Ontological approach and computer ontologies of knowledge domain*

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Abstract

This study advances the ontological approach as a critical framework for systematizing transdisciplinary knowledge across heterogeneous domains. We develop and apply ontological engineering methods—integrating linguistic and conceptual modeling—to construct formalized ontologies and knowledge repositories. The research establishes a novel framework for hierarchical ontological worldviews, enabling precise knowledge structuring, integration, and processing within knowledge bases. Our methodology synthesizes conceptualization techniques from diverse scientific fields to formalize domain-specific knowledge, thereby facilitating transdisciplinary research. Results demonstrate the implementation of intelligent computer systems that leverage ontological structures for advanced knowledge management and analysis. By rigorously formalizing domain knowledge, this work directly contributes to solving complex scientific and technical problems through transdisciplinary knowledge-oriented technologies, underscoring ontologies' essential role in next-generation intelligent systems.

Keywords

transdisciplinary scientific research, intellectual information technologies, knowledge-oriented system and network, ontological engineering, computer ontology, sensor Semantic Web, convergence cluster

1. Introduction

The contemporary trajectory of scientific advancement and its application is unequivocally characterized by transdisciplinarity. This paradigm necessitates the development of a rigorous transdisciplinary (TD) research methodology, the establishment of international TD research centers and educational institutions, and the critical delineation of informatics' role within the systemic and technological frameworks supporting TD inquiry and its application to contemporary global challenges [1]. The transdisciplinary paradigm aims to construct a unified scientific worldview – or equivalently, a coherent system of transdisciplinary knowledge – capable of enabling formalized problem formulation and resolution within complex, high-stakes projects of significant societal import, which often encompass elements of conflict and competition.

While a substantial body of recent literature has addressed the philosophical foundations, phenomenological dimensions, and conceptual frameworks of transdisciplinary research, publications specifically addressing methodological approaches and applied implementations merit particular scholarly attention. This chapter accordingly proposes specific information technology methodologies and tools to advance the formation and maturation of transdisciplinary research practices. It is within the ongoing transition toward a knowledge society, underpinned by transdisciplinary, knowledge-oriented technologies, that the systemic integrative function of informatics becomes critically evident.

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2. Ontological approach and virtual paradigm

The ontological approach formalizes heterogeneous knowledge domains (KD) [2], providing foundational tools for knowledge-oriented systems and transdisciplinary interaction. It constructs linguistic ontological world pictures (LOWP) as lexicographic components of scientific worldviews, forming the categorical superstructure of knowledge bases. Systemic integration requires formal criteria for reliable conclusions, with LOWP’s categorical level defining hierarchy apex and concept operations [3]. Despite enabling holistic KD analysis, current science lags in managing transdisciplinary research life cycles and knowledge integration. Spontaneous clustering of disciplines (e.g., NBIC) addresses convergence needs [2 – 6].

This process is accompanied by the formation of new scientific theories and disciplines and appeals to the canonical form of concept definition, which allows for the creation of new concepts as a result of logical operations on concepts (and in parallel on their definitions). The main ones are the operations of generalization and restriction. Indication of the main part of the concept's content has the form of bringing the concept to be defined under a closer generic concept on the basis of species-forming (essential and defining) features: $X_{ij} = A_j X_i$, where X_i and X_{ij} are respectively the generic (defining) and species (defining) concepts, and A_j – the set of species features. The genus-species definition is the most representative, but not the only one. There are other types of definitions: genetic, operational, axiomatic, contextual, inductive, etc. It is worth noting that the rigor of the definition of concepts directly determines the quality of knowledge, and thus the completeness of the description of subject areas and scientific theories. A special role in TD knowledge systems is played by the formation of a hierarchy of basic categories (categorical stratification), as it is systemic.

