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Article

A Triad Architecture for Knowledge Organization Ecosystems: Designing Explainable and Sustainable Semantic Infrastructures

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Abstract

Knowledge Organization Ecosystems (KOEs) represent the next evolutionary stage in the management and curation of digital knowledge, demanding conceptual models that transcend static classification and embrace dynamic, multi-actor semantic processes. This paper introduces and elaborates a comprehensive triad-based conceptual architecture, in which fundamental knowledge units are modeled as structured entities composed of three interdependent and co-evolving layers: referential grounding (Base), representational encoding (Representation), and procedural-relational linkage (Linkage). This framework is philosophically grounded in the triplet model of scientific concepts, which overcomes the limitations of reductive singlet and duplet models by capturing the asynchronous evolution of a concept's ontic commitments, symbolic forms, and the practices that bind them. Moving beyond traditional Knowledge Organization Systems (KOSs), which prioritize stable, hierarchical structures, the proposed architecture conceptualizes knowledge objects as dynamic, operationally embedded semantic entities. These entities evolve within complex digital ecosystems shaped by algorithmic mediation, collaborative curation, and institutional governance. The triad architecture directly supports semantic interoperability across distributed systems, version-managed knowledge resources that track conceptual drift, and explainable Human–Artificial Intelligence (human–AI) knowledge workflows that make semantic assumptions transparent. By aligning conceptual modeling with ontology engineering practices, knowledge graph infrastructures, and the principles of responsible AI, this paper provides a scalable, epistemically robust foundation for building transparent, accountable, and sustainable knowledge organization infrastructures. The framework is demonstrated through a detailed application scenario tracing the evolution of the 'Open Science' concept within the European Open Science Cloud (EOSC), illustrating the model's utility for analyzing and designing real-world semantic infrastructures. It contributes a significant theoretical advance to the study of KOEs and offers a concrete, transferable design framework for next-generation semantic infrastructures in data-intensive, AI-mediated research and cultural heritage environments.

Keywords: knowledge organization ecosystems; triplet model; triad model; semantic infrastructure; ontology engineering

1. Introduction: Conceptual Foundations for Ecosystemic Knowledge Organization

1.1 Contribution Statement

This article makes four distinct contributions to Knowledge Organization research and to the emerging field of Knowledge Organization Ecosystems.

First, it introduces a formally structured conceptual architecture grounded in the triplet model of scientific concepts, as developed by Kuznetsov (1997; Kuznetsov and Kuznetsova, 1998). This model posits that any mature scientific concept is a structured triad of Base (B), Representation (R), and Linkage (L).

Second, and crucially, it advances this model through a novel operational decomposition of the Linkage layer into three sub-components L_1 (Empirical-Technical), L_2 (Explanatory-Theoretical), and L_3 (Institutional-Social), a development contributed by the first author (Belkheiri and Kuznetsov, 2026a, 2026b). This decomposition transforms the philosophical model into an actionable information architecture.

Third, it maps this enriched triad architecture directly onto contemporary semantic infrastructures, including knowledge graphs (Hogan et al., 2021), ontology engineering workflows (Kendall and McGuinness, 2019), version management systems, and explainable Artificial Intelligence (AI) mechanisms, demonstrating how each triad layer can be operationalised.

Finally, it bridges philosophical concept theory (Feest and Steinle, 2012; Margolis and Laurence, 2015) and infrastructural design, offering a transferable framework that integrates epistemic rigour with ecosystem-scale implementation requirements, and demonstrates its analytical power through a detailed applied scenario of conceptual evolution within the European Open Science Cloud (EOSC).

Furthermore, the paper demonstrates the architecture's analytical power through a detailed applied scenario of conceptual evolution within the European Open Science Cloud (EOSC).

1.2 The Evolving Landscape of Knowledge Organization

Knowledge Organization, as a discipline, has historically been anchored in the development and maintenance of structured systems: classification schemes (e.g., Dewey Decimal, Universal Decimal Classification), controlled vocabularies (e.g., Library of Congress Subject Headings), and thesauri (e.g., Agricultural Vocabulary (AGROVOC)). These systems emerged from and served institutional contexts libraries, archives, and scientific communities characterized by relatively stable document typologies, bounded disciplinary domains, and centralized expert curation (Hjørland, 2008; Smiraglia, 2014). Their primary function was to support consistent retrieval and bibliographic control, presupposing a linear workflow from the human indexer to the static catalogue to the human user.

The digital turn has fundamentally destabilized these assumptions. Knowledge production is now massively distributed across global networks, digital platforms, and collaborative environments. It is increasingly algorithmically mediated, generated, filtered, and recommended by AI systems, and embedded within vast, interoperable sociotechnical infrastructures such as data repositories, digital libraries, and collaborative knowledge graphs (Borgman, 2015). Knowledge is no longer merely organized by separate/ independent systems but is actively co-constituted within dynamic ecosystems involving human experts, automated agents, hybrid workflows, and diverse user communities.

In this environment, traditional Knowledge Organization Systems (KOSs) reveal critical limitations. Their static, monolithic structures struggle with concept drift (the natural evolution of meaning in living domains), interdisciplinary integration (requiring the fusion of incommensurate classifications), and the rapid emergence of new entities and relationships (e.g., in biomedicine or social media). They often lack granularity and flexibility to support continuous semantic enrichment, provenance tracking, and context-aware retrieval. Most fundamentally, they model concepts as fixed points in a semantic space rather than as dynamic processes shaped by use, instrumentation, and theory.

1.3 The Promise and Peril of Knowledge Organization Ecosystems

In response, the metaphor of the Knowledge Organization Ecosystem (KOE) has gained traction (Bagchi, 2021) in recent years, reflecting a broader shift towards understanding KO as an emergent property of networked interactions rather than a top-down application of fixed systems. This perspective reframes KO not as the application of a system but as the ongoing, emergent coordination within a network of actors (human and machine), resources (data, schemas, software), institutions, and practices. KOE thinking emphasizes modularity (over monolithic design), interoperability (over isolated silos), adaptability (over permanence), and polycentric governance (over top-down control). It aligns with broader shifts towards open science, linked data ecosystems, and platform-based scholarship.

However, a metaphor is not a methodology. While evocative, the ecosystem concept alone lacks the conceptual precision and formal structure needed to design, implement, and critically evaluate these complex infrastructures. Without a clear model of the fundamental "atomic unit" of organization the concept or knowledge object and how it behaves within an ecosystem, KOE research risks remaining descriptive. There is an urgent need for a conceptual architecture that can bridge high-level ecosystem principles with low-level implementation details, providing a blueprint for semantic infrastructures that are both dynamic and robust, flexible and accountable.

1.4 The Triplet Model: A Philosophical Foundation for Dynamic Concepts

The required architectural foundation can be found not only in information science but also in a synthesis with the philosophy of science. As elaborated in the Theoretical Prolegomena that follows immediately below, scientific inquiry operates on the presupposition of a mind-independent reality, yet our access to and understanding of that reality is always mediated by our senses, our instruments, our theories, and our linguistic and social practices. Knowledge, especially scientific knowledge, is not a static mirror of nature but is an evolving and improving construct (Feest and Steinle, 2012).

Prevailing models of conceptual structure within information systems often rely on philosophically reductive formulations of concepts, categorized as singlets or duplets. Singlet models (e.g., $C(X) = \langle N(X) \rangle$) reductively equate a concept with its name or an undifferentiated idea, assuming a stable, one-to-one correspondence between word and world. Duplet models (e.g., $C(X) = \langle Z(X), Y(X) \rangle$), such as the classic pairing of extension (set of referents) and intension (set of defining properties)[1] ([1]The world-renowned Russian mathematician Kolmogorov clearly and undoubtedly stated that "traditional logic deals with concepts. Concepts are divided into singular and general. A singular concept is simply the name of a specific object. A general concept is defined by a set of properties that characterize the objects it encompasses. The class of objects possessing this characteristic set of properties constitutes the scope of the concept." (Kolmogorov and Dragalin, 1962, p. 15).) offer more structure but still portray concepts as relatively static, pre-formed pairings. Both model types treat concepts as deus ex machina, ready-made units rather than as complex constructs generated and continuously modified through empirical, theoretical, and social practices. They are thus "ill-equipped to analyze the processes of conceptual change" (see Fig. 1).

The triad model overcomes these deficiencies by positing that any mature scientific concept (C) is a structured triad of functionally distinct yet interconnected components that evolve asynchronously:

$C(t) = \langle B(t), R(t), L(t) \rangle$

1. The Base (B): A concept can be about anything. In this article, we take the referential domain (corresponding to the 'Domain of Possibility' as visually represented in Fig. 1) of the concept in question to be the set of entities, phenomena, or processes to which the concept applies. This embodies the concept's ontic commitments (what it is fundamentally about).

2. The Representation (R): The system of specific/particular symbolic and linguistic means used to denote, describe, and reason about the base. This includes nomenclature, terminology, mathematical formalisms, diagrams, and visual models, i.e., the artificial and natural (Overmann, 2023) sign tools for the representation and processing of concepts.

3. The Linkage (L): The complex of mechanisms that connect representations to the base. This is tripartite:

○ **L_1: Empirical-Technical Linkage:** The physical procedures, instruments, measurement protocols, and data pipelines that interact with the material base.

