Usage Note	Use when a path requires identity, metadata, validation, or serialization; otherwise, implicit path composition via arrow mappings suffices.
Rationale	Enables reproducible, governed, and interoperable exchange of paths (IDs, provenance, metrics) while keeping navigation arrow-driven.

12.2.5.2. Properties Summary

TABLE 189: Property Definitions for hspace:Path

Predicate	JSON(-LD) name	Description	Cardinality
hspace:startsAt	startsAt	Start **element node** (when elements are resources).	0..1
hspace:endsAt	endsAt	End **element node** (when elements are resources).	0..1
hspace:pathStep	pathStep	Ordered steps (elements, edges, or step nodes per profile).	0..1
hspace:onPath	onPath	Membership assertion that an element node lies on this path.	0..n
hspace:startsAtValue	startsAtValue	Start **literal** (when elements are literals).	0..1
hspace:endsAtValue	endsAtValue	End **literal** (when elements are literals).	0..1
hspace:stepList	stepList	`rdf:List` of ordered **literal** elements (when elements are literals).	0..1

Predicate	JSON(-LD) name	Description	Cardinality
hspace:pathValue	pathValue	Serialized path payload (e.g., WKT/GeoJSON LineString, JSON array/polyline).	0..1

12.2.5.2.1. Property: startsAt

TABLE 190: Property Definition: hspace:startsAt

Property	hspace:startsAt
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace#startsAt`
JSON name	startsAt
Requirement Level	Optional (resource-element profiles)
Cardinality	0..1
Domain	hspace:Path (and subclasses)
Range	owl:ObjectProperty IRI (targeting the element class named by `hspace:hasElementType`)
Definition	Links a path to its start **element node** when elements are resources.
Usage Note	For literal-element profiles, use `hspace:startsAtValue`.

12.2.5.2.2. Property: endsAt

TABLE 191: Property Definition: hspace:endsAt

Property	hspace:endsAt
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace#endsAt`
JSON name	endsAt
Requirement Level	Optional (resource-element profiles)
Cardinality	0..1
Domain	hspace:Path (and subclasses)
Range	owl:ObjectProperty IRI (targeting the element class named by `hspace:hasElementType`)
Definition	Links a path to its end **element node** when elements are resources.
Usage Note	For literal-element profiles, use `hspace:endsAtValue`.

12.2.5.2.3. Property: pathStep

TABLE 192: Property Definition: hspace:pathStep

Property	hspace:pathStep
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace#pathStep`
JSON name	pathStep
Requirement Level	Optional
Cardinality	0..1
Domain	hspace:Path (and subclasses)
Range	owl:ObjectProperty IRI
Definition	Ordered property listing the steps of a path. Steps MAY reference elements, edges, or step nodes per profile.
Usage Note	Ordering MAY be expressed via RDF Collections (e.g., `rdf:List`) or `sh:order` metadata on step nodes.

12.2.5.2.4. Property: onPath

TABLE 193: Property Definition: hspace:onPath

Property	hspace:onPath
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace#onPath`
JSON name	onPath
Requirement Level	Optional
Cardinality	0..n
Domain	hspace:Path (and subclasses)
Range	owl:ObjectProperty IRI (targeting element nodes)
Definition	Indicates that an element node lies on this explicit path.

12.2.5.2.5. Property: startsAtValue

TABLE 194: Property Definition: hspace:startsAtValue

Property	hspace:startsAtValue
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace#startsAtValue`

JSON name	startsAtValue
Requirement Level	Optional (literal-element profiles)
Cardinality	0..1
Domain	hspace:Path (and subclasses)
Range	rdfs:Literal (typed with the Hyperspace's `hspace:hasElementType` datatype)
Definition	Records the **start literal** of the path when elements are literals.

12.2.5.2.6. Property: endsAtValue

TABLE 195: Property Definition: hspace:endsAtValue

Property	hspace:endsAtValue
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace#endsAtValue`
JSON name	endsAtValue
Requirement Level	Optional (literal-element profiles)
Cardinality	0..1
Domain	hspace:Path (and subclasses)
Range	rdfs:Literal (typed with the Hyperspace's `hspace:hasElementType` datatype)
Definition	Records the **end literal** of the path when elements are literals.

12.2.5.2.7. Property: stepList

TABLE 196: Property Definition: hspace:stepList

Property	hspace:stepList
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace#stepList`
JSON name	stepList
Requirement Level	Optional (literal-element profiles)
Cardinality	0..1
Domain	hspace:Path (and subclasses)
Range	rdf:List

Definition	Points to an RDF Collection whose items are the ordered **literal elements** that constitute the path.
Usage Note	Each list item **MUST** be typed with the datatype named by `hspace:hasElementType` when elements are literals.

12.2.5.2.8. Property: pathValue

TABLE 197: Property Definition: hspace:pathValue

Property	hspace:pathValue
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace#pathValue`
JSON name	pathValue
Requirement Level	Optional
Cardinality	0..1
Domain	hspace:Path (and subclasses)
Range	rdfs:Literal
Definition	Serialized realization of the path for rendering or exchange (e.g., WKT/GeoJSON LineString, JSON array/polyline).
Usage Note	Navigation semantics (reachability) are derived from arrow mappings, not from this serialization.

NOTE **Conformance.** A profile that names a class in `hspace:hasPathType` MAY use `hspace:Path` directly or a subclass thereof (e.g., `ex:Route`, `vector:LineString`), applying the properties above as appropriate to the element representation (resource-based or literal-based).

12.2.6. Class: hspace:Operation

The class `hspace:Operation` declares a **portable operation** that can be applied to a given Hyperspace (e.g., reachability, shortest path, similarity routing, subspace formation). An Operation binds to the Hyperspace's declared mappings (element/arrow/path) so that different implementations can interoperate while using the same inputs and producing comparable outputs.

12.2.6.1. Class Definition

TABLE 198: Class Definition for hspace:Operation

RDF Class	`hspace:Operation`
Is Abstract	No
Definition	A declarative, reusable operation over a Hyperspace that references the mappings it consumes and the types it produces.

Subclass Of	hspace:Entity
Usage Note	A Hyperspace links to its supported operations with `hspace:hasOperation`. An Operation MAY be reused by multiple Hyperspaces if their mappings are compatible.
Rationale	Separates **what** to compute from **how** the Hyperspace is encoded, enabling consistent contracts for queries, analytics, validation, and services.

12.2.6.2. Properties Summary

TABLE 199: Property Definitions for hspace:Operation

Predicate	JSON(-LD) name	Description	Cardinality
rdf:type	@type	Declares the resource as an instance of `hspace:Operation`.	1..n
hspace:usesArrowProperty	usesArrowProperty	Binds the operation to the **atomic edge predicate** it traverses (when arrows are direct triples).	0..1
hspace:usesArrowClass	usesArrowClass	Binds the operation to the **reified edge class** it traverses (when arrows are edge resources).	0..1
hspace:usesAnnotationProperty	usesAnnotationProperty	Declares which **edge annotation properties** (e.g., weight, cost) the operation consumes.	0..n
hspace:returnsPathClass	returnsPathClass	Declares the **path class** produced (if the operation returns explicit paths).	0..1
hspace:returnsValueType	returnsValueType	Declares the **datatype or class** of the scalar/complex result (e.g., `xsd:boolean`, `xsd:decimal`, `prov:Entity`).	0..n
hspace:parameterShape	parameterShape	SHACL shape describing the **named parameters** and their constraints for invoking the operation.	0..1
hspace:implementation	implementation	IRI of an **algorithm, function, or service** (e.g., `prov:Plan`, API endpoint) that realizes this operation.	0..n

12.2.6.2.1. Property: rdf:type

TABLE 200: Property Definition: rdf:type

Property	rdf:type
IRI	`http://www.w3.org/1999/02/22-rdf-syntax-ns#type`
JSON name	@type
Requirement Level	Mandatory

Cardinality	1..n
Domain	hspace:Operation
Range	hspace:Operation
Definition	Declares the resource as an instance of `hspace:Operation`.

12.2.6.2.2. Property: usesArrowProperty

TABLE 201: Property Definition: hspace:usesArrowProperty

Property	hspace:usesArrowProperty
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace#usesArrowProperty`
JSON name	usesArrowProperty
Requirement Level	Optional
Cardinality	0..1
Domain	hspace:Operation
Range	owl:ObjectProperty IRI
Definition	Binds the operation to the arrow **predicate** to traverse (e.g., `ex:connect`).
Usage Note	Use this when the Hyperspace uses direct RDF edges (hspace:arrowProperty). Mutually exclusive with `hspace:usesArrowClass` in a single invocation context.