3. Architecture of intelligent computer systems

The scientific worldview's multidimensionality necessitates visual equivalents in ontographs alongside conceptual components. The ontological paradigm evolved concurrently with the virtual paradigm—now pervasive in concepts like virtual laboratories and organizations. VRML/X3D standards for 3D graphics catalyzed the shift to image-conceptual ontology (ICO), integrating concepts with images at each node.

Knowledge-based systems represent a critical Computer Science domain enhancing computational efficiency. This necessitates formalized knowledge integration across logic, computational linguistics, and semantic networks, forming transdisciplinary research foundations [2, 5, 7]. Ontology-driven intelligent computer systems (ICS) require generalized architectures, formal ontological models, and knowledge processing algorithms, where subject-domain ontologies define categorical hierarchies and axiom systems [7 – 14]. Personalized healthcare AI demands specialized ontological models [15 – 17] utilizing service-oriented ontologies (SOO) with loaded ontograph functions (Fig. 1).

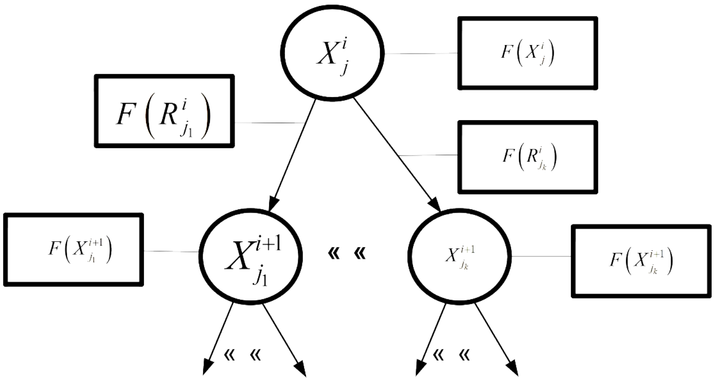

Figure 1: Fragment of a loaded ontograph.

ICS architecture integrates external (user-oriented) and internal (functional) frameworks, operating via "input signal ⟶ knowledge system ⟶ reaction" with self-developing knowledge bases through multimodal formalized knowledge base (FKB) expansion (Fig. 2). ICS solves task classes: (a) known method mapping inputs to outputs; (b) transition-path determination between states. System integration technology (SIT) enables lifecycle-standardized component assembly and interaction using formalized specifications and international standards.

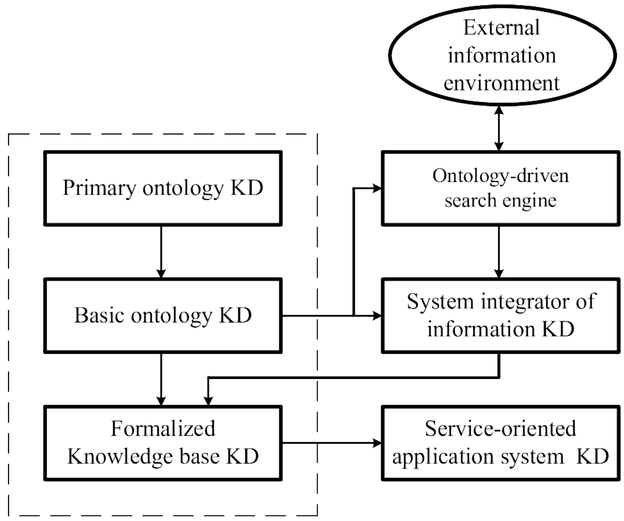

Figure 2: Evolving ICS architecture.

4. Intelligent information technologies for ontology-oriented support of transdisciplinary research

Transdisciplinary (TD) research methodology requires formal ontological frameworks for complex scientific problem-solving, implemented through computer ontologies of specific knowledge domains (KD) [2, 7, 18]. Ontologies – advanced conceptual systems – address knowledge representation standardization gaps and enable TD knowledge integration. Implementation necessitates: integrated linguistic corpus processing; ontograph construction (sets C, R); scientific-theory formalization; and semantic analysis tools, exemplified by the POLYEDRON toolkit for transdisciplinary ontological dialogues [8 – 12]. This enables the workflow: semantic corpus analysis ⟶ ontograph construction ⟶ elementary meaning identification ⟶ knowledge formalization ⟶ task solution.