○ **L_2: Explanatory-Theoretical Linkage:** The intangible/ideal frameworks, theories, laws, and inferential rules used to interpret data, explain phenomena, and predict outcomes.

○ **L_3: Institutional-Social Linkage:** The communal practices, educational traditions, professional norms, validation processes, and governance structures that stabilize and transmit conceptual meaning within a community.

The triad model's pivotal insight is asynchronous evolution. During scientific progress/advancements one component may change rapidly (e.g., L_1 through a new instrument like the telescope or mass spectrometer) while others exhibit inertia (e.g., the core ontic base, B, or the dominant theoretical framework, part of L_2). This differential change allows for continuity within discontinuity: established practices and representations can persist, providing stability even as foundations are reshaped. Furthermore, concepts are objectified and intersubjectively accessible primarily through scientific texts (and, by extension, datasets, models, and code), making their evolution amenable to analysis.

This paper argues that the triad model provides the exact conceptual architecture needed to ground the vision of Knowledge Organization Ecosystems. By recontextualizing knowledge units as dynamic triads, we can design semantic infrastructures that natively support explanation, evolution, and ecosystemic coordination.

While we acknowledge the rich and ongoing debates surrounding the nature of concepts across philosophy, psychology, and cognitive science (a topic of renewed interest in fields such as concept engineering) (McCaffrey and Machery, 2012), our aim in this paper is not to resolve these debates. Instead, we focus on operationalizing one specific, philosophically grounded model, i.e., the triplet model as a practical architecture for Knowledge Organization of Philosophy.

2. From Static Systems to Dynamic Ecosystems: The Imperative for a New Architecture

2.1 The Limitations of Traditional KOS Architectures in a Digital World

Traditional KOSs were engineered for a world of documents and controlled access. Their architectures are optimized for consistency and stability, which are virtues in closed-world scenarios but become liabilities in open, dynamic digital environments.

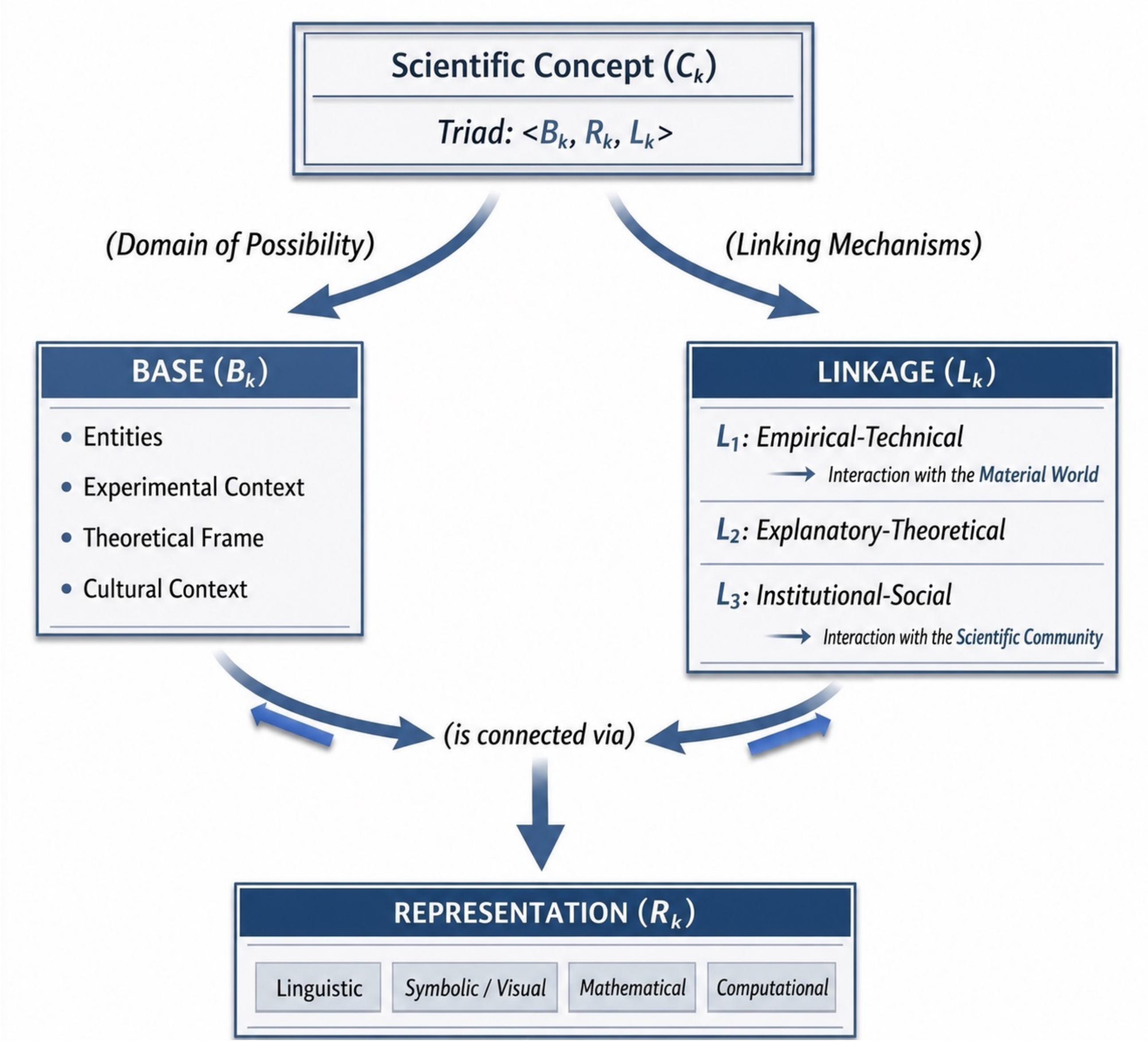

Fig. 1. The triad diagram of the scientific concept: Base, Representation, and Linkage (L). (Arrows of varying thickness symbolize asynchronous change: R may change rapidly while L_2 remains stable, and *vice versa*).

• **Conceptual rigidity vs. conceptual drift:** Hierarchical classifications and authority files fix concepts at a point in time. They struggle to capture how the meanings of "machine learning", "climate justice", or "COVID-19 variant" evolve through scientific discovery, public discourse, and algorithmic recommendations. This leads to semantic misalignment between the organization system and the living knowledge domain.

• **Monolithic silos vs. interdisciplinary integration:** Disciplinary KOSs (e.g., Medical Subject Headings (MeSH) for medicine, Physics and Astronomy Classification Scheme (PACS) for physics) are not designed to talk to each other. Integrating data across genomics, clinical medicine, and social determinants of health requires mapping between these systems, a process that is often ad-hoc, lossy, and reveals the underlying ontic incompatibilities of the original, static models.

• **Human-centric workflow vs. hybrid human-AI curation:** The classical KO workflow is linear and human-centric: a cataloger/indexer applies a schema to a document, creating metadata. In modern ecosystems, metadata is often generated automatically by AI (e.g., image tagging, entity extraction), refined by crowdsourcing, validated by experts, and then reused and transformed by other algorithms. Static KOSs provide no native model for this iterative, multi-agent, procedural lifecycle.

• **Opaque semantics vs. demand for explainability:** When a search engine or recommendation system uses a taxonomy to filter results, the semantic rationale is typically buried in code. Why was this document retrieved? On what conceptual grounds were these two entities linked? Traditional KOSs, as implemented, rarely expose the linkage mechanisms (the why and how) behind their organizational decisions, creating "black box" effects that undermine trust and accountability, especially in high-stakes domains like healthcare or law.

2.2 The Emergence of Ecosystem-Oriented Models: Beyond the Metaphor

The ecosystem perspective responds to these challenges by shifting the unit of analysis from the system to the network of interactions. A KOE encompasses:

- **Actors:** Domain experts, librarians, algorithm designers, end-users, citizen scientists.
- **Artefacts:** Datasets, publications, metadata records, ontologies, software tools, Application Programming Interfaces (APIs).
- **Processes:** Curation, annotation, alignment, reasoning, validation, versioning, governance.
- **Infrastructures:** Computational platforms, storage systems, network protocols.

In this view, knowledge organization is the emergent outcome of coordinated activities within the network. Key principles include:

- **Modularity & loose coupling:** Components (e.g., a specific ontology, a curation tool) can be developed and updated independently, interacting through standardized interfaces.
- **Evolution & feedback:** The ecosystem learns and adapts. New data can prompt refinement of ontologies; user behavior can inform the tuning of recommended algorithms.
- **Polycentric governance:** Control is distributed. Standards may be set by consortia, ontologies maintained by community groups, and specific collections curated by institutions.

While this perspective is powerful, it lacks a common conceptual vocabulary to describe the "stuff" that flows and transforms within the ecosystem, the knowledge units themselves. We need an architecture that defines these units in a way that inherently reflects their ecosystemic nature: grounded in reality, represented for computation, and linked through actionable procedures. This is precisely what the triad model provides.

The present work builds on foundational contributions within the field of information organization. Where prior frameworks have provided high-level characterizations of the principles underlying bibliographic systems (such as consistency, predictability, and sufficiency), the triad architecture offers a complementary micro-level model of the fundamental units namely, the concepts and knowledge systems whose interactions constitute knowledge ecosystems. In this sense, the two levels of analysis are not competing but operate at different granularities: macro-level properties of organized systems are complemented by a structural blueprint for their atomic components. Together, they offer a more complete picture of Knowledge Organization Ecosystems (KOEs).