12.2.6.2.3. Property: usesArrowClass

TABLE 202: Property Definition: hspace:usesArrowClass

Property	hspace:usesArrowClass
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace#usesArrowClass`
JSON name	usesArrowClass
Requirement Level	Optional
Cardinality	0..1
Domain	hspace:Operation
Range	rdfs:Class

Definition	Binds the operation to the edge class to traverse (reified edges, e.g., ex:Edge).
Usage Note	Pair with endpoint properties defined in the profile (e.g., hspace:arrowSource / hspace:arrowTarget or their literal variants at execution time).

12.2.6.2.4. Property: usesAnnotationProperty

TABLE 203: Property Definition: hspace:usesAnnotationProperty

Property	hspace:usesAnnotationProperty
IRI	https://www.spatialwebfoundation.org/ns/hsml/hyperspace#usesAnnotationProperty
JSON name	usesAnnotationProperty
Requirement Level	Optional
Cardinality	0..n
Domain	hspace:Operation
Range	rdf:Property IRI
Definition	Declares which edge annotations the operation reads (e.g., ex:weight, ex:capacity, rdfs:label).
Usage Note	For shortest path, bind the weight property; for multi-criteria, list multiple properties and constrain via hspace:parameterShape.

12.2.6.2.5. Property: returnsPathClass

TABLE 204: Property Definition: hspace:returnsPathClass

Property	hspace:returnsPathClass
IRI	https://www.spatialwebfoundation.org/ns/hsml/hyperspace#returnsPathClass
JSON name	returnsPathClass
Requirement Level	Optional
Cardinality	0..1
Domain	hspace:Operation
Range	rdfs:Class
Definition	Declares the path class produced by the operation when it returns explicit paths (e.g., ex:Route, vector:LineString).

Usage Note	If omitted, the operation likely produces a scalar or set (see `hspace:returnsValueType`).

12.2.6.2.6. Property: returnsValueType

TABLE 205: Property Definition: hspace:returnsValueType

Property	hspace:returnsValueType
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace#returnsValueType`
JSON name	returnsValueType
Requirement Level	Optional
Cardinality	0..n
Domain	hspace:Operation
Range	rdfs:Class or datatype IRI
Definition	Declares the non-path **result type(s)** (e.g., `xsd:boolean` for reachability, `xsd:decimal` for distance, `prov:Entity` for artifacts).

12.2.6.2.7. Property: parameterShape

TABLE 206: Property Definition: hspace:parameterShape

Property	hspace:parameterShape
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace#parameterShape`
JSON name	parameterShape
Requirement Level	Optional
Cardinality	0..1
Domain	hspace:Operation
Range	sh:NodeShape
Definition	SHACL shape describing required/optional **parameters** (e.g., `ex:source`, `ex:target`, `ex:k`, `ex:maxCost`), their datatypes, and constraints.
Usage Note	Encourages portable invocation contracts across engines.

12.2.6.2.8. Property: implementation

TABLE 207: Property Definition: hspace:implementation

Property	hspace:implementation
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace#implementation`
JSON name	implementation
Requirement Level	Optional
Cardinality	0..n
Domain	hspace:Operation
Range	IRI (e.g., `prov:Plan`, code/package/service endpoint)
Definition	Identifies an algorithm, plan, or service that realizes the operation.
Usage Note	Use `prov:wasAssociatedWith` / `prov:used` alongside this property for full provenance, if desired.

NOTE **Binding model.** A Hyperspace links to operations via `hspace:hasOperation`. Each operation declares how it binds to the Hyperspace's mappings: - **Direct edges** → `hspace:usesArrowProperty`. - **Reified edges** → `hspace:usesArrowClass` (and profile-known source/target predicates). - **Weights/labels** → `hspace:usesAnnotationProperty`. Outputs are described by `hspace:returnsPathClass` and/or `hspace:returnsValueType`. Parameters are validated by `hspace:parameterShape`.

12.2.6.3. Minimal Example (Informative)

FIGURE 7

```
@prefix hspace: <https://www.spatialwebfoundation.org/ns/
hsml/hyperspace#> .
@prefix ex:     <https://example.org/ns/> .
@prefix xsd:    <http://www.w3.org/2001/XMLSchema#> .

# Hyperspace (excerpt)
ex:RoadNet a hspace:Hyperspace ;
  hspace:hasElementType ex:Intersection ;
  hspace:hasArrowType   ex:connectsTo ;
  hspace:arrowProperty  ex:connectsTo ;
  hspace:hasPathType    ex:Route ;
  hspace:hasOperation   ex:ShortestPath .

# Operation bound to the arrow predicate and weight
annotation
ex:ShortestPath a hspace:Operation ;
  hspace:usesArrowProperty ex:connectsTo ;
  hspace:usesAnnotationProperty ex:travelTime ;
  hspace:returnsPathClass ex:Route ;
```

```
      hspace:returnsValueType xsd:decimal ;       # total cost
      hspace:implementation <https://svc.example.org/ops/
    shortest-path> .
```

12.2.7. Class: hspace:HyperspaceOfHyperspace

hspace:HyperspaceOfHyperspace is a **higher-order Hyperspace** whose **elements are themselves Hyperspaces**. It enables composition, federation, and holarchic organization of spaces (systems-of-systems), allowing navigation and operations to traverse relationships among multiple constituent Hyperspaces without collapsing their internal structure.

12.2.7.1. Class Definition

TABLE 208: Class Definition for hspace:HyperspaceOfHyperspace

RDF Class	hspace:HyperspaceOfHyperspace
Is Abstract	No
Definition	A Hyperspace whose element type is hspace:Hyperspace, supporting relations and composed paths among Hyperspaces (e.g., containment, interoperability, federation).
Subclass Of	hspace:Hyperspace
Usage Note	Use when modeling networks or hierarchies of Hyperspaces (e.g., regional grids aggregated into a national grid; organizational spaces federated into a sector space). Internal structures of member Hyperspaces remain intact and navigable via their own declarations.
Rationale	Provides a principled way to build **holarchies** and **federations** in the Spatial Web: spaces as elements of larger spaces, with clear separation of concerns and reusable navigation semantics.

12.2.7.2. Specialization Constraints (Normative)

- **Element Type.** hspace:hasElementType **MUST** be hspace:Hyperspace.
- **Arrow Type.** hspace:hasArrowType **MAY** denote relations **between Hyperspaces** (e.g., interoperability, containment, dependency). The specific predicate (if using direct edges) is given by hspace:arrowProperty; if using reified edges, profiles SHALL provide the edge class and endpoint predicates.
- **Path Type.** hspace:hasPathType **MAY** be declared to represent composed relations across multiple Hyperspaces (e.g., federation traversal). Path instances (if used) employ the standard **Path-class properties** (hspace:startsAt, hspace:endsAt, hspace:pathStep, etc.).

NOTENOTEThis class **reuses the same Hyperspace-level, Element-class, and Path-class property model** defined for hspace:Hyperspace. The only additional constraint is that

elements are Hyperspaces. Consequently, any path over this space is a chain of Hyperspaces, and any arrow relates one Hyperspace to another.

12.2.7.3. Example: Holarchy (Hyperspace of Hyperspaces)

This example models a **higher-order Hyperspace** whose **elements are themselves Hyperspaces** (holons). It preserves each member Hyperspace's internal logic while expressing **whole–part** links across scales.

- **What is modeled.** `ex:Holarchy` contains `ex:RoomSpace`, `ex:BuildingSpace`, `ex:DistrictSpace`, `ex:CitySpace`—each a `hspace:Hyperspace`.
- **Arrow semantics.** `ex:containsHolon` is the **atomic arrow** (one step) relating Hyperspace → Hyperspace (Room → Building → District → City). Connectivity across levels is computed by arrow composition, e.g., `(ex:containsHolon)+`.
- **Explicit path (optional).** `hspace:Path` records a composed traversal (with identity and lightweight metadata). It **complements** arrow-based navigation; arrows remain authoritative for reachability.

NOTENOTEConformance reminders: - The enclosing space sets `hspace:hasElementType = hspace:Hyperspace`. - The arrow mapping relates Hyperspace → Hyperspace (`hspace:hasArrowType` / `hspace:arrowProperty`). - If used, `hspace:Path` endpoints target Hyperspace instances.