Real ontology-driven systems feature three hierarchical components: meta-ontology (categorical level), subject ontology, and application ontology [7]. Figure 3 details the categorical (levels 0–5) and domain (levels 1–3) structure, centered on "Nature⟶Society⟶Human⟶World Knowledge⟶TD Research". Level 0 (Universe, B) anchors the hierarchy [19], with levels 1–4 defining TD research foundations. Domain levels facilitate "convergence clusters" (e.g., NBIC-technology), while discipline levels specify subject theories [7, 20]. Concepts interact via volume relations (semantic links (R) to superordinate concepts) and content relations (interpretation functions (F) and axioms (A)).

Categorization follows the inverse volume-content principle, with generalization expanding conceptual scope through feature exclusion. POLYEDRON supports TD project lifecycle stages, convergence cluster development, and social impact assessment, underpinning intelligent systems like Research Design Systems and Neurocomputing.

Contemporary scientific advancement necessitates transdisciplinary (TD) integration for studying complex self-developing systems, exemplified by ecology, cybernetics, and informatics. TD research increasingly relies on neurocomputing, multi-agent systems, and intelligent information systems [21 – 23].

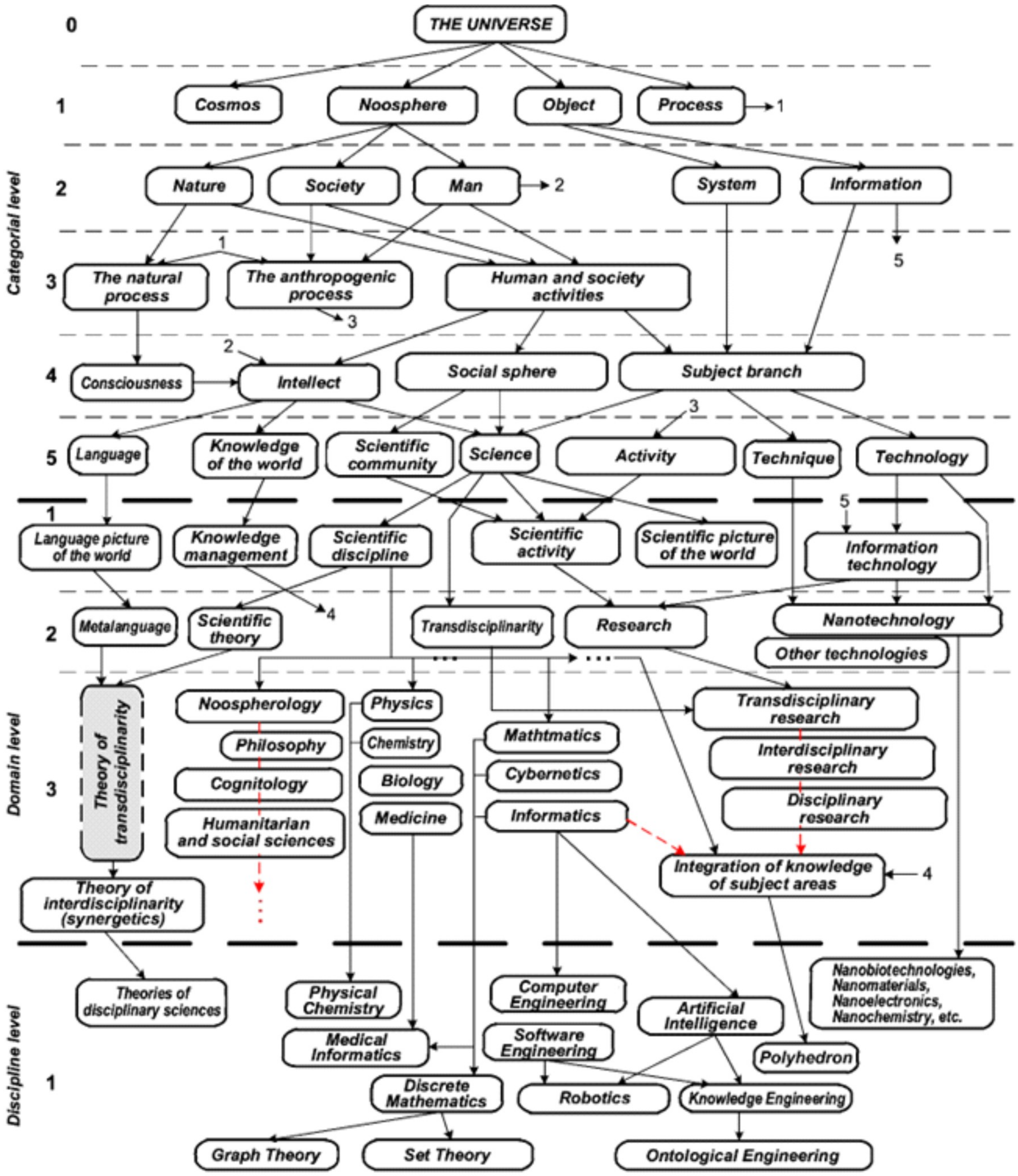

Figure 3: Ontograph of the categorical level of representation of scientific theories.