2.3 A Comparative Analysis of Conceptual Models in Knowledge Organization

To fully appreciate the necessity of the triad model for KOEs, a systematic comparison with prevailing conceptual models is essential (see Table 1). These models are not just abstract philosophical positions; they are often embedded implicitly in the design of our classification systems, metadata schemas, and database structures. Their limitations become acutely visible in dynamic, ecosystemic environments.

This comparative analysis reveals a clear trajectory. It should be reiterated that the "Singlet model" is not presented as a philosophical theory attributable to any scholar or school of indexing. It is a diagnostic abstraction that captures the architectural constraints of early computational systems, such as keyword-based inverted indexes, where the absence of an explicitly modelled semantic layer forces the system to treat lexical tokens as the primary operational units. Such architectural patterns are fundamentally inadequate for modern KO, reducing rich conceptual meaning to a lexical token. Duplet models, while foundational for logic and early information retrieval, offer a binary snapshot that cannot capture the processual, multi-faceted nature of concepts in action. Their static nature makes them brittle in the face of the continuous, multi-sourced evolution characteristic of KOEs.

The triad model emerges as the necessary successor. By incorporating the Linkage (L) as a first-class component itself, decomposed into technical, theoretical, and social sub-dimensions, it provides a dynamic and pragmatic framework. It doesn't discard the insights of earlier models but subsumes them: the Base (B) encompasses the extension, and the Representation (R) formalizes aspects of intension. Crucially, it adds the missing dimension of practice, which is the very engine of semantic evolution and coordination in an ecosystem. This makes it uniquely suited to address the core challenges of interoperability, explainability, and sustainable evolution in large-scale, hybrid human-AI knowledge environments.

2.4 The Triad Model in Relation to Dynamic Theories of Concepts

To fully appreciate the contribution of the triad architecture, it is essential to situate it within the broader intellectual landscape of dynamic, practice-oriented theories of concepts. Far from being an isolated or idiosyncratic proposal, the model synthesizes and operationalizes insights from several major philosophical and KO traditions that have long recognized the evolving, socially embedded nature of conceptual structures.

Table 1. Comparative analysis of conceptual models in knowledge organization.

Model dimension	Singlet model ($C=\langle N \rangle$)	Duplet model ($C=\langle$extension, intension$\rangle$)	Triad model ($C=\langle B, R, L \rangle$)
Core premise[2] ([2]. See Table 1 for details).	An architectural abstraction for certain computational regimes where a concept's operational identity is reduced to its lexical form due to the absence of an explicitly modeled conceptual layer. This is not a description of human indexing practices (which implicitly distinguish terms from concepts) but rather a diagnostic category for systems such as keyword-based retrieval architectures (e.g., inverted indexes), where tokens serve as the primary units of storage and retrieval, and where synonymy, polysemy, and conceptual differentiation are not structurally encoded within the system itself.[3] ([3]In a classical inverted index, the system cannot distinguish between the term "student" and the concept "learner" unless an external thesaurus is integrated. The architecture itself does not formally encode the conceptual relation, making it operationally "singlet". This is distinct from professional indexing, where controlled vocabularies explicitly distinguish terms from concepts, and where synonym rings or thesauri are employed as separate, managed resources.)	A concept is a pairing of its referents and its defining properties/sense. (Kolmogorov and Dragalin, 1962)	A concept is a structured entity constituted by its referential base, its representational forms, and the procedural linkages that connect them.
Ontic commitment	The severely simplified nominalistic view of a concept assumes a stable mapping between labels and referents.	The somewhat more realistic view distinguishes reference from sense but treats them as static.	The realist & pragmatist view acknowledges a mind-independent base but insists access is always mediated by representational and linkage practices.
Handling of semantic change	**Poor**. Change is handled as a label mutation or replacement. This reflects the limitations of systems built on this model, which lack mechanisms for tracking conceptual evolution.	**Limited**. Change is modeled as transformations to the set of referents (extension) or the definition (intension). (Hampton, 2010). It treats change as a discrete replacement of one static pair with another.	**Sophisticated**. Employs the principle of asynchronous evolution. A change in one component (e.g., new instrumentation in L_1) can occur without an immediate change in others (B, R, L_2, L_3), allowing for continuity and gradual restructuring.
Modeling of practice & process	**Absent**. The "how" of concept application is invisible.	**Implied but static**. Intension implies rules for application, but they are not modeled as dynamic or situated.	**Explicit & Central**. The Linkage component (L) explicitly models the empirical (L_1), theoretical (L_2), and social-institutional (L_3) practices that enact and stabilize the concept.
Suitability for interoperability	**Low**. Relies on term matching. Fails with synonyms, polysemy, and cross-disciplinary term variance.	**Moderate**. Supports alignment via definition matching. Struggles when underlying theories (L_2) or measurement practices (L_1) differ.	**High**. Provides multiple points for alignment: base entities (B), representations (R), or shared linkage practices (L). Enables understanding of why mappings succeed or fail (e.g., due to differing L_1 protocols).
Support for explainability	**None**. The decision is just a label assignment.	**Basic**. The decision can be justified by citing the definition (intension).	**Rich**. Any semantic decision (classification, linking) can be explained by referencing the specific base entity (B), the representational rule (R), and the justifying linkage (e.g., "based on algorithm X (L_1) validated by community Y (L_3)").
Fit for human-AI collaboration	**Problematic**. AI output is a label; human oversight is reduced to label validation without context.	**Adequate**. AI can match patterns to definitions. Humans can audit the definition.	**Optimal**. Provides a structured schema for AI output: the suggested Base, Representation, and the confidence level/model used (L_1). Humans can audit at the level of representation (R) or at the levels of linkage (L_1, L_2, L_3).
Embeddedness in the ecosystem	**Detached**. Concepts exist as isolated tokens.	**Abstracted**. Concepts exist as abstract pairings divorced from the infrastructure that uses them.	**Inherently embedded**. The triad is defined by its connections to data (B), schemas (R), and workflows/governance (L). It is a native unit of the ecosystem.

AI, Artificial Intelligence.

2.4.1 Independence From Peircean Semiotics

Any contemporary triadic model of concepts invites comparison with Charles Sanders Peirce's foundational theory of signs. Peirce famously distinguished three components in any act of signification: the representamen (the form the sign takes), the object (what the sign stands for), and the interpretant (the sense made of the sign in the mind of an interpreter) (Peirce, 1932, Vol. 2, pp. 274–308). For Peirce, meaning is not a static relation but an ongoing, triadic process.

It is essential, however, to recognise that the present model and Peirce's semiotics belong to different intellectual traditions and address different questions. Peirce developed a universal theory of signification, applicable to any sign in any context. The triad model, by contrast, is a specialised theory of scientific concepts within the philosophy of science. It does not ask "How does a sign signify in general?" but "What are the constitutive components of a mature scientific concept, and how do they evolve asynchronously?"

The apparent triadic form is a superficial numerical coincidence, not a genealogical derivation. Three fundamental differences underscore this independence:

(i) Differing purpose and scope. Peirce's framework is descriptive and universal, aiming to capture the logical structure of any semiotic event. Our framework is prescriptive and domain-specific, aiming to provide a design architecture for knowledge organization systems.

(ii) Differing internal architecture of the third component. Peirce's interpretant is a mental or logical effect generated in the mind of an interpreter. The Linkage (L) in our model, particularly through its operational decomposition into L_1 (empirical-technical procedures), L_2 (explanatory-theoretical frameworks), and L_3 (institutional-social governance), does not model mental effects but the material, theoretical, and institutional mechanisms that connect representations to their referential base. This tripartite decomposition of L has no equivalent in Peirce's semiotics and is a novel contribution of the present article (Belkheiri and Kuznetsov, 2026a, 2026b).

(iii) Differing intellectual lineage. Peirce's semiotics belongs to the pragmatist tradition in American philosophy. The triplet model of concepts originates in the methodological analysis of scientific knowledge within the philosophy of science (Kuznetsov, 1997), engaging with problems of concept formation, theory change, and scientific practice.

We thus do not claim, as earlier formulations may have inadvertently suggested, that our model is a "domain-specific operationalisation" of Peirce. It is a parallel and independent development. We acknowledge Peirce's historical priority in proposing triadic structures in semiotics, while firmly situating our contribution within the philosophy of science and its application to knowledge organization infrastructures.

2.4.2 Wittgenstein's Later Philosophy: Meaning as Use

Ludwig Wittgenstein's later work, particularly his concept of "meaning as use" and his notion of "family resemblances", fundamentally challenged static, definitional theories of concepts (Wittgenstein, 1953). For Wittgenstein, the meaning of a concept is not given by a fixed set of necessary and sufficient conditions (intension) but by its actual employment within a "form of life", i.e., the complex of linguistic, social, and practical activities in which it is embedded.

