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Ontology Engineering for Modeling National Student Achievements in Higher Education

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Abstract

The need for structured and semantically rich data in higher education underscores the role of ontology-based knowledge modeling. This study develops an ontology to represent national-level student achievements, covering key aspects such as institution, achievement field, category, year, level, and student status. Using a formal ontology engineering approach, the ontology was developed in Protégé and encoded in OWL. Evaluation involved technical validation and reasoning tests including class subsumption, consistency checking, instance classification, and rule-based inference to assess logical soundness and semantic correctness. Description Logic (DL) queries were also executed based on competency questions to evaluate the ontology's ability to support semantic querying. The results demonstrate that the ontology effectively supports knowledge inference and structured data retrieval, offering strong potential for integration within semantic web environments. This provides a foundation for data interoperability and knowledge sharing across educational systems at the national level. Future work includes expanding the ontology to incorporate dynamic achievement updates and linking with external educational data sources.

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INTRODUCTION

Information plays a vital role in the representation and management of data (Cabada et al., 2023). In the current digital era, the distribution and exchange of information have become increasingly seamless with the aid of technology. One of the most widely used technologies for sharing and accessing data is the World Wide Web (www), which functions as a dynamic and powerful platform for knowledge dissemination. With an almost limitless supply of information and resources, the web contains diverse and often complex data structures—including names of individuals, places, documents, and bibliographic references—all of which are typically identified using Uniform Resource Identifiers (URIs) (Hamdana & Apriyani, 2020). Despite the abundance of information available online, unstructured data storage across different sources often results in semantic ambiguity and difficulties in data integration. This poses a significant challenge to achieving effective data interoperability (Fusco & Aversano, 2020; Masmoudi et al., 2024).

To address these challenges, ontology engineering has emerged as a promising approach for organizing and interpreting domain-specific knowledge. Ontology refers to a formal, explicit specification of a shared conceptualization that models' entities, their attributes, and interrelationships within a particular domain (Kotis et al., 2020a; Lei et al., 2022). In computer science and information systems, ontology provides a means to structure knowledge semantically and machine-readably, enabling consistent reasoning and intelligent information retrieval. It serves as a foundation for Semantic Web technologies, where machines can understand, interpret, and infer new information from existing data (George Andreas, 2023; Hagedorn et al., 2020).

The application of ontology engineering has been widely explored across domains for its ability to improve semantic clarity and data interoperability. In healthcare, agriculture, e-learning, and cultural heritage, ontologies support tasks such as medical diagnostics, smart farming, personalized learning, and metadata linking (Dwyer et al., 2025; Fahad et al., 2021; Goldstein et al., 2021; Ilkou et al., 2021; Meghini et al., 2021; O'Neill & Stapleton, 2022). Various studies further highlight ontology's role in enabling semantic integration and structured knowledge modeling in smart cities, biomedical diagnostics, wireless communication, halal certification, and manuscript standardization (Chen et al., 2021; Mohamad Hashim et al., 2023; Shi et al., 2019; Wan et al., 2021; Zahila et al., 2021). These works collectively underscore the practical value of ontology engineering in solving semantic problems and enhancing data discoverability across sectors.

In the context of higher education, student achievements are critical indicators of institutional performance. These achievements encompass a wide range of activities, including academic competitions, research outputs, entrepreneurship, sports, arts, and other extracurricular pursuits. National-level student performance data are typically collected and submitted to the Ministry of Education to evaluate and rank institutions. These rankings are intended to motivate universities to enhance support for student development and to recognize outstanding accomplishments. However, the increasing volume and complexity of student achievement data—originating from diverse institutions and involving various categories and formats—present significant challenges for data processing, integration, and retrieval (Beerkens, 2022; Wu, 2024).

To overcome these issues, there is a growing need for a semantic model that can represent, organize, and retrieve student achievement data in a structured manner. An ontology-based approach provides a viable solution for this purpose (Ashour et al., 2020). By formally modeling the key components of student achievements—such as the source institution, achievement category, year, level, field, and student status—an ontology can facilitate semantic reasoning and enable advanced querying over the data. This, in turn, supports better data interoperability between educational institutions and government bodies and enhances the efficiency of national ranking systems.

This study aims to develop an ontology for modeling national student achievements using an ontology engineering methodology. The goal is to design a semantic structure that enables efficient data organization and supports semantic web integration for improved information retrieval. The ontology is developed using Protégé, a widely used tool for ontology modeling, and follows a systematic engineering process encompassing requirement gathering, conceptualization, formalization, and evaluation. The resulting ontology is intended to serve as a semantic foundation for systems that handle student performance data at a national scale, ensuring better interoperability, accessibility, and decision-making.