Effective TD management requires integrated information technologies enabling lifecycle regulation, knowledge synergy, and cross-disciplinary collaboration [24]. Core components include ontologically structured knowledge bases and distributed services for pattern recognition, decision support, and virtualized collaboration. Transitioning to formalized knowledge management—anchored in computer ontologies as the unifying paradigmatic framework (noosphere-SPW-TD-ontology-intellectual systems)—transforms knowledge into intellectual capital [24]. Essential requirements for TD-supporting technologies encompass: (1) problem-solving knowledge adequacy; (2) continuous methodological refinement; (3) idempotent information sharing; (4) Big Data/Grid/Cloud integration with Green Computing.

5. System-ontological analysis of the Knowledge Domain. Models of computer ontologies

System analysis dismembers objects into constituent elements and interconnections, yielding interpretive subject knowledge models [3, 7, 19, 24 – 26]. As a methodological cornerstone, it determines system functioning laws, structural alternatives, and optimal solutions through decomposition, analysis, and synthesis, guided by principles including hierarchy, functionality, and uncertainty [19, 24].

A subject-domain computer ontology is formally defined as a hierarchical structure comprising: concept vertices and semantic relation arcs (ontograph); interpretation functions from domain knowledge sources; axioms/constraints; formal language description; theory-grounded interpretation [27, 28]. Represented as the ordered triple ⟨C, R, I⟩ (concepts, relations, interpretation functions), ontologies dichotomize into: simple – ⟨C, R⟩ for unambiguous concept perception and somplete – ⟨C, R, I, A, D, C⟩ (axioms, definitions, constraints) as formal conceptual knowledge expression.