FIGURE 8

```
@prefix hspace: <https://www.spatialwebfoundation.org/ns/
hsml/hyperspace#> .
@prefix ex:     <https://example.org/ns/> .
@prefix xsd:    <http://www.w3.org/2001/XMLSchema#> .

# Enclosing higher-order hyperspace: elements are
Hyperspaces (holons)
ex:Holarchy a hspace:HyperspaceOfHyperspace ;
  hspace:hasElementType hspace:Hyperspace ;
  hspace:hasArrowType   ex:containsHolon ;     # whole-
part relation among hyperspaces
  hspace:arrowProperty  ex:containsHolon ;
  hspace:hasPathType    hspace:Path .

# Member hyperspaces at different scales (each is a whole/
part)
ex:RoomSpace      a hspace:Hyperspace .
ex:BuildingSpace  a hspace:Hyperspace .
ex:DistrictSpace  a hspace:Hyperspace .
ex:CitySpace      a hspace:Hyperspace .

# Holarchic containment (arrows): Room ⟶ Building ⟶
District ⟶ City
ex:RoomSpace     ex:containsHolon ex:BuildingSpace .
ex:BuildingSpace ex:containsHolon ex:DistrictSpace .
ex:DistrictSpace ex:containsHolon ex:CitySpace .
```

```
    # Optional explicit path: aggregation from Room to City
    through the holarchy
    ex:upwardAggregation a hspace:Path ;
      hspace:startsAt ex:RoomSpace ;
      hspace:endsAt   ex:CitySpace ;
      hspace:pathStep ( ex:RoomSpace ex:BuildingSpace
    ex:DistrictSpace ex:CitySpace ) ;
      ex:levelCount "4"^^xsd:integer .
```

13. HSML TopologicalSpace SubModule

13.1. Introduction

The TopologicalSpace Module specializes the Hyperspace abstraction for structures defined by **neighborhoods, adjacency, and continuity**, rather than numeric coordinates. It realizes the **TOPOLOGICAL SPACE** concept referenced in IEEE P2874™/D-3.3.1-2025-03, Clause 6.2.1 and HSML Hyperspace design:

> A topological space is a set of elements together with a structure that specifies which subsets are 'open,' thereby defining notions of adjacency, neighborhood, and continuity without reference to metric distance.

In HSML, a TopologicalSpace provides a declarative way to represent **connectivity, adjacency, boundaries, and regions**. It is the natural home for **geometries beyond points**, including **LineStrings**, **Polygons**, and **Spheres**, which are not valid vector elements but can be modeled in a topological sense.

Typical use cases include:

- Geographic features — regions, boundaries, polygonal areas, networks of connected edges.
- Computational grids — adjacency of cells in raster or tessellated models.
- Continuity spaces — abstract topologies for states, neighborhoods, or coverage.

A TopologicalSpace inherits from `hspace:Hyperspace` and introduces adjacency and region semantics. It does not assume distances (`metric:Metric`) unless combined with a MetricSpace; instead, it captures **purely topological relations**.

13.2. Architecture and Design Rationale

13.2.1. Core Principle

TopologicalSpaces in HSML are relation-first: they define what is "next to" or "contained in what," rather than how far apart elements are. This makes them suitable for qualitative spatial reasoning and boundary-driven models.

13.2.2. Subclassing Strategy

- `topo:TopologicalSpace` is a subclass of `hspace:Hyperspace`.
- Optional specializations include:
  - `topo:TopologicalMetricSpace` — adds metric distance on top of adjacency.
  - `topo:CellularSpace` — specialization for discrete grids and tessellations.

13.2.3. Elements and Paths

- Element Type — any spatial unit such as `geo:Polygon`, `geo:LineString`, or `cell:Cell`.
- Path Type — adjacency relations such as `topo:adjacentTo` or `topo:connectedTo`.
- Elements may represent continuous regions (polygons, spheres) or discrete cells.
- Paths represent adjacency chains (sequences of touching elements, border walks).

13.2.4. Neighborhoods and Open Sets

Unlike VectorSpaces, which define neighborhoods via coordinates and metrics, TopologicalSpaces rely on declared adjacency or open sets:

- `topo:hasNeighborhood` links an element to its set of neighboring elements.
- SHACL profiles may constrain neighborhood semantics (e.g., Moore vs. Von Neumann adjacency in a grid).

13.2.5. Regions and Boundaries

TopologicalSpaces support grouping and edge semantics:

- `topo:Region` — a contiguous set of adjacent elements treated as one area.
- `topo:Boundary` — the separating edge or border between a region and its exterior.

These abstractions allow modeling polygon boundaries, country borders, adjacency of cellular clusters, and more.

13.2.6. Generic Operations

TopologicalSpaces extend the universal Hyperspace algebra with **qualitative operations**:

- **Neighborhood query** — return adjacent elements of a given element.
- **Adjacency test** — check if two elements share a border or node.
- **Connectivity test** — check if two elements belong to the same connected component.
- **Path composition** — concatenate adjacency steps into longer paths.
- **Reachability** — determine if a path exists between two elements.
- **Boundary extraction** — identify the separating elements between regions.
- **Region closure / interior** — derive closed vs. open sets.
- **Union / intersection of regions** — form composite regions.
- **Subspace formation** — restrict to a subset of elements with induced adjacency.
- **Quotienting by equivalence** — merge elements under an equivalence relation (e.g., administrative aggregation).

These operations are **generic** and apply across polygonal, line-based, cellular, and spherical topologies.

13.2.7. Separation of Concerns

- **Domain vs Hyperspace** — a Domain provides identity; attaching a TopologicalSpace defines adjacency and region semantics.
- **Topology vs Metric** — adjacency is qualitative; distances are layered on top when required.
- **Profiles** — SHACL profiles constrain adjacency semantics (e.g., polygons must be closed, cells must tessellate consistently).

13.2.8. Examples of Spaces

TopologicalSpaces are not limited to geometry — they capture **adjacency and connectivity** in many domains:

Geometric Topologies - **Polygonal Topology**: elements are polygons; adjacency = "share an edge." - **Line Network**: elements are line segments; adjacency = "share a node." - **Spherical Topology**: elements are regions on a sphere; adjacency defined by great-circle boundaries. - **Cellular/DGGS Topology**: elements are discrete cells; adjacency defined by tessellation rules.

Computational / Data Structures - **Graph Topology**: elements are graph nodes; adjacency defined by edges. - **Tree Topology**: elements are tree nodes; adjacency = parent–child relations. - **Cellular Automaton Topology**: elements are cells; adjacency defined by automaton rules (Moore, Von Neumann).

Abstract / Conceptual Topologies - State Space Topology: elements are states in a machine; adjacency defined by transitions. - Semantic Neighborhood Topology: elements are SKOS concepts; adjacency via broader/narrower/related links. - Linguistic Topology: elements are words; adjacency via co-occurrence in a context window. - Process Topology: elements are workflow activities; adjacency via "precedes" or "depends on" relations.

Scientific / Physical Topologies - Biological Cell Topology: elements are cells in tissue; adjacency via direct contact. - Protein Folding Topology: elements are amino acids; adjacency via sequential bonds + folding contacts. - Neural Network Topology: elements are neurons; adjacency via synaptic connections.

To summarize, the TopologicalSpace Module captures adjacency and neighborhood semantics without relying on coordinates or metrics. It provides the structural foundation for representing Polygons, LineStrings, Spheres, and beyond as elements, enabling qualitative reasoning, boundary logic, and region-based navigation in HSML.

14. Metric Space Submodule

The Metric Space Submodule provides metric-aware, format-agnostic hooks that work with any element or path encoding chosen via the core hspace: mappings. It adds distance/similarity semantics without imposing a particular geometry, graph model, or storage format, and integrates cleanly with Vector, Graph, Cellular, Concept, or custom domains.

Namespace. `https://www.spatialwebfoundation.org/ns/hsml/hyperspace/metric#`

Prefix. metric:

- Structural neutrality. Element and path types are still declared with hspace: (e.g., hspace:hasElementType, hspace:hasPathType). The metric module does not force vectors, geometries, or specific classes.
- Pluggable metrics. A Hyperspace MAY declare one or more metrics and optionally a default metric for operations.
- Literal or resource elements. Metrics can operate on resource elements (with an operand value carried by a property) or directly on literal elements (e.g., embeddings, strings, colors).
- Distance or similarity ("polarity"). A metric SHALL be explicitly tagged as distance or similarity; operations can uniformly convert via an optional monotone transform.
- Operations-ready. Metric declarations are consumable by hspace:Operation (e.g., kNN, range query, clustering, path cost evaluation) without additional coupling.