The triad model provides formal architecture for operationalizing Wittgenstein's insights. The **Linkage (L)** component, with its tripartite structure, explicitly models the "use" of a concept. L_1 captures the empirical and technical practices (measurements, instruments, algorithms) through which the concept engages with the world. L_2 models the theoretical and inferential rules that guide its application within a scientific or scholarly community. L_3 represents the social and institutional practices (validation, governance, training) that constitute the "form of life" within which the concept has meaning. By making these dimensions explicit, the triad model transforms Wittgenstein's philosophical insight into a tool for analyzing and designing knowledge infrastructures. The theory of conceptual spaces, as developed by Gärdenfors and extended by Belastegui (2025), offers a complementary geometric framework for representing the similarity structures that underlie family resemblances and prototype effects, which can be mapped onto the Representation (R) layer of the triad.

2.4.3 Kuhn's Paradigms and Conceptual Change

Thomas Kuhn's work on scientific revolutions and paradigm shifts remains the most influential account of large-scale conceptual change in science (Kuhn, 1962/2012). Kuhn argued that science does not progress through the simple accumulation of facts but through periodic revolutions in which the entire conceptual framework of a discipline, its paradigms, is transformed. However, Kuhn's account has been criticized for its vagueness regarding the mechanisms of conceptual change.

The triad model's principle of asynchronous evolution provides precisely such a mechanism. A Kuhnian paradigm can be understood as a stabilised configuration of the triad components, a particular alignment of ontic commitments (B), representational systems (R), and theoretical/practical commitments (L) that is shared by a scientific community. Scientific revolutions occur when asynchronous changes in one component (e.g., new empirical techniques in L_1, or new theoretical insights in L_2) gradually destabilize the existing configuration, leading to a fundamental reconfiguration of the entire triad. The model thus offers a granular, operationalizable framework for analyzing the kind of conceptual discontinuities that Kuhn described, without losing sight of the continuities that persist across revolutionary change.

2.4.4 The Socio-Epistemological Tradition in KO: Hjørland, and Mai

The triad model also finds deep resonance within the theoretical tradition of Knowledge Organization itself. It is widely recognized within the field that classification systems are not neutral mirrors of nature but are shaped by the intellectual and institutional contexts of their creators, and that libraries and information systems play a key role in the broader ecology of knowledge production and dissemination. The triad model's **L_3 (institutional-social linkage)** provides a concrete mechanism for modeling this insight, capturing the community norms, validation practices, and governance structures that stabilize meaning within a knowledge domain.

Birger Hjørland's domain-analytic approach to KO holds that concepts and their organizations are best understood within the specific theoretical and pragmatic contexts of the knowledge domains they serve (Hjørland, 2008). A domain's theories, methodologies, and goals shape its conceptual structures. The triad model aligns powerfully with this view. The **L_2 (explanatory-theoretical linkage)** directly corresponds to the domain-specific theories and inferential frameworks that Hjørland identifies as crucial for concept formation. Furthermore, the asynchronous evolution of the triad components explains how different domains, or even sub-domains, can develop divergent conceptualizations of ostensibly similar phenomena, based on differing theoretical commitments (L_2) or measurement practices (L_1).

Finally, **Jens-Eric Mai's** work on the interplay between classification and interpretation highlights the need to move beyond static, predefined categories towards more flexible, context-sensitive models that accommodate multiple perspectives (Mai, 2011). Mai's call for transparency in the design and application of classification schemes is directly addressed by the triad model's inherent explainability: by making the Linkage layer explicit, the framework exposes the interpretive decisions (L_2) and the social negotiations (L_3) that underlie any act of classification.

A recent articulation of social epistemology applied directly to knowledge organization systems, particularly concerning the treatment of data as documents, is provided by Schöpfel et al. (2021). Their analysis demonstrates how L_3 (institutional-social linkage) must account for the evolving evidentiary status of data in digital ecosystems.

In this light, the triad model is not an isolated philosophical construct but a synthesis and formalization of a long-standing, interdisciplinary trajectory that recognizes concepts as dynamic, practice-bound, and socially constituted entities. It provides a shared vocabulary and a structural blueprint that bridges the philosophical insights of Peirce, Wittgenstein, and Kuhn with the domain-specific and socio-epistemological concerns of the KO community.

2.4.5 Positioning the Triad Model Within Concept Theories in Knowledge Organization

Dahlberg's referent-oriented, analytical concept theory (1978) defines a concept as a synthesis of verifiable statements about a referent, represented by a term. This rigorous framework was designed to bring terminological clarity to classification systems. The triad model does not reject this view; rather, the Representation (R) layer can encapsulate the precise propositional content that Dahlberg requires, while the Base (B) corresponds to her notion of the referent. What the triad model adds are the explicitly modelled procedural and institutional dimensions (L_1, L_2, L_3) that explain how such statements are generated, validated, and revised over time, dimensions that lie outside the scope of Dahlberg's primarily definitional approach.

Robert Arp's Building Ontologies with Basic Formal Ontology (2015) argues that ontologies should represent universals and particulars in reality, not "concepts" understood as mental entities. The triad model is fully compatible with this realist commitment: the Base (B) is explicitly referential, denoting the mind-independent entities or domain-specific phenomena to which the concept is ontically committed. The model simply insists that, in digital infrastructures, this base is always accessed and mediated through representational (R) and procedural (L) layers, which must be modelled explicitly if the system is to be transparent and auditable.

Taxonomic pluralism (see Feest and Steinle, 2012 and the entry on scientific pluralism in the Stanford Encyclopedia of Philosophy) holds that different scientific domains can legitimately employ different, sometimes incommensurable, taxonomies. A contemporary defense of pluralism in scientific classification, with direct implications for ontology design, is provided by Brigandt (2022). The triad model inherently embodies this pluralism. Because it allows multiple representations (multiple Rs) and multiple theoretical frameworks (multiple L_2s) to coexist for the same referential base (B), and because it treats governance (L_3) as an open, negotiable process, the architecture is structurally pluralistic. It does not impose a single authoritative taxonomy but provides a framework for managing and explaining taxonomic diversity.

In summary, the triad model does not compete with Dahlberg, Robert, or pluralist accounts as a theory of what concepts are. It operates at a different logical level: it is an infrastructural architecture that specifies how a knowledge unit must be modeled to support explainable evolution, multiple perspectives, and distributed governance in digital ecosystems. It thus complements, rather than contradicts, these established positions.

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3. The Triad Model as a Dynamic Conceptual Architecture for KOEs

3.1 Translating the Philosophical Model Into an Information Architecture

Having established the philosophical foundations of the triad model and its resonance with existing KO theories, we now face a critical question: how can this abstract philosophical framework be translated into a concrete blueprint for designing semantic infrastructures? If the triad model is to move beyond description and become a generative tool for KOEs, its components must map directly onto the core concerns and building blocks of modern Knowledge Organization. This section undertakes that translation, laying the groundwork for the implementation strategies that follow in Section 4.

$C(t) = \langle B(t), R(t), L(t) \rangle$

• The Base (B) – referential grounding:

○ In philosophy/science: The set of real-world entities/phenomena the concept is about (e.g., elementary particles, chemical elements, biological species).

○ In KOEs: The domain objects and data assets that constitute the ecosystem's referential fabric. This includes:

▪ Digital objects: Research datasets, archived websites, 3D models of artifacts, sensor feeds.

▪ Physical objects: Museum specimens, archival documents, geological samples that have digital surrogates.

▪ Abstract entities: Legal cases, musical compositions, clinical trials, virtual entities in quantum field theories.

○ Design implication: A KOE must maintain persistent, unique identifiers (Persistent Identifiers (PIDs) like Digital Object Identifiers (DOIs), Archival Resource Keys (ARKs)) for entities in the Base, and mechanisms to link these identifiers to their multiple, evolving representations.

• The representation (R) – symbolic encoding:

○ In philosophy/science: The nomenclature, formulas, diagrams, and theories used to talk about the Base (e.g., physical and chemical symbols, structural formulas, the periodic table).

○ In KOEs: The formal schemas and languages used to describe, categorize, and reason about the Base. This includes:

▪ Metadata schemas (e.g., Dublin Core, DataCite, domain-specific standards like Darwin Core for biology).

▪ Ontologies and vocabularies (e.g., Systematized Nomenclature of Medicine Clinical Terms (SNOMED CT), CIDOC Conceptual Reference Model (CRM) (with CIDOC originating from Comité International pour la Documentation, though the model is formally known by its acronym), Schema.org). For a systematic introduction to the principles and practices of ontology engineering in the context of knowledge ecosystems, see Keet (2018).

▪ Classification notations and subject headings.

▪ File formats and data models (e.g., JavaScript Object Notation for Linked Data (JSON-LD), RDF).

○ Design implication: A KOE must support multiple, coexisting representations for the same base entity (reflecting different perspectives or uses) and manage the mappings and translations between them.

• The linkage (L) – procedural-relational mechanisms:

This is the most innovative and critical component for KOEs, as it models the processes of meaning-making. The decomposition of L into these three operational sub-layers is a key architectural contribution of the present article, advanced by Belkheiri and Kuznetsov (2026a, 2026b).

○ L_1: Empirical-technical linkage – the data pipeline:

▪ In science: Measurement protocols, laboratory techniques, instrument calibration.

▪ In KOEs: The algorithms, services, and workflows that interact with the Base to generate or process data. This includes:

▪ Ingestion and extraction tools (web scrapers, Optical Character Recognition (OCR), entity recognition).

▪ Measurement and analysis software (image classifiers, genomic sequence aligners).

▪ Indexing and search engines.