RESEARCH METHODS

The development of an ontology requires a systematic engineering process to ensure that the resulting model accurately reflects the intended domain and supports semantic reasoning. According to (Reginato et al., 2022), ontology development generally begins by identifying the domain and scope of the ontology, reusing existing ontologies where appropriate, defining classes and class hierarchies (subclasses), specifying properties (also known as slots or roles), and creating instances to populate the ontology.

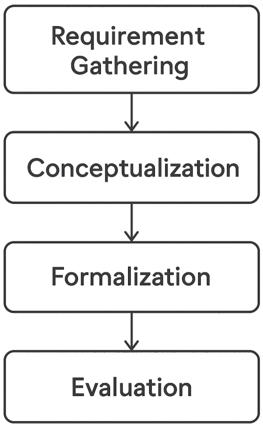

Figure 1. Ontology stage

In this study, the ontology was developed and evaluated using dummy data synthetically constructed to simulate plausible scenarios of student achievement in higher education. The dummy data were generated using predefined templates based on actual student achievement forms submitted to national ranking platforms. These templates modeled typical fields such as student names (anonymized), types of achievements (e.g., science olympiad, arts festival), years, institution names, and competition levels. While no real student records were used, the structure and value distributions followed patterns observed in publicly available summary reports, ensuring representativeness in the data modeling. The use of this data aimed to validate the logical structure, consistency, and semantic queryability of the ontology while adhering to privacy and confidentiality standards. Future work may include applying the ontology to real datasets upon obtaining appropriate ethical clearance and institutional access.

Building upon this foundational approach, the ontology engineering process used in this study follows a more structured framework commonly adopted in semantic web development. This framework typically consists of four major stages: requirement gathering, conceptualization, formalization, and evaluation (Kotis et al., 2020b), as illustrated in Figure 1.

A. Requirement Gathering

Requirement Gathering involves identifying the key objectives of the ontology, the scope of knowledge to be captured, and the competency questions that the ontology should be able to answer (Espinoza et al., 2021). This stage is crucial to ensure alignment with stakeholder needs and to define the boundaries of the domain—in this case, national-level student achievements.

In this study, the main objective of the ontology is to semantically represent student achievement data to support efficient data retrieval, interoperability among higher education institutions, and integration into national student performance ranking systems. The domain is scoped to include various dimensions of student achievements such as the achievements category (competitive or non-competitive), achievements field (e.g., sciences or social sciences), achievements level (e.g., university, regional, national), and student status (e.g., scholarship or regular).

The intended stakeholders for this ontology include the Ministry of Education, university student affairs departments, and developers of academic information systems, all of whom require accurate and structured data for reporting, evaluation, and decision-making purposes. To guide the ontology design, a set of competency questions was formulated to ensure the ontology can answer practical queries relevant to the domain. Examples include: Which students from a particular university won national-level awards in a given year? What fields of achievement are most represented among non-competitive student accomplishments? How many students participated in international competitions under the science and technology category in the last five years? Which institutions have the highest number of student achievements in entrepreneurship?

These questions helped determine the necessary classes, properties, and relationships to be modeled in the ontology. They also ensured that the developed ontology would not only represent data adequately but also support inferencing and semantic search functionalities when integrated into semantic web platforms. The outcomes of this requirement gathering phase formed the foundation for the conceptualization and formalization stages of the ontology development process.

B. Conceptualization

Conceptualization is the process of abstracting and structuring domain knowledge into a model composed of core entities (classes), their attributes (properties), and their interrelationships (Castellanos et al., 2020). At this stage, relevant concepts such as achievement category, student status, institution, achievement level, and achievement year are identified and organized into a formal, hierarchical structure that reflects the underlying semantics of the domain.

C. Formalization

In the formalization stage, the conceptual entities identified in the previous phase are systematically structured into a formal ontology schema. This process involves defining a class hierarchy, specifying subclass relationships, and establishing the structural foundation for the ontology (Boudia & Bourahla, 2022). The ontology is composed of four main classes: Student, Achievement, Status, and Institution, all of which are subclasses of the universal Thing class. Each class and subclass contribute to a well-defined semantic hierarchy that reflects the structure of student achievement data.

D. Evaluation

The evaluation phase in ontology engineering is crucial to ensure that the developed ontology meets the intended objectives in terms of correctness, consistency, and practical applicability (Espinoza et al., 2021). In this study, the evaluation focused on technical validation and functional alignment, particularly in relation to competency questions and reasoning support. This approach aligns with the evaluation framework proposed by Zaitoun et al. (2023), which emphasizes consistency, completeness, conciseness, and pragmatic utility.

Consistency was validated using the HermiT reasoner in Protégé to detect logical contradictions in class hierarchies and instance assertions. Completeness was examined by assessing whether the ontology could fully represent all the concepts needed to answer the predefined competency questions. Conciseness was achieved by eliminating redundant or overlapping axioms using built-in ontology metrics.