- Monoid path aggregation. Path costs are aggregated via a declared associative aggregator (e.g., sum, max, product) with an identity element; engines MAY override.

14.1. Normative Classes

TABLE 209: Class Summary for Metric Module

Class	Description
metric:MetricSpace	Specialization of hspace:Hyperspace indicating that distance/similarity semantics are available via one or more metric:Metric declarations.
metric:Metric	Declarative description of a distance/similarity over the element domain of a Hyperspace, including operand extraction (metric:operandProperty / metric:onType), polarity (metric:polarity), unit/scale (metric:unit / metric:scaleKind), and axiom kind (metric:kind)
metric:Measure (Optional)	First-class resource for pairwise measurements (distance or similarity) computed under a given metric:Metric—useful for caching, provenance, or exchange.
metric:Aggregator (Vocabulary/Class)	Declarative path aggregator with monoid semantics (associative op + identity). Includes ready-to-use instances (sum, max, min, product, lexicographic).
metric:MetricKind (Vocabulary)	Lightweight vocabulary tagging the axiom flavor: metric:Metric, metric:Pseudometric, metric:Quasimetric, metric:Semimetric, metric:Dissimilarity.
metric:Polarity (Vocabulary)	Lightweight vocabulary for polarity: metric:Distance, metric:Similarity.
metric:ScaleKind (Vocabulary)	Optional measurement scale hint: metric:Ratio, metric:Interval, metric:Ordinal, metric:UnitInterval.

14.1.1. Class: metric:MetricSpace

A `metric:MetricSpace` is a specialization of `hspace:Hyperspace` that **equips a domain with quantitative semantics**. While a Hyperspace already defines elements, paths, and their connectivity, a MetricSpace adds the notion of **distance or similarity functions**.

This enables: * **Quantitative reasoning** – e.g., nearest neighbor search, clustering, radius queries. * **Comparative analysis** – measuring similarity between embeddings, geometries, or categorical features. * **Path evaluation** – computing shortest paths, least-cost routes, or similarity-based traversals.

By separating **structural relationships** (adjacency, connectivity) from **metric semantics**, HSML supports **portable and engine-independent computations** across graphs, cellular grids, and vector spaces. In IEEE P2874™/D-3.3.1-2025-03 terms, this corresponds to the requirement that a Hyperspace may declare one or more **Metrics** to enable interoperable spatial and similarity-based operations.

14.1.1.1. Class Definition

TABLE 210: Class Definition for metric:MetricSpace

RDF Class	metric:MetricSpace
Is Abstract	No
Definition	A hspace:Hyperspace that declares one or more metrics (distance or similarity) applicable to its elements.
Subclass Of	hspace:Hyperspace
Usage Note	Use when your domain supports metric-based operations. Element and path types remain bound via hspace: mappings.
Rationale	Separates structure (core hyperspace) from quantitative semantics (metrics), enabling portable operations (kNN, radius search, path cost).

TABLE 211: Properties Summary for metric:MetricSpace

Predicate (anchor)	JSON name	Description	Range	Card.	Req.
metric:has Metric	hasMetric	Declares a metric available in this Hyperspace.	metric:Metric	0..*	Optional
metric:default Metric	defaultMetric	Identifies the default metric to use when none is specified by an operation.	metric:Metric	0..1	Optional
metric:weight Property (Optional)	weight Property	Names a property that holds precomputed edge/step weights (when used).	rdf:Property (IRI)	0..1	Optional

14.1.1.2. Properties (MetricSpace)

14.1.1.2.1. Property: hasMetric

TABLE 212: Property Definition: metric:hasMetric

Property	metric:hasMetric
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace/metric#hasMetric`
Domain	hspace:Hyperspace (typically metric:MetricSpace)
Range	metric:Metric
Definition	Declares a metric available for this Hyperspace.

14.1.1.2.2. Property: defaultMetric

TABLE 213: Property Definition: metric:defaultMetric

Property	metric:defaultMetric
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace/metric#defaultMetric`
Domain	hspace:Hyperspace
Range	metric:Metric
Definition	Identifies the default metric to use in absence of an explicit metric selection.

14.1.1.2.3. Property: weightProperty (Optional)

TABLE 214: Property Definition: metric:weightProperty

Property	metric:weightProperty
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace/metric#weightProperty`
Domain	hspace:Hyperspace
Range	rdf:Property (IRI)
Definition	Indicates a property on edges/steps that carries precomputed weights (e.g., travel time, cost) that operations MAY use instead of evaluating a metric.
Usage Note	A metric:Metric MAY override at the metric level via metric:edgeWeightProperty.

14.1.2. Class: metric:Metric

Metrics are the backbone of quantitative reasoning in a Hyperspace. They declare **how closeness, likeness, or difference is measured** between elements of a domain, enabling engines to evaluate k-nearest neighbor queries, range filters, clustering, and other operations consistently across heterogeneous data types.

Unlike raw functions, a `metric:Metric` is a **declarative description**: it specifies the polarity (distance vs similarity), expected operand type, optional units and scale, theoretical bounds, and a reference to the computation plan. This separation of **semantics** from **implementation** allows a metric definition to be portable across engines, reproducible across versions, and validatable via SHACL.

Key design principles:

- **Declarative, not imperative** — the ontology does not encode formulas but points to plans or algorithms while capturing semantic guarantees (e.g., symmetry, triangle inequality).

- Polarity-aware — every metric must declare whether values are interpreted as distances (lower is better) or similarities (higher is better), ensuring uniform ranking and threshold semantics.
- Context-bound — a metric may be attached to a Hyperspace (via `metric:hasMetric` or `metric:defaultMetric`) to make its applicability explicit.
- Extensible — additional properties such as `metric:unit`, `metric:scaleKind`, `metric:monotoneTransform`, and `metric:aggregator` provide optional but powerful hints for engines, user interfaces, and interoperability.

By elevating metrics to first-class declarative entities, HSML enables predictable, portable, and semantically rich measurement across the Spatial Web.

14.1.2.1. Mathematical Guarantees (The Four Axioms)

The boolean properties `nonNegative`, `identityOfIndiscernibles`, `symmetric`, and `triangleInequality` are more than just metadata; they are formal mathematical guarantees. When all four are true, the function is a true metric, which allows query engines and algorithms to make powerful assumptions and drastic optimizations. Declaring these guarantees enables a system to validate data, select the most efficient algorithms, and ensure logically consistent results.

14.1.2.1.1. Non-Negativity

Property: `metric:nonNegative`

Axiom: The distance between two points is never negative. $d(x, y) \geq 0$.

Why it's needed: This is a fundamental sanity check. It establishes a baseline where the minimum possible distance is zero. Algorithms that find shortest paths, like Dijkstra's, rely on this, as a negative distance would imply that traversing a path could somehow "reduce" the total cost, creating nonsensical loops.

Example — Physical Distance: The distance between two cities is always a positive number of miles or kilometers. The distance is 0 only if they are the same location.

When it's false: A function measuring financial "distance" as `cost - revenue`. Traveling from A to B might cost $50 in fuel but generate $80 in profit, yielding a "distance" of -$30. This is a gain/loss function, not a metric.

14.1.2.1.2. Identity of Indiscernibles

Property: `metric:identityOfIndiscernibles`

Axiom: The distance between two points is zero if and only if they are the same point. $d(x, y) = 0 \iff x = y$.

Why it's needed: This axiom guarantees that every element is unique. It ensures that if two items are indistinguishable (zero distance apart), they are identical. This is crucial for search, deduplication, and clustering, as it prevents distinct items from being treated as the same.

Example — Hamming Distance: For strings of equal length, this is the number of positions at which the characters are different. `d("apple", "apply")` is 1, but `d("apple", "apple")` is 0. The distance is only zero if the strings are identical.

When it's false (Pseudometric): A function measuring the distance between two people as 0 if they live in the same city. Alice and Bob might have a distance of 0, but they are clearly not the same person.

14.1.2.1.3. Symmetry

Property: `metric:symmetric`

Axiom: The distance from x to y is the same as the distance from y to x.
$d(x, y) = d(y, x)$.

Why it's needed: Symmetry allows algorithms to assume reciprocity. This dramatically simplifies problems in routing, graph analysis, and indexing. For example, a query engine only needs to compute or store a distance matrix in one direction, cutting storage requirements nearly in half.

Example — Euclidean Distance: The straight-line distance between your home and the library is the same as the distance from the library back to your home.