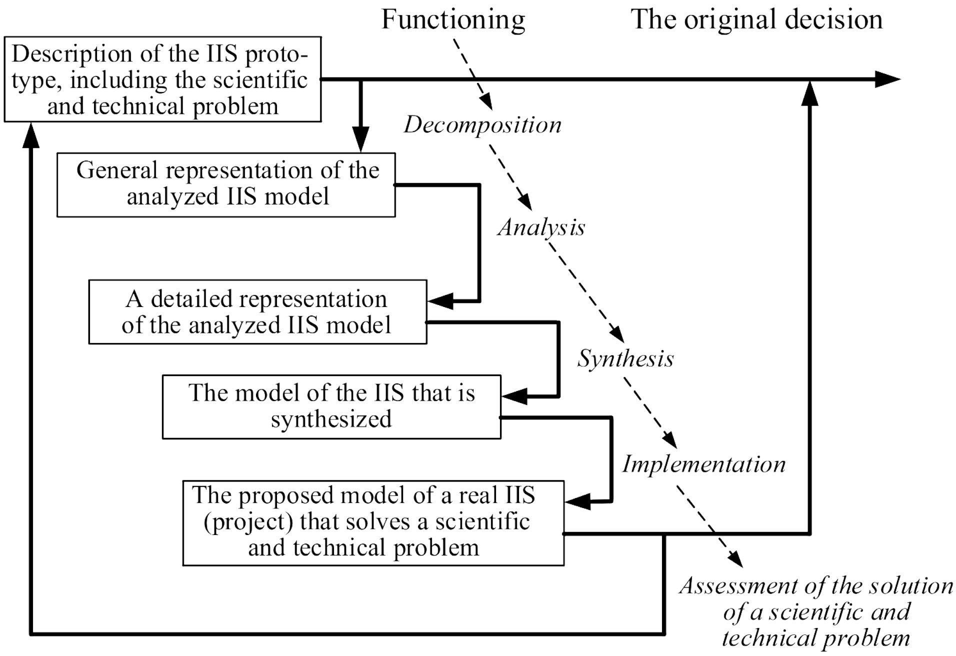

Figure 4: General scheme of solving a scientific and technical problem.

Ontology development diverges from object-oriented programming: ontologies prioritize structural class properties and explicit concept content, whereas OOP emphasizes operational properties and encapsulation [29, 30]. The system-ontological approach integrates ontological tools for applied tasks, modeling problem space (PS) through invariant (objects, processes) and variable task components [7, 31]. This paradigm establishes ontological foundations for transdisciplinary knowledge integration, where complete ontologies serve as knowledge bases for intelligent systems. System analysis iteratively supports knowledge-oriented information system design across the research lifecycle (Figure 4).

6. Methodology for developing a computerized ontology of the knowledge domain

Synthesizing a knowledge domain (KD) ontograph requires specification of the KD and its linguistic corpus. Preliminary analysis entails abstraction to isolate task-relevant aspects from reference materials (dictionaries, thesauri) [20, 28, 32 – 34]. This stage compiles a systematized knowledge representation, identifies knowledge sources, and documents a KD glossary. Key steps include: fragment selection of problem space (PS); method selection (abstraction, decomposition); and term classification (object/process/task terms).

The ontology of objects of a KD is understood as a quadruple:

$$O^O = < X^O, R^O, F^O, A^O(D, Rs) >, \tag{1}$$

where $X = \{ x_1, x_2, ..., x_i, ..., x_n \}$, $i = \overline{1, n}, n = Card\ X$ is a finite set of con-concepts (concepts-objects) of a given KD;

$R = \{ R_1, R_2, ..., R_k, ..., R_m \}, R \subseteq X_1 \times X_2 \times ... \times X_n$, $k = \overline{1, m}$, $m = Card\ R$,

– is a finite set of semantically significant relations between the concepts-objects of the KD. They determine the type of relationship between the concepts. In general, relations are divided into general significant ones (from which, as a rule, relations of partial order are distinguished) and specific relations of a given KD;

$F : X \times R$ – a finite set of interpretation functions defined on concepts-objects and/or relations;

A – a finite set of axioms, consisting of a set of definitions D_i^l and a set of constraints Rs_i^t for the concept X_i. The definitions are written in the form of identically true statements that can be taken, in particular, from the explanatory dictionaries of the KD. They may indicate additional relationships X_i of concepts with concepts X_j. The set of constraints may contain restrictions on the interpretation of the corresponding concepts X_i.

Construction requires on-empty C derived from explanatory dictionaries or comprehensive term lists (synonyms mapped to single concepts). R should be established via k-ary relations, forming an oriented graph with generic concepts as roots and primitives as leaves. Hierarchies follow top-down/ascending/combined approaches, ensuring subclasses share generalization levels and inherit properties. I and A interpretation per functional requirements: axioms may define relations, constraints, or task mappings [29, 32]. Protégé synthesizes the ontograph into formal ontology descriptions.