To evaluate pragmatic utility, a series of Description Logic (DL) queries was designed and executed based on real-world competency questions, such as retrieving students with scholarships who received international awards, or those involved in non-competition achievements in specific years. The successful execution of these queries confirmed the ontology's capability to support semantic querying and automated inference.

To simulate realistic scenarios, the ontology was populated with dummy data representing students, affiliations, and types of achievements. Reasoning processes, including instance classification, property inference, and rule-based reasoning using SWRL, were implemented. For example, the system correctly inferred that a student who received a national-level entrepreneurship award qualifies as a high-impact achiever, based on defined SWRL rules.

While the evaluation confirmed the ontology's logical soundness and functional alignment, its domain scope remains limited to simulated national-level achievement data. Future work should involve validation using real institutional datasets and integration with external ontologies to enhance robustness and applicability.

RESULT AND DISCUSSION

This section presents the results obtained from the development and evaluation of the student achievement ontology and discusses its effectiveness in representing the knowledge domain. The ontology was evaluated through structural analysis, reasoning implementation, and semantic querying to determine whether it meets the design objectives and answers predefined competency questions.

A. Ontology Hierarchy and Class Structure

In this study, the domain being modeled is national-level student achievements. The design process of the ontology began with the construction of a class hierarchy that systematically organizes concepts related to student recognition in various academic and non-academic contexts. The ontology comprises four principal classes: Student, Status, Achievement, and Institution. These classes serve to capture distinct aspects of the domain and are interlinked to allow comprehensive semantic representation.

The Student class represents individuals who have earned achievements, whether through competitive or non-competitive activities. Each student instance is associated with a particular higher education institution, which is further classified under the institution class into Public and Private institutions. The Status class provides information on the enrollment category of each student, such as whether they are recipients of the Bidikmisi scholarship or are regular students, thereby embedding a socio-academic context into the ontology.

The most elaborated component of the ontology is the Achievement class, which is subdivided into four key dimensions: Achievement Field, Achievement Category, Achievement Year, and Achievement Level. The Achievement Field class is further categorized into Soshum (Social Sciences and Humanities) and Saintek (Science and Technology), each of which contains specific subdomains such as Religion, Language, Economics, Sports, Arts, and Natural Sciences. The Achievement Category class distinguishes between competitive and non-competitive accomplishments. Competitive achievements include titles such as Winner 1, Winner 2, Winner 3, Honorable Mention, and Best Performer, while non-competitive achievements encompass areas like Entrepreneurship, Community Service, Student Exchange, and Recognition Awards.

To capture the temporal aspect of accomplishments, the Achievement Year class was introduced, enabling queries to be conducted across specific timeframes. Similarly, the Achievement Level class identifies the scale of recognition, ranging from institutional, municipal, provincial, and national to international levels. The inclusion of these classes allows for multidimensional classification and querying of student achievement data.

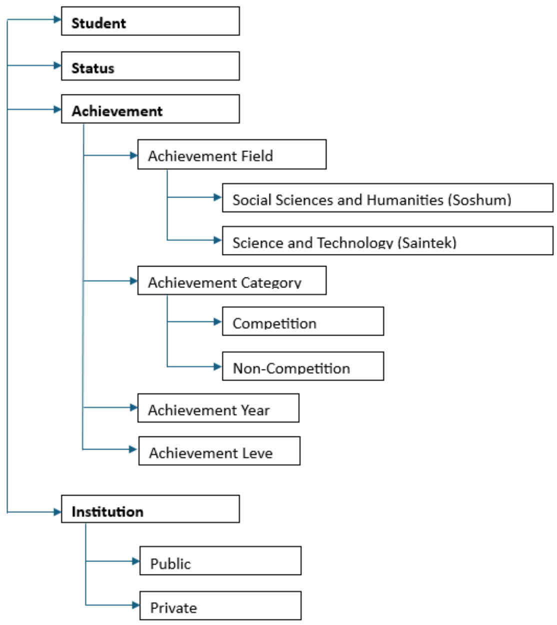

Figure 2. Class and subclass hierarchy

This hierarchical structure was modeled using the Protégé ontology editor and is visualized in Figure 2. The ontology design and class organization were guided by an initial domain analysis and validated against a predefined set of competency questions to ensure alignment with the ontology's intended purpose. Moreover, the use of subclassing and property restrictions reflects a structured taxonomy that supports semantic reasoning and effective data retrieval within a Semantic Web environment. Overall, the ontology structure enables meaningful inference, enhances interoperability, and facilitates advanced knowledge representation in the domain of student achievements.