When it's false (Quasimetric): Driving time in a city with one-way streets. The route from the office to the gym might be 10 minutes, but the return trip could be 20 minutes due to different required paths.

14.1.2.1.4. Triangle Inequality

Property: `metric:triangleInequality`

Axiom: The direct path between two points is always the shortest.
$d(x, z) \leq d(x, y) + d(y, z)$.

Why it's needed: This is the most powerful axiom for **optimization**. It guarantees that there are no "wormholes" or unexpected shortcuts. Search algorithms (like A*) and indexing structures (like M-trees) rely on this principle to prune massive portions of the search space.

Example — Geographic Distance: The direct flight distance from New York to Tokyo is never greater than the distance of flying from New York to London and then from London to Tokyo.

When it's false (Semimetric): Airline ticket pricing. A flight from New York to London might be $500, and a flight from London to Tokyo might be $600. However, a direct flight from New York to Tokyo could cost $1800, which is far greater than the sum of the two legs ($1100).

14.1.2.2. Class Definition

TABLE 215: Class Definition for metric:Metric

RDF Class	metric:Metric
Is Abstract	No
Definition	A reusable definition of a distance or similarity function over elements (or their operand values) of a Hyperspace.
Subclass Of	owl:Thing

RDF Class	metric:Metric
Usage Note	Bind to a Hyperspace via metric:hasMetric / metric:defaultMetric. Operations (e.g., kNN) consume this declaration to evaluate measures.
Rationale	Enables portable, implementation-independent metric evaluation across engines and data encodings.

TABLE 216: Properties Summary for metric:Metric

Predicate (anchor)	JSON name	Description	Range	Card.	Req.
metric:kind	kind	Axiom flavor of the measure (Metric, Pseudometric, Quasimetric, Semimetric, Dissimilarity).	metric:MetricKind	1	Mandatory
metric:polarity	polarity	Declares whether values are distance (lower is better) or similarity (higher is better).	metric:Polarity	1	Mandatory
metric:onType	onType	Declares the element type (class) or literal datatype the metric expects.	rdfs:Class or Datatype (IRI)	1	Mandatory
metric:operandProperty	operandProperty	Property from a resource element to its operand value (e.g., embedding vector, WKT, color triple).	rdf:Property (IRI)	0..1	Optional
metric:valueType	valueType	Datatype of operand and/or measure values used by the metric (e.g., xsd:decimal, xsd:double, rdf:JSON).	rdfs:Datatype	0..1	Optional
metric:unit	unit	Unit of the measure (e.g., a QUDT/UCUM IRI).	IRI	0..1	Optional
metric:scaleKind	scaleKind	Optional measurement scale hint (Ratio, Interval, Ordinal, UnitInterval).	metric:ScaleKind	0..1	Optional
metric:rangeMin	rangeMin	Minimum attainable value (e.g., 0).	xsd:decimal	0..1	Optional
metric:rangeMax	rangeMax	Maximum attainable value (e.g., 1 for normalized similarity).	xsd:decimal	0..1	Optional
metric:function	function	IRI of an algorithm/function/plan that computes the measure (e.g., prov:Plan, code/service IRI).	IRI	0..*	Optional
metric:functionVersion	functionVersion	Version tag for the referenced function/plan to ensure reproducibility.	xsd:string	0..1	Optional

Predicate (anchor)	JSON name	Description	Range	Card.	Req.
metric: aggregator	aggregator	Default path aggregation for step-wise costs (e.g., metric: Sum, metric:Max).	metric: Aggregator	0..1	Optional
metric:edge Weight Property	edgeWeight Property	Edge/step property to read precomputed weights for this metric (overrides metric: weightProperty on the space).	rdf:Property (IRI)	0..1	Optional
metric: monotone Transform	monotone Transform	Monotone mapping (IRI) to convert distance↔similarity or re-scale (e.g., f(d)=1/(1+d), f (s)=1−s).	IRI	0..1	Optional
metric: symmetric	symmetric	Whether d(x,y)=d(y,x). Defaults TRUE for metrics.	xsd:boolean	0..1	Optional
metric: identity OfIndiscernible	identity OfIndiscernible	Whether d(x,y)=0 ⇒ x=y. Defaults TRUE for metrics.	xsd:boolean	0..1	Optional
metric: triangle Inequality	triangle Inequality	Whether d(x,z) ≤ d(x,y)+d(y,z). Defaults TRUE for metrics.	xsd:boolean	0..1	Optional
metric:non Negative	nonNegative	Whether values are guaranteed ≥ 0. Defaults TRUE.	xsd:boolean	0..1	Optional

14.1.2.3. Properties (Metric)

14.1.2.3.1. Property: kind

TABLE 217: Property Definition: metric:kind

Property	metric:kind
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace/metric#kind`
Domain	metric:Metric
Range	metric:MetricKind
Definition	Tags the axiom flavor (e.g., metric:Metric, metric:Pseudometric).

14.1.2.3.2. Property: polarity

TABLE 218: Property Definition: metric:polarity

Property	metric:polarity

IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace/metric#polarity`
Domain	metric:Metric
Range	metric:Polarity
Definition	Declares whether the metric yields distance (lower is better) or similarity (higher is better).

14.1.2.3.3. Property: onType

TABLE 219: Property Definition: metric:onType

Property	metric:onType
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace/metric#onType`
Domain	metric:Metric
Range	rdfs:Class or Datatype (IRI)
Definition	Declares the expected element class (resource elements) or literal datatype (literal elements) over which the metric operates.

14.1.2.3.4. Property: operandProperty (Optional)

TABLE 220: Property Definition: metric:operandProperty

Property	metric:operandProperty
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace/metric#operandProperty`
Domain	metric:Metric
Range	rdf:Property (IRI)
Definition	If elements are resources, names the property that yields the operand value used by the metric (e.g., ex:embedding, geo:asWKT, vector:asArray).
Usage Note	Omit when elements are literals of the declared metric:onType; the literal itself is the operand.

14.1.2.3.5. Property: valueType (Optional)

TABLE 221: Property Definition: metric:valueType

Property	metric:valueType
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace/metric#valueType`

Domain	metric:Metric
Range	rdfs:Datatype
Definition	Datatype of operands and/or distance/similarity values used by the metric (e.g., xsd:decimal, xsd:double, rdf:JSON).

14.1.2.3.6. Property: unit (Optional)

TABLE 222: Property Definition: metric:unit

Property	metric:unit
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace/metric#unit`
Domain	metric:Metric
Range	IRI (e.g., QUDT/OM/UCUM)
Definition	Unit associated with the measure values (when applicable).

14.1.2.3.7. Property: scaleKind (Optional)

TABLE 223: Property Definition: metric:scaleKind

Property	metric:scaleKind
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace/metric#scaleKind`
Domain	metric:Metric
Range	metric:ScaleKind
Definition	Optional hint about the measurement scale (e.g., Ratio for distances; UnitInterval for normalized similarities).

14.1.2.3.8. Property: rangeMin (Optional)

TABLE 224: Property Definition: metric:rangeMin

Property	metric:rangeMin
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace/metric#rangeMin`
Domain	metric:Metric
Range	xsd:decimal
Definition	Theoretical or enforced minimum of the measure domain.

14.1.2.3.9. Property: rangeMax (Optional)

TABLE 225: Property Definition: metric:rangeMax

Property	metric:rangeMax
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace/metric#rangeMax`
Domain	metric:Metric
Range	xsd:decimal
Definition	Theoretical or enforced maximum of the measure domain (e.g., 1.0 for normalized similarity).

14.1.2.3.10. Property: function (Optional)

TABLE 226: Property Definition: metric:function

Property	metric:function
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace/metric#function`
Domain	metric:Metric
Range	IRI
Definition	Identifies an algorithm, plan, or service endpoint that evaluates the metric (e.g., prov:Plan, API/operation IRI).

14.1.2.3.11. Property: functionVersion (Optional)

TABLE 227: Property Definition: metric:functionVersion

Property	metric:functionVersion
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace/metric#functionVersion`
Domain	metric:Metric
Range	xsd:string
Definition	Version string for the referenced function/plan (for reproducibility).

14.1.2.3.12. Property: aggregator (Optional)

TABLE 228: Property Definition: metric:aggregator

Property	metric:aggregator

IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace/metric#aggregator`
Domain	metric:Metric
Range	metric:Aggregator
Definition	Default aggregator for composing step costs into a path cost (e.g., sum, max). Engines MAY override at operation time.