▪ Data transformation and cleaning pipelines.

○ L_2: Explanatory-theoretical linkage – the interpretive framework:

▪ In science: Theories and their nets, models, and laws that explain and predict phenomena.

▪ In KOEs: The rules, constraints, and inferential logic that give meaning to representations and guide their use. This includes:

▪ Ontology axioms and inference rules (e.g., "if X is a 'Publication', then it must have a 'creator' ").

▪ Conceptual models and frameworks that guide schema design.

▪ Domain theories embedded in software (e.g., a disease progression model used to annotate patient data).

○ L_3: Institutional-social linkage – the governance layer:

▪ In Science: Peer review, academic societies, fundamental research and applied institutions, universities, so-called scientific schools, textbook traditions, and research ethics.

▪ In KOEs: The human and institutional processes that authorize, validate, and stabilize meaning. This includes:

▪ Community curation and peer review of metadata/ontologies.

▪ Editorial boards for authority files.

▪ Governance bodies for data standards (e.g., World Wide Web Consortium (W3C), Research Data Alliance (RDA)).

▪ Professional norms and best practices (e.g., Findable, Accessible, Interoperable, and Reusable (FAIR) Guiding Principles) (Wilkinson et al., 2016).

▪ Licensing, access controls, and ethical use policies.

• The analytic-synthetic distinction and faceted classification.

Within the Knowledge Organization tradition, the triad architecture also resonates with the analytic synthetic distinction and the faceted classification approach pioneered by S. R. Ranganathan. Faceted systems recognize that concepts are not monolithic entities but structured combinations of properties, perspectives, and relations (Ranganathan, 1937). The process of facet analysis involves identifying fundamental categories and synthesizing them to represent complex subjects.

The triad model can be interpreted as offering a meta-level framework for understanding the relationship between analytic and synthetic dimensions of concept formation. The L_2 (explanatory-theoretical linkage) can be understood as encompassing the analytic or nomological aspects of a concept, the rules, axioms, and theoretical frameworks that define its logical structure and permissible inferences. This approximates the domain of definitional relations and conceptual coherence. The L_1 (empirical-technical linkage) can be seen as handling the synthetic or empirical aspects: the data, measurements, and observations that instantiate the concept in the world and ground its application. This corresponds to the domain of empirical verification and material engagement.

It should be noted that this interpretation does not commit the triad model to a strong metaphysical distinction between analytic and synthetic truths. Rather, it offers a heuristic framework for understanding how different types of conceptual work (theoretical definition vs. empirical application) interact within knowledge infrastructures, without presupposing a rigid epistemological boundary between them.

The model's principle of asynchronous evolution helps explain how these two dimensions can change at different rates. A new empirical discovery (change in L_1) may precede and eventually necessitate a revision of the theoretical framework (change in L_2), or *vice versa*. This dynamic interplay between the analytic and synthetic dimensions of concepts has long been recognized in KO, but the triad architecture provides a formal mechanism for modeling and managing it within semantic infrastructures.

3.2 Asynchronous Evolution: The Engine of Ecosystemic Adaptability

The triad model's principle of asynchronous evolution is key to understanding and managing change in KOEs. Changes in one layer do not necessitate immediate, synchronous changes in others.

• Scenario 1 (evolution in L_1): A new, more powerful AI tool for named entity recognition (L_1) is deployed. It extracts entities from text with higher accuracy and identifies new entity types. The Base (the corpus of documents) remains the same. The Representation (the ontology used for tagging) may initially stay the same, but the new tool's output might reveal gaps or ambiguities, eventually prompting an ontology update (R). The $\mathbf{L_3}$ governance process would oversee the evaluation and integration of this new tool.

• Scenario 2 (evolution in R): A scientific community agrees on a new, more granular metadata standard for genomic data (R). Existing datasets (**B**) are retrospectively annotated or versioned with links to the new standard. The data processing pipelines ($\mathbf{L_1}$) are updated to produce the new metadata format. Theoretical models ($\mathbf{L_2}$) may need adjustment if the new representation enables finer-grained analysis. Training and documentation ($\mathbf{L_3}$) are updated to support the change.

• Scenario 3 (evolution in L_3): New data privacy regulations (e.g., General Data Protection Regulation (GDPR)) are enacted ($\mathbf{L_3}$-social-institutional). This forces changes into access control mechanisms ($\mathbf{L_1}$-technical), may require new metadata fields to record consent (**R**-representation), but does not alter the fundamental nature of the research data itself (**B**).

This asynchronous model allows ecosystems to be both stable (core referents and functions persist) and adaptive (components can be upgraded independently). It provides a structured way to manage versioning, provenance, and backward compatibility.

4. Operationalizing the Triad Architecture: Building Blocks for KOEs

With the conceptual blueprint of the triad architecture in place (Section 3), we now turn to the practical question of operationalization: what existing or emerging infrastructural building blocks can bring this model to life? A triad, after all, is not a physical object but a pattern that must be instantiated in code, data structures, and workflows. This section argues that three families of technologies and practices are uniquely suited to this task: Knowledge Graphs for native representation, Version Management systems for tracking evolution, and Explainable AI workflows for making linkage transparent. Each addresses a specific requirement derived directly from the triad's components

4.1 Knowledge Graph Integration: The Natural Habitat for Triads

The triad requires an environment where Base entities, their multiple Representations, and the Links between them can coexist and be queried integrally. This is precisely what Knowledge Graphs were designed to do. Knowledge Graphs (KGs) are the preeminent infrastructure for instantiating the triad architecture. An RDF-based KG natively separates and connects the three layers (Hogan et al., 2021). For a comprehensive contemporary survey of KG architectures and their applications in semantic infrastructures, see Hogan et al. (2021). Beyond static architectures, the dynamic evolution of knowledge graph relationships can be modeled using complex network approaches, which provide insights into how the Linkage (L) components reconfigure over time (Abdallah et al., 2025):

• **Base (B)** is modeled as nodes/vertices representing real-world entities (identified by Uniform Resource Identifiers (URIs)).

• **Representation (R)** is embodied in the ontology or schema (the Terminological Box (TBox)), which defines classes (concepts) and properties (relationships) using Resource Description Framework Schema (RDFS) or Web Ontology Language (OWL) OWL.

• **Linkage (L)** is implemented throughout:

◦ $\mathbf{L_1}$**:** Data ingestion pipelines that populate the graph (triplification), and graph algorithms that run on it.

◦ $\mathbf{L_2}$**:** The logical axioms (OWL restrictions, property characteristics) that enable automated reasoning and consistency checking.

◦ $\mathbf{L_3}$**:** The namespace management, URI persistence policies, and community governance around the ontology and dataset.

A triad, therefore, can be seen as a subgraph centered on a class or instance, encompassing its referents (B-instances), its formal definition (R-ontology statements), and the provenance and inference trails that justify its assertions (L). Techniques for refining and validating such subgraphs, including approaches to detect inconsistencies across B, R, and L, are surveyed by Paulheim (2017).

However, a static graph is insufficient. The triad's principle of asynchronous evolution demands that we track changes across its components over time. This leads us to the necessity of robust version management. Recent advances in biomedical ontology leverage deep learning for enrichment analysis, demonstrating how L_1 (empirical-technical linkage) can be operationalized in domain-specific knowledge graphs (Fu et al., 2025).

4.2 Version Management and Semantic Evolution

KOEs require fine-grained control over semantic change. The triad architecture provides a framework for structured versioning:

• **Versioning B:** Tracking changes to datasets (new records, corrections) using PIDs and timestamped archives.

• **Versioning R:** Managing ontology evolution (e.g., using OWL ontology versioning, or tools like Vocabulary of Interlinked Datasets (VoID)). Changes can be mapped to triad components: adding a new class (expanding R), deprecating a property (changing L_2 rules), and adding a scope note for curators (L_3 guidance).

• **Versioning L:** Recording changes to algorithms (L_1), updating inference rules (L_2), or documenting new governance policies (L_3).

Provenance standards (e.g., Provenance Ontology (PROV-O)) can be used to link a specific triad state C(t) at time t to the versions of B, R, and L that constituted it, enabling full reproducibility and audit trails of conceptual evolution.

Finally, if the Linkage layer (especially L_1) is to be populated by algorithmic processes, those processes must be auditable. This connects the triad directly to the growing field of Explainable AI (XAI).

4.3 Enabling Explainable Human–AI Collaboration

A major challenge in AI-mediated KO is the "black box" problem. The triad architecture promotes explainability (**XAI for KO**) by design (Floridi et al., 2018). Recent surveys of explainable AI principles, such as Belle and Papantonis (2021), provide a taxonomy of explanation types that can be mapped directly onto the triad's L_1, L_2, and L_3 layers:

• When an AI system classifies an image, the output is not just a label. The explanation can be structured as:

◦ **Base:** The image (URI).

◦ **Representation:** The assigned class from ontology Y (e.g., Darwin Core (dwc): Insect).

◦ **Linkage:**

▪ $\mathbf{L_1}$**:** The specific neural network model (with version) and the confidence score.

▪ $\mathbf{L_2}$**:** The definition of dwc: Insect from the ontology, providing the semantic criteria.

▪ $\mathbf{L_3}$**:** The fact that this ontology is endorsed by Biodiversity Community Z, and the model was validated on dataset D.