The ontology of processes of a KD is understood as a triple [7]:

$$O^P = < P, R^P, F^P > \tag{2}$$

where P – a finite set of concepts (concepts-processes) of a given KD;

$R^P = \{ r_1^P, r_2^P, ..., r_k^P, ..., r_K^P \}, \quad \forall k = (1 \div K)$ – is a finite set of semantically significant relations between the concepts-processes of the KD. They determine the type of relationship between the processes;

$F^P = P \times R^P = \{ f_g^P \} = \{ pp_l \} \times \{ r_k^P \}, \quad \forall g = (1 \div G)$ – a finite set of interpretation functions defined on concepts-processes and/or relations.

Figure 5 shows a general scheme of the KD process ontology, in which the category "Process" is represented by an ontograph with p levels and n_p subprocesses (SP) at each level. The penultimate $(p-1)$ level is represented by a set of actions (A), into which each subprocess of the previous level is divided. In turn, each action at the last (p-th) level is divided into a sequence of operations $O_{i_j}^p$.

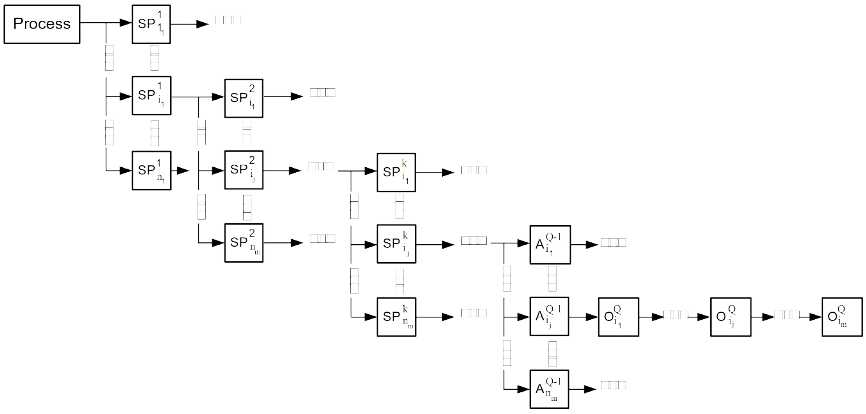

Figure 5: General scheme of the process ontology.

The connections between subprocesses for adjacent levels correspond to the "whole-part" relationship, and within each level – to some mixed form of connection organization. Figure 5 shows a special case of such an organization – a parallel one. Further development (specification) of the process ontology is possible when a specific subject area and the corresponding problem space are specified, and in a narrower sense, specific branching features (conditions for initiating a SP, conditions for terminating a SP, and constraints) in the ontograph.

KD ontology integrates object/process ontologies; task ontology handles PS dynamics. Target tasks distinguish required objects/processes, forming reusable basic task fragments. Task schemes span "Choice" (trivial selection) to "Construction" (unknown components), with complex problems decomposed hierarchically.

The scheme of the task ontology model is described by the triple [29]:

$$O^{T} = \left\langle GT^{PP}, M, TS \right\rangle \tag{3}$$

where GT^{SP} is a generalized task of the problem space consisting of p tasks, which, in turn, consist of w $=\overline{1,W}$ fragments each. Each fragment is represented by a procedure implemented on a set $v=\overline{1,V}$ of operations each. In addition, the task

$$T^{P} = \left\langle D_{in}^{p}, R^{p}, C^{p}, D_{out}^{p} \right\rangle \tag{4}$$

is defined by the sets D_{in}^{p} of input data, requirements (conditions, constraints) R^{p}, task context C^{p} and output data (or the goal of solving the task) D_{out}^{p};

M is a set of methods for solving problems. It is defined as a mapping

$$M^{p} : \left(D_{in}^{p},\ R^{p}, C^{p}\right) \rightarrow D_{out}^{p} \tag{5}$$

whose components are defined above;

TS – task solver.