14.1.2.3.13. Property: edgeWeightProperty (Optional)

TABLE 229: Property Definition: metric:edgeWeightProperty

Property	metric:edgeWeightProperty
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace/metric#edgeWeightProperty`
Domain	metric:Metric
Range	rdf:Property (IRI)
Definition	Names a property on edges/steps that carries precomputed weights for this metric (overrides space-level metric:weight Property).

14.1.2.3.14. Property: monotoneTransform (Optional)

TABLE 230: Property Definition: metric:monotoneTransform

Property	metric:monotoneTransform
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace/metric#monotoneTransform`
Domain	metric:Metric
Range	IRI
Definition	Identifies a monotone mapping to invert polarity or re-scale results (e.g., distance→similarity via f(d)=1/(1+d); similarity→distance via f(s)=1−s)).
Usage Note	The target of this IRI MAY be a prov:Plan, code function, or math expression resource.

14.1.2.3.15. Property: symmetric (Optional)

TABLE 231: Property Definition: metric:symmetric

Property	metric:symmetric
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace/metric#symmetric`

Domain	metric:Metric
Range	xsd:boolean
Definition	Indicates whether the measure is symmetric.

14.1.2.3.16. Property: identityOfIndiscernibles (Optional)

TABLE 232: Property Definition: metric:identityOfIndiscernibles

Property	metric:identityOfIndiscernibles
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace/metric#identityOfIndiscernibles`
Domain	metric:Metric
Range	xsd:boolean
Definition	Indicates whether d(x,y)=0 implies x=y.

14.1.2.3.17. Property: triangleInequality (Optional)

TABLE 233: Property Definition: metric:triangleInequality

Property	metric:triangleInequality
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace/metric#triangleInequality`
Domain	metric:Metric
Range	xsd:boolean
Definition	Indicates whether the triangle inequality holds.

14.1.2.3.18. Property: nonNegative (Optional)

TABLE 234: Property Definition: metric:nonNegative

Property	metric:nonNegative
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace/metric#nonNegative`
Domain	metric:Metric
Range	xsd:boolean
Definition	Indicates whether values are guaranteed to be non-negative (typical for distances).

14.1.3. Class: metric:Measure (Optional)

metric:Measure represents the computed outcome of applying a specific metric:Metric to an ordered pair of elements: metric:from and metric:to. It is deliberately structure-neutral (works with vectors, geometries, strings, graphs, etc.) and polarity-neutral (covers both distances and similarities). The how of measurement (function, axioms, operands, units) lives in metric:Metric; the what (the numeric result and its context) lives in metric:Measure. This separation keeps declarations portable and engine-independent while making results easy to cache, audit, exchange, and reason over.

14.1.3.1. Why a first-class metric:Measure?

- Caching & performance. Persist kNN/range results or expensive pairwise evaluations to avoid recomputation across queries and sessions.
- Audit & reproducibility. Record the value (metric:value), the metric used (metric:wrtMetric), and optional unit (metric:unit); link to provenance (e.g., prov:wasGeneratedBy) and implementation version (metric:functionVersion) for traceable, repeatable analytics.
- Interchange & federation. Share precomputed measures between heterogeneous engines and domains without leaking internal encodings or storage choices.
- Governance & evidence. Attach quantitative evidence to decisions/contracts in policy evaluation pipelines.
- Evaluation & ML. Store gold standards or inferred pairs for model training, validation, active learning, and drift monitoring.

14.1.3.2. Usage semantics

- Operands. metric:from and metric:to may be resources or literals. When elements are resources, the metric can declare metric:operandProperty to extract the value it operates on (e.g., embeddings, WKT). When elements are literals, the literal itself is the operand and metric:onType SHOULD be a datatype IRI.
- Polarity & transforms. Polarity is determined by the referenced metric (metric:polarity = metric:Distance or metric:Similarity). Engines MAY normalize for ranking via metric:monotoneTransform (e.g., similarity→distance). Unless stated otherwise, the stored metric:value SHOULD be the native output of the metric prior to any downstream normalization.*
- Typing & units. Prefer a numeric datatype consistent with the metric's metric:valueType (e.g., xsd:double, xsd:decimal). Provide metric:unit when the quantity is dimensional (e.g., meters, seconds) and consider metric:scaleKind / metric:rangeMin / metric:rangeMax for UI and validation hints.
- Identity & lifecycle. Ephemeral results can be blank nodes. Persisted results SHOULD mint stable IRIs (e.g., a content hash over {metric, from, to, functionVersion, params} with a timestamp). Capture provenance (prov:*) when reproducibility or explainability matters.
- Paths & aggregation. metric:Measure is pairwise by design. Path-level outcomes can be represented as additional metric:Measure instances whose endpoints denote the path start/end, with provenance pointing to the path and its metric:Aggregator

(e.g., metric:Sum, metric:Max). Engines MAY also introduce a domain-specific path result class if needed.

14.1.3.3. Interoperability notes

- Works uniformly with any Hyperspace that declares metrics (see metric:MetricSpace and metric:hasMetric / metric:defaultMetric).
- Compatible with operation planning and evaluation (e.g., kNN, radius search, clustering, shortest path) without binding to a specific data model or algorithm.
- Encourages consistent cross-system semantics through explicit references to functions (metric:function), versions (metric:functionVersion), units (metric:unit), and axioms (metric:kind).

14.1.3.4. Class Definition

TABLE 235: Class Definition for metric:Measure

RDF Class	metric:Measure
Is Abstract	No
Definition	A first-class pairwise measure (distance or similarity) computed under a specific metric:Metric.
Subclass Of	hspace:Entity
Usage Note	Useful for caching, provenance, audit, or exchanging computed distances/similarities. Use prov:wasGeneratedBy to link computation runs if desired.

TABLE 236: Properties Summary for metric:Measure

Predicate (anchor)	JSON name	Description	Range	Card.	Req.
metric:using Metric	usingMetric	Links the measurement to the metric used.	metric:Metric	1	Mandatory
metric:from	from	First element (resource or literal).	rdfs:Resource or rdfs:Literal	1	Mandatory
metric:to	to	Second element (resource or literal).	rdfs:Resource or rdfs:Literal	1	Mandatory
metric:value	value	Numeric value of the measure (datatype SHOULD match the metric's metric: valueType when provided).	rdfs:Literal	1	Mandatory
metric:unit	unit	Unit of the measure value (if any).	IRI	0..1	Optional
metric: confidence	confidence	Optional confidence in the computed value, in [0,1].	xsd:decimal	0..1	Optional

14.1.3.5. Properties (Measure)

14.1.3.5.1. Property: usingMetric

TABLE 237: Property Definition: metric:usingMetric

Property	metric:usingMetric
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace/metric#usingMetric`
Domain	metric:Measure
Range	metric:Metric
Definition	Associates the measurement with the metric definition used.

14.1.3.5.2. Property: from

TABLE 238: Property Definition: metric:from

Property	metric:from
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace/metric#from`
Domain	metric:Measure
Range	rdfs:Resource or rdfs:Literal
Definition	First element of the ordered pair.

14.1.3.5.3. Property: to

TABLE 239: Property Definition: metric:to

Property	metric:to
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace/metric#to`
Domain	metric:Measure
Range	rdfs:Resource or rdfs:Literal
Definition	Second element of the ordered pair.

14.1.3.5.4. Property: value

TABLE 240: Property Definition: metric:value

Property	metric:value
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace/metric#value`
Domain	metric:Measure
Range	rdfs:Literal (numeric)
Definition	Numeric value of the measurement.

14.1.3.5.5. Property: unit (Optional)

TABLE 241: Property Definition: metric:unit

Property	metric:unit
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace/metric#unit`
Domain	metric:Measure
Range	IRI
Definition	Unit for the reported value (when applicable).

14.1.3.5.6. Property: confidence (Optional)

TABLE 242: Property Definition: metric:confidence

Property	metric:confidence
IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace/metric#confidence`
Domain	metric:Measure
Range	xsd:decimal
Definition	Confidence in [0,1] for the computed value (if provided by the engine).

14.1.4. Class: metric:Aggregator

A `metric:Aggregator` defines **how step-level measures are combined into a path-level measure**. In HSML Hyperspaces (graphs, cellular spaces, vector paths), a path consists of multiple segments. To evaluate the overall cost, distance, or similarity of a path, step measures must be aggregated.