This layered explanation allows a human curator to audit the decision: they can evaluate the tool (L_1), question the classification criteria (L_2), or consider the source's authority (L_3).

4.4 Governance and Institutional Linkage (L_3) as First-Class Citizens

The triad architecture uniquely elevates governance to a core component of conceptual modeling. Designing a KOE means explicitly designing its $\mathbf{L_3}$ layer:

• **Attribution & provenance:** Mandating that all contributions (data, annotations, schema edits) are attributed to agents (people or organizations), creating accountability.

• **Community validation:** Designing workflows where algorithmic suggestions (L_1) are presented to human experts for confirmation or correction, blending L_1 and L_3.

• **Policy-aware infrastructure:** Building systems where access controls and use licenses (L_3 policies) are not just attached to files but are semantically integrated into the graph, influencing data discovery and linkage (L_1).

• **Sustainability models:** Recognizing that maintaining the linkages especially the curatorial and governance work (L_3) requires resourcing. The architecture makes these costs visible and integral to the system's design.

5. Discussion: Implications and Applications of the Triad Architecture

The previous section outlined how the triad architecture can be operationalized using contemporary infrastructural building blocks. The crucial question that remains is: does this architecture hold analytical and diagnostic power when confronted with real-world complexity? A theoretical model, no matter how elegant, must prove its utility by illuminating phenomena that other models obscure. In this section, we put the triad architecture to the test by applying it to three distinct cases of conceptual evolution. We begin with two classic examples from the philosophy of science the species concept and the periodic table to demonstrate its analytical depth. We then return to the contemporary challenge of the European Open Science Cloud (EOSC) to show its practical utility for diagnosing and designing real-world semantic infrastructures. Together, these cases build a cumulative argument for the model's explanatory power.

5.1 Reframing Knowledge Organization as Ecosystem Coordination

The triad architecture fundamentally shifts the goal of KO from creating perfect categorization to orchestrating coherent semantic coordination across a dynamic ecosystem. The focus shifts to managing the relationships and alignments among the evolving B, R, and L components across different actors and platforms.

5.2 Enabling Transparent and Sustainable Infrastructures

By making all three dimensions of a knowledge unit explicit, architecture fosters:

• **Transparency:** The rationale for semantic decisions is exposed in the Linkage layer.

• **Interoperability:** Mapping between systems becomes a process of aligning corresponding B, R, and L components, rather than just terms.

• **Sustainability:** The model highlights dependencies. The long-term preservation of a knowledge resource requires plans for preserving not just the data (B) and schemas (R), but also the documentation of the tools and social processes (L) needed to understand and use them.

5.3 Domain-Specific Applications

The framework is general but manifests differently across domains:

• **Digital libraries & archives:** B = digitized collections; R = library metadata standards Machine-Readable Cataloging (MARC), Bibliographic Framework Initiative (BIBFRAME) (Smiraglia, 2014); L_1 = ingestion workflows; L_2 = cataloging rules (RDA); L_3 = library policies, professional ethics.

• **Research data infrastructures:** B = scientific datasets; R = discipline-specific metadata (e.g., Investigation, Study, and Assay - Tabular (ISA-Tab), Ecological Metadata Language (EML)); L_1 = computational workflows; L_2 = scientific models; L_3 = data management plans, repository certification (CoreTrustSeal). The application of knowledge graphs in research data infrastructures is further explored by Meroño-Peñuela et al. (2021), who provide a framework for integrating heterogeneous scientific datasets. For a philosophical analysis of how data-centric practices reshape the Base (B) and Linkage (L_2) components in contemporary biology, see Leonelli (2016).

• **Cultural heritage:** B = artifacts/monuments; R = standards like CIDOC CRM; L_1 = 3D scanning/photography; L_2 = art historical theories; L_3 = museum curation practices, indigenous knowledge protocols.

• **Corporate knowledge graphs:** B = business entities (products, clients, projects); R = enterprise ontology; L_1 = ERP/CRM integration pipelines; L_2 = business rules; L_3 = data governance committees, compliance requirements.

5.4 Applied Scenario: Conceptual Evolution in the European Open Science Cloud (EOSC)

Methodological Note: The following analysis of the European Open Science Cloud (EOSC) is presented as a conceptual demonstration and theory-driven analytical application of the triad architecture. Its primary purpose is threefold:

1. Illustrative: To render the abstract components of the triad model (B, R, L_1, L_2, L_3) tangible by mapping them onto a real-world, large-scale semantic infrastructure familiar to many researchers in knowledge organization and data science.

2. Diagnostic: To demonstrate the model's analytical utility in tracing and explaining complex, multi-stakeholder conceptual evolution over time. The scenario shows how the triad model can diagnose misalignments and asynchronous changes that would be invisible to traditional, static conceptual models.

3. Generative: To offer a preliminary, yet concrete, example of how the framework can be used to generate insights for designing more resilient and explainable infrastructures.

The analysis draws on publicly available documentation, strategic implementation plans, and official reports from the European Commission and EOSC governing bodies (e.g., European Commission, 2021). It is thus an interpretive synthesis of existing materials through the lens of the triad model, not an empirical study based on new data collection. This approach is appropriate for a conceptual demonstration that illustrates the model's analytical categories and their application to a complex real-world case. The scenario serves as a proof-of-concept of the analytical power of the proposed architecture, bridging the gap between high-level theoretical principles and the complex realities of ecosystem-scale knowledge organization. It lays the groundwork for future empirical research that could operationalize the framework through metrics, user studies, or system implementation.

To demonstrate the analytical and practical value of the triad architecture, we trace the evolution of the core concept "Open Science Resource" within the European Open

Science Cloud (EOSC) infrastructure. This scenario illustrates how the triad model makes sense of the complex, multi-stakeholder negotiations that define semantic infrastructures at an ecosystem scale.

- **Initial state (c. 2018): the policy-driven base**
  - **Base (B):** The initial referent was primarily policy documents and declarations (e.g., FAIR Principles, Bonn Declaration) advocating open science. The concrete, technical instantiation was vague.
  - **Representation (R):** Represented through high-level terminology in project charters and governance documents (e.g., "findable, accessible, interoperable, and reusable resources").
  - **Linkage (L):**
    - **L_1 (Technical):** Minimal. Early pilots focused on cataloguing existing repositories.
    - **L_2 (Theoretical):** Driven by the **FAIR guiding principles** as an abstract, interpretative framework (Wilkinson et al., 2016).
    - **L_3 (Institutional):** Governance by high-level stakeholder assemblies informed by formal strategy documents (European Commission, 2021). Meaning was stabilized through political agreement, not technical implementation.
- **Evolutionary phase 1: technical grounding (asynchronous change in L_1)**

  The development of core technical services forced a refinement of the concept.
  - **B:** The base expanded to include specific, registered research outputs: datasets with PIDs, computational workflows, and software containers in certified repositories.
  - **R:** Representation became more formalized through metadata schemas (e.g., DataCite, discipline-specific standards) and the EOSC resource catalogue data model.
  - **L: L_1 changed radically** with the rollout of the EOSC Core Infrastructure, as outlined in its strategic implementation (European Commission, 2021): PID services, resource onboarding APIs, and interoperability frameworks. This technical layer created new material constraints. **L_2** (FAIR principles) began to be operationalized into concrete metrics and validation rules. **L_3** saw the emergence of technical governance boards working alongside political ones.
- **Evolutionary phase 2: conceptual refinement through use (change in R & L_2)**

  As researchers and providers interacted with the infrastructure, tensions emerged, leading to conceptual restructuring.
  - **B:** The base fractured into distinct sub-types: "FAIR Data", "Open Access Publication", "Virtual Research Environment", "Training Material". The monolithic concept diversified.
  - **R:** New representational artifacts were created: the "EOSC Resource Profile" ontology, detailed classification trees for resource types, and differentiated metadata requirements for each subtype.
  - **L: L_2 evolved** to incorporate more nuanced theories of research artifact lifecycle and reuse. **L_1** adapted with specialized onboarding workflows for different resource types. **L_3** institutionalized these distinctions through specialized working groups (e.g., for data, software, services) and new curation and certification roles (e.g., "EOSC Resource Provider").
- **Current state & model insight:**

  The concept of an "EOSC Open Science Resource" is now a constellation of related triads, each with its own stabilized base-representation-linkage alignment for data, software, services, etc. The triad model explains this evolution not as a simple definition change, but as an asynchronous process:

  1. **Technical linkage (L_1)** advanced first, providing a material anchor.
  2. **Representation (R)** and **theoretical linkage (L_2)** then evolved to describe and explain the complexities revealed by the infrastructure.
  3. **Institutional linkage (L_3)** continuously adapted to validate and govern the emerging distinctions.

This scenario demonstrates how the triad architecture provides a diagnostic lens for ecosystem builders. It allows them to:

- **Identify misalignments:** Pinpoint tensions (e.g., when user needs clash with governance rules) as misalignments between B, R, and L components.
- **Design for evolution:** Proactively design linkage mechanisms (like adaptable metadata schemas and modular governance) that can absorb asynchronous change.
- **Achieve explainability:** Trace why a resource is classified a certain way back to specific technical validations (L_1), ontic definitions (R/L_2), and community endorsements (L_3).