It should be noted that problem solver algorithms will work much faster if they are implemented partially or completely in hardware and according to the methodology [35].

System integration unifies ontologies via:

$$\bigcup_{CU} O_{i}, i = \overline{1,N} \tag{6}$$

where I_{CU} is the sign of conceptual unification. The meaning of this sign is the systematic integration of the initial ontological graphs, taking into account the areas of definitions $O_i\,(i=\overline{1,N})$ and their interconnection (interaction). The volume of knowledge W in KDs can be estimated through the characteristics (parameters) of their formal ontological representations. In particular, when represented by an ontological graph (without taking into account the types of relations and the complexity of interpretation functions), the value of W can be characterized by the number of nodes of the OG. In the case of a simple tree structure, this number can be expressed by the formula:

$$W=\sum_i\sum_h\sum_l O_i\cdot S_{h,l} \tag{7}$$

where O_i is the ontograph of the i-th KDs $i=\overline{1,N}$, $S_{h,l}$ is the degree of the node equal to the number of edges coming out of it, $h=\overline{1,H}$ is the number of levels of the ontograph, $l=\overline{1,L_h}$ is the number of the node at the corresponding $(h-мy)$ level of the ontograph.

With a uniform density of distribution the ontograph, i.e., $S_{h,l}=S(H,l=1,2,\ldots)$ at (5), reduces to the well-known formula for the sum of the geometric progression:

$$W=\sum_i O_i\left(\frac{1-S^h}{1-S}\right) \tag{8}$$

Taking into account the types of relations and the complexity of the interpretation functions leads to ontograph a weighted graph with weighted nodes and edges. In this case, expression (8) is transformed into form:

$$W=\sum_i\sum_h O_i\left(\alpha_l+\sum_j\beta_{l,j}\right), \tag{9}$$

where α_l and $\beta_{l,j}$ are the values of the weighting functions of the corresponding relations and interpretation functions assigned to the nodes (α_l) and edges $(\beta_{i,j})$ of the ontograph. Expression (9) gives a complete assessment of the complexity of the ontograph, and the ratio $\omega=W^0/W$ characterizes the average density of the weighted ontograph.

These assessments make it possible to compare different options for representing knowledge about KD and to track the evolution of scientific theories.

The process of knowledge development in any KD is associated with its analysis, conceptualization and construction of a formal theory. In this case, formalization generally refers to four main types of information representation:

$$I=I(V,A,T,G), \tag{10}$$

i. e., verbal (V), analytical (A), tabular (T), and graphical (G). There is a mutually unambiguous correspondence between them, which is not always strictly and completely realized in practice. Therefore, they all find their own, quite specific place in the description of a scientific theory. In many cases, it is correct to limit them to two: verbal and analytical.

As a rule, the process of theory development is accompanied by a redistribution of information about the KD between verbal and formal components, i.e. between a natural language description of the subject matter and a formal analytical (formula F, tabular T, graphical G representation of the essence of the theory). Obviously, the formalized representation is more compact, and most importantly, more rigorous and suitable for computer processing [36].

Semantic Web (SW) uses ontologies for machine-processable information via RDF (metadata), OWL (ontology language), SPARQL (query language), and agents [1, 37, 38]. The key components are: Dublin Core which standardizes RDF metadata and DBpedia that extracts structured data from Wikipedia via RDF.

SPARQL processors (e.g., ARQ/Jena) enable local/remote querying [37]. Known ontology editors are Protégé (open-source) and TopBraid Composer (commercial) simplify OWL modeling. OWL reasoners (Pellet, HermiT) derive new triples from RDF(S), enhancing SPARQL queries via pre-inference or integrated execution. SW tasks include semantic search, metadata management, service discovery, and agent-based automation [1, 37].