The `metric:Aggregator` provides a declarative, machine-readable way to specify: * **Operation** (`metric:op`) – associative binary operator (sum, max, product, lexicographic). * **Identity** (`metric:identity`) – neutral element for the operation. * **Commutativity** (`metric:commutative`) – whether operands can be reordered. * **Parameters** (`metric:parameter`) – structured bindings (e.g., p for Lp norms, `weights` for weighted sums).

This ensures **interoperability, optimization, and validation** across engines.

14.1.4.1. Class Definition

TABLE 243: Class Definition for metric:Aggregator

RDF Class	metric:Aggregator
Is Abstract	No
Definition	Declarative monoid for composing step measures into a path measure.
Subclass Of	hspace:Entity
Usage Note	Hyperspatial Engines may provide optimized implementations for standard aggregators.

14.1.4.2. Properties Summary (Aggregator)

TABLE 244: Property Summary for metric:Aggregator

Predicate	JSON name	Description	Range	Card.	Req.
metric:op	op	Operation IRI (associative binary operator).	IRI	1	Mandatory
metric: identity	identity	Identity element (neutral value for the operation).	rdfs:Literal	0..1	Optional
metric: commutative	commutative	Whether the operation is commutative.	xsd:boolean	0..1	Optional
metric: parameter	parameter	One or more structured parameters configuring the op.	metric: Parameter	0..*	Optional

14.1.4.2.1. Property: op

TABLE 245: Property Definition: metric:op

IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace/metric#op`
Domain	metric:Aggregator
Range	IRI
Definition	Identifies the associative binary operation used for aggregation.

IRI	https://www.spatialwebfoundation.org/ns/hsml/hyperspace/metric#op
Why it matters	Engines require the algebraic operation to compute path measures deterministically.
Examples	sw:sum, sw:max, sw:product, sw:lexicographic

14.1.4.2.2. Property: identity

TABLE 246: Property Definition: metric:identity

IRI	https://www.spatialwebfoundation.org/ns/hsml/hyperspace/metric#identity
Domain	metric:Aggregator
Range	rdfs:Literal
Definition	Neutral element for the operation.
Why it matters	Enables valid evaluation of zero-length paths and ensures algebraic closure.
Examples	Sum → 0; Product → 1; Max → -INF

14.1.4.2.3. Property: commutative

TABLE 247: Property Definition: metric:commutative

IRI	https://www.spatialwebfoundation.org/ns/hsml/hyperspace/metric#commutative
Domain	metric:Aggregator
Range	xsd:boolean
Definition	Indicates if operand order affects the result.
Why it matters	Guides algorithmic optimization (parallelism, reordering).
Examples	Sum → true; Max → true; Lexicographic → false

14.1.4.2.4. Property: parameter

TABLE 248: Property Definition: metric:parameter

IRI	https://www.spatialwebfoundation.org/ns/hsml/hyperspace/metric#parameter
Domain	metric:Aggregator
Range	metric:Parameter

IRI	`https://www.spatialwebfoundation.org/ns/hsml/hyperspace/metric#parameter`
Definition	Associates the aggregator with one or more structured parameters.
Why it matters	Makes configuration machine-readable, disambiguating free-form literals.
Examples	Lp norm (p=2); Weighted sum (`weights=[0.3,0.7]`)

14.1.5. Class: metric:Polarity

metric:Polarity captures the ordering semantics of measures produced by a metric:Metric. It tells engines whether lower values are better (metric:Distance) or higher values are better (metric:Similarity). Polarity is attached to a metric via metric:polarity and is intentionally decoupled from both metric axioms (see metric:MetricKind) and the computation plan (see metric:function). This separation lets systems perform uniform ranking, thresholding, pruning, and planning across heterogeneous metrics without knowing the metric's internal math.

Polarity also coordinates with optional scale hints and bounds declared on the metric (see metric:scaleKind, metric:rangeMin, metric:rangeMax) so UIs and algorithms can choose consistent comparators, normalize scores, and validate thresholds. When conversions are needed—such as consuming a similarity where a distance is expected or vice-versa—engines may apply the declared monotone transform (see metric:monotoneTransform) while preserving order.

Polarity is mandatory for metrics (enforced by SHACL), ensuring that operations like kNN, range queries, and top-k selection behave predictably. Note that metric:Measure remains polarity-neutral: the interpretation of a stored measurement is taken from its associated metric via metric:usingMetric.

14.1.5.1. Class Definition

TABLE 249: Class Definition for metric:Polarity

RDF Class	metric:Polarity
Is Abstract	No
Definition	Vocabulary class whose instances tag whether a measure behaves as a distance (lower-is-better) or a similarity (higher-is-better).
Subclass Of	owl:Thing
Usage Note	Used as the range of metric:polarity on metric:Metric to declare the intended ordering of values and to guide ranking, thresholding, and conversion via metric:monotoneTransform.
Rationale	Separates numeric ordering semantics from metric axioms (see metric:MetricKind) and from the computation plan (see metric:function), enabling uniform treatment of distances and similarities.

14.1.5.2. Instances

TABLE 250: Instances for metric:Polarity

Individual	Description
metric:Distance	Polarity tag indicating distance semantics: lower values indicate greater closeness; typical domains are ratio-scaled and non-negative. Often paired with aggregators such as metric:Aggregator = metric:Sum.
metric:Similarity	Polarity tag indicating similarity semantics: higher values indicate greater likeness; often normalized to metric:UnitInterval with optional bounds supplied via metric:rangeMin / metric:rangeMax.

14.1.5.2.1. Individual: metric:Distance

TABLE 251: Instance Definition: metric:Distance

RDF Individual	metric:Distance
Type	metric:Polarity
Definition	Declares that measurements produced by a metric are interpreted as distances (lower is better).

14.1.5.2.2. Individual: metric:Similarity

TABLE 252: Instance Definition: metric:Similarity

RDF Individual	metric:Similarity
Type	metric:Polarity
Definition	Declares that measurements produced by a metric are interpreted as similarities (higher is better).

15. HSML VectorSpace SubModule

15.1. Introduction

The VectorSpace Module specializes the Hyperspace abstraction for **linear spaces**. It realizes the **VECTOR SPACE** concept of IEEE P2874™/D-3.3.1-2025-03, Clause 6.2.x as a Hyperspace whose elements admit **linear combination over a scalar field**, with an abstract **origin** and **composable arrows** corresponding to linear displacements.

> A vector space is a set whose elements can be added and scaled, satisfying linearity axioms. In HSML, a VectorSpace is a Hyperspace that also qualifies as a MetricSpace, exposing linear and distance semantics without prescribing a particular element encoding or path representation.

This module is intentionally **non-prescriptive** about representation. It defines vector-space semantics and mapping hooks while allowing deployments to bind coordinates, arrays, or geometries according to their needs. Vector spaces are used across the Spatial Web for **geometric coordinates**, **embeddings and feature spaces**, **signal/field representations**, and **local linearizations** of complex manifolds.

By design, a `vector : VectorSpace`:

- Inherits all properties of `hspace : Hyperspace` (elements, arrows, paths, operations).
- Inherits all properties of `metric : MetricSpace` (distance, polarity, axioms, metrics).
- Adds linear structure hooks (scalar field, dimension, origin policy, CRS).

16. HSML CellularSpace Module

16.1. Introduction

The CellularSpace Module defines the HSML specialization of Hyperspace for **discrete partitioned structures**. It realizes the **CELLULAR SPACE** concept of IEEE P2874™/D-3.3.1-2025-03, Clause 6.2.1, which states:

> A space partitioned into finite, discrete units (cells) such that adjacency between units is explicitly defined by shared boundaries, vertices, or faces. Cells may be uniform or hierarchical, and together they form a covering of the domain.

This definition allows HSML to treat diverse gridded or tiled representations—raster images, Discrete Global Grid Systems (DGGS), and voxel volumes—under one unifying abstraction.

CellularSpaces make it possible to reason over **adjacency, clustering, and coverage** in contexts where continuous metrics or coordinates are less important than **discrete neighborhood relationships**.

Crucially, CellularSpaces are **modular extensions** of Hyperspace: they inherit the universal notions of elements, arrows, and paths, and specialize them for tessellations. This means that a Domain can seamlessly switch between a VectorSpace view

(coordinates), a MetricSpace view (distances), or a CellularSpace view (discrete tilings) without losing identity or consistency.

16.2. Architectural Principles and Design Rationale

16.2.1. The Partitioned View of Space: cell:Cell

A CellularSpace is built upon the concept of the `cell:Cell`, a discrete unit that partitions a continuous region into finite, indivisible elements. Unlike vector coordinates (continuous) or topological sets (abstract neighborhoods), a cell represents a **bounded piece of space** with an identifier, optional geometry, and adjacency relations.