Thus, the triad model moves from a descriptive framework to a generative tool for designing resilient semantic infrastructures within complex knowledge ecosystems like EOSC.

5.5 Illustrative Examples From the Philosophy of Science

To further demonstrate the analytical power of the triad architecture beyond digital infrastructures, we apply it to two classic cases from the history and philosophy of science: the biological species concept and the Periodic Table of Elements. These examples illustrate how the model provides diagnostic leverage that static singlet or duplet models cannot achieve.

5.5.1 Example 1: The Evolving Concept of "Species" in Biology

The long-standing 'species problem' in philosophy of biology and taxonomy provides a rich case study. A classical essentialist interpretation, often associated with a static duplet model (extension/intension), would define a species by a set of necessary and sufficient properties (e.g., reproductive isolation). However, as scholars from Mayr (1942) to Brigandt (2022) have demonstrated, this essentialist view fails to capture the dynamic and contested nature of species concepts, which are better understood through frameworks like population thinking or homeostatic property clusters. We draw on these critiques as evidence that static, definition-based models (i.e., duplet structures) are inadequate for capturing scientific concepts. The triad model, by contrast, provides a formal architecture that can account for the dynamic, practice-dependent, and theory-laden character that these scholars identified, without implying that they themselves endorsed a triadic model.

The triad model reveals a more complex picture:

• **Base (B):** The referential domain remains relatively stable: populations of organisms that exhibit some form of lineage separation and evolutionary independence.

• **Representation (R):** Multiple, competing representations coexist. These include the morphological species concept (diagnostic morphological traits), the Biological Species Concept (reproductive isolation), and the Phylogenetic Species Concept (monophyly on a phylogenetic tree). These different Rs are not merely alternative definitions; they are embedded in different theoretical frameworks and empirical practices, and they often coexist in taxonomic databases, linked to the same base entities.

• **Linkage (L):** This is where the model reveals the source of the debates:

○ **L_1 (empirical-technical):** The advent of DNA barcoding and phylogenomic analysis revolutionized the empirical linkage. It provided new data (genetic sequences) that could be used to test hypotheses derived from different Rs, sometimes challenging classifications based solely on morphology. This asynchronous change in L_1 created pressure for evolution in other components.

○ **L_2 (explanatory-theoretical):** The rise of cladistics as a dominant theoretical framework in systematics provided a new L_2, which redefined what counts as evidence for species status (shared derived characteristics) and privileged the Phylogenetic Species Concept. This theoretical shift then influenced which Rs were considered valid within certain research communities.

○ **L_3 (institutional-social):** International nomenclature commissions (e.g., the International Code of Zoological Nomenclature, ICZN) and taxonomic societies act as L_3 governance mechanisms. They debate and stabilize which species concepts are accepted for formal description, manage conflicts, and update codes of practice. A change in L_3 (e.g., a new edition of the code) can have downstream effects on L_1 and L_2.

The triad model thus diagnoses the "species problem" not as a mere definitional dispute (a conflict in R) but as a dynamic interplay of asynchronously evolving components. It provides a structured way to understand why, for example, a group of organisms might be considered one species under the Phylogenetic Species Concept (R_3) but multiple species under the Biological Species Concept (R_2), a tension rooted in differing L_2 commitments and L_1 data sources. For a more detailed philosophical analysis of the species problem and its relation to taxonomic practice, see Mayr (1942) and Brigandt (2022). The triad model provides a meta-level framework for understanding the dynamics captured in these works.

Having diagnosed a long-standing philosophical debate, we now test the model on a case of successful scientific consensus: the periodic table.

5.5.2 Example 2: The Periodic Table of Elements

The evolution of the Periodic Table offers another compelling illustration of the triad architecture's analytical power. The referential domain **(B)**, the chemical substances that would eventually be understood as elements, remained broadly stable throughout history, although the theoretical interpretation of what constitutes an "element" itself evolved (from Aristotelian principles to Daltonian atoms to subatomic particles). Lavoisier's list of simple substances in 1789, for example, included light and caloric, which are not elements by modern standards.

However, the **Representation (R)** of these substances evolved dramatically, from Döbereiner's triads (1829) to Newlands' octaves (1864) to Mendeleev's table based on atomic weight (1869) and finally to the modern table based on atomic number (1913) and electron configuration.

This evolution in R was driven by profound changes in linkage:

• **L_1 (empirical-technical):** New experimental techniques, such as spectroscopy, X-ray diffraction, and mass spectrometry, revealed previously unknown elements and their properties, providing new data that challenged existing representations. Moseley's 1913 X-ray spectroscopy experiments, for instance, provided the first empirical determination of atomic numbers.

• **L_2 (explanatory-theoretical):** The development of quantum mechanics (Bohr's model, Schrödinger's equation, Pauli's exclusion principle) provided the theoretical framework that explained the periodic law itself, grounding the table in electron configuration rather than atomic weight. This L_2 evolution fundamentally restructured the conceptual understanding of periodicity.

• **L_3 (institutional-social):** The International Union of Pure and Applied Chemistry (IUPAC), established in 1919, serves as the governance body that validates new elements, settles naming disputes (e.g., the element 104 controversy between American and Soviet claims), and standardizes the table's form, stabilizing the representation for the global chemical community.

The Periodic Table is thus not a static classification but a dynamic record of asynchronous conceptual evolution, elegantly captured by the triad architecture. The model reveals how empirical techniques (L_1), theoretical frameworks (L_2), and institutional governance (L_3) interact across time to produce and stabilize representations of the natural world.

These historical examples demonstrate the triad's analytical power over long timescales and its ability to diagnose conceptual evolution in mature scientific domains. Having tested the model on these classic cases, we now return to examine how the same analytical lens can illuminate the growing pains of a contemporary infrastructure, as previously outlined in the EOSC scenario (Section 5.4)

6. Limitations and Future Research Directions

As demonstrated in the EOSC scenario (Section 5.4), the framework provides concrete analytical value. Future empirical research should involve implementing triad-aware pilots in real-world KO environments to further test and refine their practical utility.

The triad architecture is a conceptual framework, and its real-world utility must be tested.

• **Implementation complexity:** Explicitly modeling all three layers, especially the dynamic linkage, adds complexity to system design. Future work needs to develop **practical toolkits and patterns** for implementing triad-aware systems.

• **Formalization:** While RDF/OWL elegantly handles B and R, formally representing procedural and social linkages (L_1, L_3) in a machine-actionable way remains a challenge. Integrating workflow languages (e.g., CWL, W3C, PROV Ontology) and policy languages (e.g., Open Digital Rights Language (ODRL)) with ontic representations is a key research avenue (Lebo et al., 2013).

• **Empirical studies:** There is a need for longitudinal case studies applying the triad framework to real KOE projects (e.g., the European Open Science Cloud, Wikidata, large-scale digital humanities projects) to evaluate its effectiveness in guiding design, managing change, and resolving conflicts.

• **Human factors:** How do different stakeholders (scientists, librarians, developers, end-users) perceive and interact with this three-layered model? User interface and experience research is needed (Hampton, 2010) to make the architecture accessible and usable.

• **Scalability and performance:** Managing the provenance and versioning of triads at web-scale poses significant computational and storage challenges (Thylstrup et al., 2021) that require novel database and indexing strategies.

6.1 Scope and Applicability: The Case of Contested or Vacuous Concepts

The triad model, as presented here, assumes a minimally stable referential base (B) for the concepts it analyzes. This makes it particularly well-suited to scientific and scholarly concepts that are anchored in empirical domains and institutional practices. However, the model's applicability to highly contested, vague, or metaphysically uncertain concepts (e.g., "justice", "consciousness", or prescientific notions such as "phlogiston") warrants further investigation. In such cases, the Base component may itself be unstable or subject to fundamental disagreement, and the dynamics of conceptual evolution may operate differently. Future research could explore extensions or modifications of the triad architecture to accommodate such concepts, perhaps by modeling B itself as a contested or evolving domain.

6.2 Operationalizing Asynchronous Evolution: Toward Metrics and Indicators

A key contribution of the triad model is its principle of asynchronous evolution, which provides a lens for understanding conceptual change. However, operationalizing this principle in practical infrastructure design requires developing metrics and indicators. Future research could explore:

• How to track versioning and change across B, R, and L components in knowledge graphs and semantic repositories.

• How to identify "misalignments" or "temporal lags" between components that signal the need for intervention or governance review.

• How to develop visualization tools that make asynchronous evolution visible to human curators and decision-makers.

• How to integrate provenance standards (e.g., PROV-O) with the triad framework to create auditable trails of conceptual change.

These are important directions for translating the triad model from an analytical framework into a practical tool for ecosystem governance.

6.3 Scalability and Performance

Managing the provenance and versioning of triad components at web-scale poses significant computational and storage challenges. Tracking asynchronous evolution across millions of concepts, each with potentially multiple versions of B, R, and L, requires novel database architectures and indexing strategies. Graph databases (e.g., Neo4j, Amazon Neptune) and triple stores (e.g., GraphDB, Stardog) offer some native capabilities for handling versioned RDF data, but efficient querying of historical states and temporal dynamics remains an active area of research (Thylstrup et al., 2021).

Future work could explore:

• Temporal extensions to RDF and SPARQL.

• Integration with event sourcing and Command Query Responsibility Segregation (CQRS) patterns from software engineering.