7. Conclusion

1. The ontological approach to the representation and integration of scientific knowledge allows to create effective tools for building systems and a technological basis for the systemology of transdisciplinary interaction and ontological engineering.

2. The ontological toolkit allows us to build a linguistic and ontological picture of the world (a kind of lexicographic system), considering it as a component of the scientific picture of the world, which is the basis of the transdisciplinary concept of scientific research. In this case, the linguistic and ontological picture of the world serves as a categorical superstructure of knowledge bases in specific subject areas and integrated knowledge repositories. Obviously, the systemic integration of knowledge is carried out taking into account specific formal and methodological requirements and criteria in the formation of reliable statements and conclusions, and the categorical level with the corresponding system of basic relations represents the top level of the hierarchy of the linguistic and ontological worldview.

3. The scientific picture of the world implies its multidimensional representation, and therefore, along with conceptual components, an ontograph should have their figurative equivalents. It is relevant to note here that the ontological paradigm began and developed almost simultaneously with the virtual paradigm. Today, such concepts as virtual world, virtual organization, virtual laboratory, virtual system, virtual addressing, etc. have become commonplace.

4. The theory and practice of creating and using knowledge-based systems is the most relevant and intensively developing area of Computer Science, which allows to increase the efficiency of creating and using computer technologies, application systems and tools.

5. The peculiarity of the current period of development of information engineering and technology is the integration of the results of two formerly parallel and independent areas of artificial intelligence: knowledge-engineering and computer linguistics (cognitive semantics), which reflects the natural pattern of human interaction with the world around us. Consciousness in it acts as a personalized tool that produces a set of subject, situational, or causally related entities that make up a "conscious" picture of the world.

6. Ontologies are essentially conceptual systems, and conceptual thinking is the most advanced form of functioning of consciousness and intelligence. The prototype of such a system can be actively developing knowledge-oriented information systems with ontology-driven architecture.

7. The general task of ontology is to compensate for the lack of standards for knowledge representation in user interaction with information systems and the latter with each other, as well as the integration of subject area knowledge as the main task of transdisciplinary research.

8. The transition from the non-deterministic mode of knowledge production and use by the subjects of the scientific process to the mode of effective management of knowledge presented in a unified form at all stages of its life cycle will ensure the growth of the efficiency and quality of

scientific research. At the same time, the established knowledge will become intellectual capital, and the subjects of science will become direct participants in the economic activity of society, which will create favorable conditions for stimulating the development of both science itself and the creative society.

9. The central idea of the system-ontological approach is the development of ontological tools to support the solution of applied problems - a multifunctional ontological system. Such a system (more precisely, its conceptual part) is described by a binary that includes the ontology of the subject area (consisting of the ontology of objects and the ontology of processes) and the ontology of tasks.

10. The process of theory development is accompanied by a redistribution of information about the subject area between the verbal and formal components, i. e. between the natural language description of the subject matter and the formal analytical representation of the theory. Obviously, the formalized representation is more compact, and most importantly, more rigorous and suitable for computer processing.

11. Ontologies are used in multiagent technologies in the Semantic Web environment, which is a direction of development of the World Wide Web, the main purpose of which is to present information in a form convenient for machine processing based on technological standards. The Semantic Web provides for recording information in the form of a semantic network with the participation of ontologies, which allows agents to directly extract facts from the Semantic Web and generate logical consequences from these facts in interaction with the user.

12. The Semantic Web is a dynamic and constantly evolving concept, not a set of complex working systems.

13. In terms of machine data processing, the Semantic Web is the idea of storing data on the Web in such a way that it is defined and linked to each other for the purpose of automated processing, integration, and reuse in various applications.

14. With regard to intelligent agents, the goal of the Semantic Web is to make the existing Web more "machine-readable" in order to be able to use intelligent agents to search for and process relevant information.

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Declaration on Generative AI

The authors have not employed any Generative AI tools.

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