This reflects IEEE P2874™/D-3.3.1-2025-03's notion that spatial reasoning must sometimes operate at the **granularity of discrete tiles**—pixels, hexagons, voxels—rather than continuous measures. Cells form the foundation for scalable computations such as tiling the Earth with DGGS codes, pathfinding in grid-based simulations, and aggregating spatial statistics.

16.2.2. Adjacency as the Fundamental Relation: cell:CellAdjacency

In a CellularSpace, connectivity is determined not by metric distance but by **adjacency rules**. The `cell:CellAdjacency` class provides the scaffolding to model these rules explicitly:

- Von Neumann adjacency (sharing an edge, 4-neighbor).
- Moore adjacency (sharing edge or corner, 8-neighbor).
- Hexagonal adjacency (sharing sides in a hex grid).
- Voxel adjacencies (6-, 18-, or 26-neighbor in 3D).

Adjacency may be undirected ("touches") or weighted (cost, travel time). By modeling adjacency as a first-class construct, HSML enables **region formation, boundary detection, and pathfinding** independent of geometry.

16.2.3. Hierarchy and Indexing

A key design principle is **hierarchical decomposition**. CellularSpaces may be recursive: a DGGS cell contains children at finer resolutions, while raster tiles can be subdivided into pixels. Each cell SHALL have a unique index, such as a DGGS code, Morton/Hilbert code, or `(row, col)` coordinate. This provides stable identity for referencing, linking, and computation.

16.2.4. Profiles and Extensibility

The CellularSpace Module defines a **minimal contract**: elements (cells) and arrows (adjacencies). Domain-specific profiles can extend this for raster, DGGS, or voxel models. Examples:

- **Raster Profile**: Cells as `(row, col)` indices with 4- or 8-adjacency.

- **DGGS Profile**: Hierarchical hex cells identified by DGGS addresses.
- **Voxel Profile**: Integer `(x, y, z)` indices with 6-, 18-, or 26-neighbor rules.

This ensures HSML provides both **generic interoperability** and **domain-specific fidelity**.

16.2.5. Modularity and Namespaces

The CellularSpace vocabulary resides under its own namespace:

- `https://www.spatialwebfoundation.org/ns/hsml/hyperspace/cell#`

This aligns with the modular namespace strategy of HSML, ensuring clarity, extensibility, and best practices in ontology design.

16.3. Normative Classes

This clause provides the normative definitions for all class concepts within the CellularSpace Module.

The namespace prefix `cell:` refers to `https://www.spatialwebfoundation.org/ns/hsml/hyperspace/cell#`.

TABLE 253: Summary of CellularSpace Module Classes

Class	Description
cell:CellularSpace	A specialization of `hspace:Hyperspace`` where elements are discrete cells and paths are defined by adjacency relations.
cell:Cell	A convenience class representing a discrete unit of space (pixel, hexagon, voxel). Each cell SHALL have a unique identifier and MAY carry a geometry and attributes.
cell:CellAdjacency	A convenience class representing an adjacency relation between two cells, optionally weighted by cost or distance.
cell:CellChain	An explicit path class representing an ordered sequence of adjacent cells.
cell:CellCluster	A class representing a connected region formed by a collection of adjacent cells.

17. HSML Extensions and Profiles

HSML is designed for evolution and adaptation. While the Core Model provides a universal foundation, its true power is realized through extensions that tailor the language for specific industries and applications. This is accomplished by creating

extensions and application profiles that add specialized concepts while preserving core interoperability and holonic integrity.

17.1. Subclass from the Core Model

Extensions **must** build upon the established HSML core classes. This is the primary mechanism for ensuring that new concepts are compliant, interoperable, and inherit foundational characteristics.

- How to Model: New classes **shall** be defined using `rdfs:subClassOf` to inherit from a base HSML class like `core:Thing`, `agt:Agent`, or `act:Activity`. For example, a `smartbuilding:Elevator` would be a subclass of `core:Thing`.
- Reasoning: This ensures that every new entity is a valid holon that can be uniquely identified by a `core:swid`, exist within a `core:Domain`, and participate in the governance framework.

17.2. Maximize Reuse of Existing Ontologies

To promote interoperability and avoid reinventing concepts, extensions **should** integrate with established, domain-specific vocabularies wherever possible.

- How to Model: Before creating new properties, developers should import and reuse terms from well-known ontologies like SAREF, GeoSPARQL, or the W3C Organization Ontology. Properties like `owl:equivalentClass` can be used to map the extension's concepts to these external standards.
- Reasoning: This aligns with P2874's goal of creating a "holistic and coherent technical framework" by leveraging existing work rather than creating isolated data silos.

17.3. Enforce Governance and Data Quality with SHACL

Extensions are not just data schemas; they are governable components of the Spatial Web. Therefore, extensions **must** include formal constraints that define valid data structures and enforce rules.

- How to Model: Every extension profile **must** be accompanied by a set of SHACL shapes (`sh:NodeShape`, `sh:PropertyShape`). These shapes define rules such as mandatory properties (`sh:minCount`), data types (`sh:datatype`), and value ranges.
- Reasoning: This principle directly implements the P2874 requirements for "Governance by Design" and "Compliance". It allows domains to validate incoming data and ensure that all participants in the ecosystem adhere to the same structural and business rules.

17.4. Package Extensions as Profiles

To be manageable and reusable, extensions should be packaged as self-contained Application Profiles.

- How to Model: A profile is a collection of files that includes:
  - The OWL ontology defining the new classes and properties.
  - The SHACL shapes defining the constraints.
  - Human-readable documentation.
- Reasoning: This approach allows different industries (e.g., mobility, logistics, smart building, healthcare) to develop and maintain their own extensions while ensuring their foundation remains interoperable with the core HSML model and the broader Spatial Web.

Annex A
(normative)

Compliance

Annex B
(normative)

System Requirements

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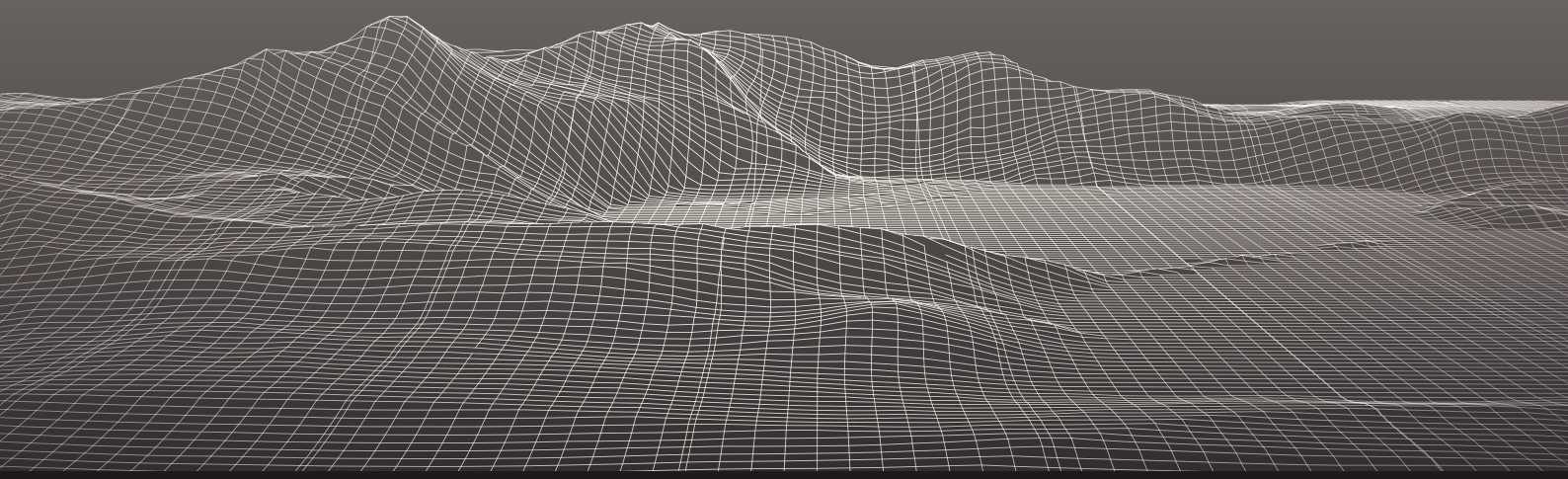

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