• Development of specialized indices for tracking change across B, R, and L components.

These challenges are not unique to the triad model but are inherent in any attempt to build truly dynamic, versioned semantic infrastructures at scale.

7. Conclusions

This paper has presented a comprehensive argument for adopting triad-based conceptual architecture as the foundation for building next-generation Knowledge Organization Ecosystems. By grounding this architecture in the philosophically robust triad model of scientific concepts, we move beyond the limitations of static, reductive models that have long underpinned traditional KOSs.

The triad framework comprising the Base (referential grounding), Representation (symbolic encoding) and Linkage (empirical, theoretical, and social procedures) provides a powerful lens for understanding knowledge units as dynamic, evolving constructs. Its core principle of asynchronous evolution offers a structured way to manage the inherent tension between stability and change in digital knowledge environments.

Operationalizing this architecture through knowledge graphs, versioned semantic resources, and explainable human–AI workflows provides a concrete path to building semantic infrastructures that are not only more powerful and interoperable but also more transparent, accountable, and sustainable. It makes the often-invisible work of curation, governance, and validation a first-class, modeled component of the system.

As we navigate an era of data deluge, algorithmic mediation, and distributed knowledge production, the need for principled, flexible, and epistemically sound organization frameworks has never been greater. The triad model offers a vital conceptual toolkit for meeting this challenge, ensuring that our future knowledge ecosystems are built to learn, adapt, and endure while remaining faithful to the complex, practice-bound nature of human understanding.

Availability of Data and Materials

All data reported in this paper will be shared by the corresponding author upon reasonable request.

Author Contributions

NB and VK conceived and designed the research study. VK developed the original philosophical foundations of the Triplet Model. NB translated, extended, and operationalized the model for application in Knowledge Organization Ecosystems, and developed the applied EOSC scenario. Both authors contributed to the analysis, writing, and critical revision of the manuscript. Both authors reviewed and approved the final version of the manuscript. Both authors have participated sufficiently in the work and agreed to be accountable for all aspects of the work.

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Conflicts of Interest

The authors declare no conflicts of interest.

Declaration of AI and AI-Assisted Technologies in the Writing Process

During the preparation of this work the authors used ChatGPT-3.5 in order to check spelling and grammar. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

References

Abdallah H, Markhoff B, Soulet A. A Complex Network Model for Knowledge Graphs' Relationships. Semantic Web: – Interoperability, Usability, Applicability. 2025; 16. https://doi.org/10.1177/22104968251361342

Arp R, Smith B, Spear AD. Building Ontologies with Basic Formal Ontology. Mit Press: Cambridge, MA. 2015.

Bagchi M. Towards Knowledge Organization Ecosystem (KOE). Cataloging & Classification Quarterly. 2021; 59: 740–756. https://doi.org/10.1080/01639374.2021.1998282

Belastegui J. A conceptual space for classical concepts. Synthese. 2025; 206. https://doi.org/10.1007/s11229-025-05148-7

Belkheiri N, Kuznetsov V. A base representation-linkage frame for historicmethodological analysis of fundamental chemical concepts. Studies in History and Philosophy of Science and Technology. 2026a; 35: 15–32. https://doi.org/10.15421/272602

Belkheiri N, Kuznetsov V. From the Triplet to the Triad Model of Scientific Concepts: A New Methodological Framework for Understanding Conceptual Evolution in Science Education. In Culture, Science, Education: Meaningful Life Values in Modern Conditions: Proceedings of the VII International Interdisciplinary Scientific-Practical Online Conference. Kyiv. Institute of Gifted Children, National Academy of Educational Sciences of Ukraine. 2026b.

Belle V, Papantonis I. Principles and Practice of Explainable

Machine Learning. Frontiers in Big Data. 2021; 4: 688969. https://doi.org/10.3389/fdata.2021.688969

Borgman CL. Big Data, Little Data, No Data: Scholarship in the Networked World. MIT Press: Cambridge, MA. 2015.

Brigandt I. How to Philosophically Tackle Kinds without Talking about "Natural Kinds". Canadian Journal of Philosophy. 2022; 52: 356–379. https://doi.org/10.1017/can.2020.29

Dahlberg I. A referent-oriented, analytical concept theory for INTERCONCEPT. KNOWLEDGE ORGANIZATION. 1978; 5: 142–151. https://doi.org/10.5771/0943-7444-1978-3-142

European Commission. European Open Science Cloud (EOSC) Strategic Implementation Plan. Publications Office of the European Union: Luxembourg. 2021.

Feest U, Steinle F. (eds.) Scientific concepts and investigative practice. Springer: Berlin. 2012.

Floridi L, Cowls J, Beltrametti M, Chatila R, Chazerand P, Dignum V, et al. AI4People-An Ethical Framework for a Good AI Society: Opportunities, Risks, Principles, and Recommendations. Minds and Machines. 2018; 28: 689–707. https://doi.org/10.1007/s11023-018-9482-5

Fu HY, Liu YY, Zhang MY, Yang HX. Enrichment Analysis and Deep Learning in Biomedical Ontology: Applications and Advancements. Chinese Medical Sciences Journal = Chung-kuo i Hsueh K'o Hsueh Tsa Chih. 2025; 40: 45–56. https://doi.org/10.24920/004464

Hampton JA. Concepts in Human Adults. In Mareschal D, Quinn PC, Lea SEG (eds.) The Making of Human Concepts (pp. 295–314). Oxford University Press: Oxford. 2010.

Hjørland B. What is Knowledge Organization (KO)? KNOWLEDGE ORGANIZATION. 2008; 35: 86–101. https://doi.org/10.5771/0943-7444-2008-2-3-86

Hogan A, Blomqvist E, Cochez M, D'amato C, Melo GD, Gutierrez C, et al. Knowledge Graphs. ACM Computing Surveys. 2021; 54: 1–37. https://doi.org/10.1145/3447772

Keet CM. An Introduction to Ontology Engineering. College Publications: Georgia. 2018.

Kendall EF, McGuinness DL. Ontology Engineering. Synthesis Lectures on Data, Semantics, and Knowledge. Springer: Cham. 2019.

Kolmogorov AN, Dragalin AG. An Introduction to Mathematical Logic. Lomonosov University: Moscow. 1962. (In Russian)

Kuhn TS. The Structure of Scientific Revolutions. 50th anniversary ed. University of Chicago Press: Chicago. 1962/2012.

Kuznetsov V, Kuznetsova E. Types of concept fuzziness. Fuzzy Sets and Systems. 1998; 96: 129–138. https://doi.org/10.1016/s0165-0114(96)00269-2

Kuznetsov V. On Triplet Classification of Concepts. KNOWLEDGE ORGANIZATION. 1997; 24: 163–175.

Lebo T, Satya S, Deborah M. PROV-O: The PROV Ontology. 2013. Available at: https://www.w3.org/TR/prov-o/ (Accessed: 1 June 2026).

Leonelli S. Data-Centric Biology: A Philosophical Study. University of Chicago Press: Chicago. 2016.

Mai J. The modernity of classification. Journal of Documentation. 2011; 67: 710–730. https://doi.org/10.1108/00220411111145061

Margolis E, Laurence S. (eds.) The Conceptual Mind: New Directions in the Study of Concepts. MIT Press: Cambridge. 2015.

Mayr E. Systematics and the Origin of Species. Columbia University Press: New York. 1942.

McCaffrey J, Machery E. Philosophical issues about concepts. Wiley Interdisciplinary Reviews. Cognitive Science. 2012; 3: 265–279. https://doi.org/10.1002/wcs.1166

Meroño-Peñuela A, Lisena P, Martínez-Ortiz C. Web Data APIs for Knowledge Graphs: Easing Access to Semantic Data for Application Developers. Springer: Berlin. 2021. https://doi.org/10.1007/978-3-031-01917-3

Overmann KA. The Materiality of Numbers. Emergence and Elaboration from Prehistory to Present. Cambridge University Press: Cambridge. 2023.

Paulheim H. Knowledge graph refinement: A survey of approaches and evaluation methods. Semantic Web. 2017; 8: 489–508. https://doi.org/10.3233/sw-160218

Peirce CS. The Icon, Index, and Symbol. In Hartshorne C, Weiss P (eds.) Collected Papers of Charles Sanders Peirce, Vol. 2, Elements of Logic (pp. 274–308). Harvard University Press: Cambridge. 1932.

Ranganathan SR. Prolegomena to Library Classification. Madras Library Association: Madras. 1937.

Schöpfel J, Hjørland B, Zane A, Prost H, Farace D. Data Documents. Knowledge Organization. 2021; 48: 307–328. https://doi.org/10.5771/0943-7444-2021-4-307

Smiraglia RP. The Elements of Knowledge Organization. Springer: Cham. 2014.

Thylstrup NB, Agostinho D, Ring A, D'Ignazio C, Veel K. Uncertain Archives: Critical Keywords for Big Data. MIT Press: Cambridge. 2021.

Wilkinson MD, Dumontier M, Aalbersberg IJJ, Appleton G, Axton M, Baak A, et al. The FAIR Guiding Principles for scientific data management and stewardship. Scientific Data. 2016; 3: 160018. https://doi.org/10.1038/sdata.2016.18

Wittgenstein L. Philosophical Investigations. Blackwell: Oxford. 1953.