B. Object Properties and Semantic Relationships

Table 1 presents the taxonomy of the ontology's classes and their subclass relationships:

Table 1. Class and Subclass

Class	Subclass of
Student	Things
Status	Things
Achievement	Things
Institution	Things
Achievement Field	Achievement
Achievement Category	Achievement
Achievement Year	Achievement
Achievement Level	Achievement
Public	Institution
Private	Institution
Soshum	Achievement Field
Saintek	Achievement Field
Competition	Achievement Category
Non-Competition	Achievement Category

As illustrated in Table 1, the ontology for student achievement is structured around four primary classes: student, status, achievement, and institution. The Achievement class encompasses four key subclasses, namely Field, Category, Year, and Level. These subclasses are designed to represent various dimensions of both competitive and non-competitive achievements attained by students. The institution class is further divided into two subclasses: Public and Private, which denote the type of higher education institution to which a student belongs. Furthermore, the Achievement Field and Category subclasses each contain additional layers of subclasses to capture the specific domain and type of the student's achievements. This hierarchical structure reflects a comprehensive conceptual model of student achievement, allowing for semantically rich representation.

In the design of the student achievement ontology, object properties play a crucial role in establishing semantic relationships between classes within the domain. The ontology model incorporates six primary object properties that describe the connections from the student class to other relevant concepts, as seen in Table 3. The property "Institution" links a student to their affiliated institution, represented by the Universitas class. "Recognition As" connects the student to the type of recognition received, defined by the "Achievement Category". The "Student Status" property indicates the student's enrollment status by linking to the Status class. In addition, "Achievement Field" relates a student to the academic or non-academic field in which the achievement was earned, represented by the "Achievement Field" class. "Achievement Level" associates students with the scope or level of the achievement, such as university, regional, national, or international, while "Achievement Year" indicates the year the achievement took place. These object properties form the structural foundation of the ontology, enabling meaningful data representation and retrieval across various dimensions of student achievements.

C. Data Properties

In the design of the national-level student achievement ontology, two data properties were defined to capture additional descriptive details of the activities undertaken by instances of the Student class. These properties are presented in Table 2 and serve to enrich the ontology with structured, retrievable metadata. The first data property, "ActivityID", has the domain Student and a range of "xsd:integer", representing the unique identification number of each activity. The second, "ActivityTitle", also has the domain Student and a range of "xsd:string", capturing the descriptive title of the respective activity. Together, these data properties facilitate more precise querying and support use cases such as reporting, tracking student involvement, or integrating achievement into external system.

Table 2. Data Properties

Data Properties	Domain	Range
ActivityID	Student	xsd:Integer
ActivityTitle	Student	xsd:Integer

D. Rule Definition and Reasoning

The ontology includes a set of logical rules designed to enable automated reasoning and inference over the data. These rules were defined by applying object property restrictions on specific subclasses, where the restriction type was set to "some" to accommodate one-to-many relationships commonly found in student achievement data. For example, in the Championship subclass, rules were applied to associate students with multiple types of achievements, such as awards or recognitions, thereby enabling the ontology to infer broader participation patterns.

Through this mechanism, the ontology can automatically classify individuals based on the relationships they hold with other entities. For instance, if a student is linked to a recognition type categorized under "non-competition," and the achievement year is set to 2020, the ontology can infer that the student participated in non-competitive activities during that year. This kind of logical reasoning strengthens the ontology's utility in supporting semantic queries and intelligent data retrieval.

While the rules were defined using the Protégé editor, their functionality was validated through successful reasoning processes using built-in reasoners such as HermiT or Pellet. The outcomes confirmed that the class hierarchies and individual instances were logically consistent and that the inferences aligned with the expected semantic relationships defined in the model. These inferences serve as a critical validation step, ensuring that the ontology supports advanced, criteria-based classification and decision-making in future applications.

E. DL Queries for Ontology Validation

To assess the functionality and usefulness of the ontology, Description Logic (DL) queries were implemented. These queries were designed to retrieve individuals who meet specific criteria, validating whether the ontology could answer predefined competency questions. Table 4 presents a selection of queries and their respective results, for instance: (1) Querying for Bidikmisi scholarship recipients who achieved international recognition; (2) Finding students from specific universities with notable achievements; (3) Identifying students who participated in non-competition events in a specific year. These queries demonstrate the ontology's ability to process logical conditions and return accurate information, confirming its readiness for use in a semantic application.

Table 3. Object Property

Object Property	Sub Property of	Domain	Range
Institution	-	Student	Institution
Recognized As	-	Student	Achievement Category
Student Status	-	Student	Status
Achievement Field	Recognized As	Student	Achievement Field
Achievement Level	Recognized As	Student	Achievement Level
Achievement Year	Recognized As	Student	Achievement Year

Table 4. Queries

Query	DL Query	Query Result (Dummy Instances)
Who are the Bidikmisi students with international-level achievements?	Student that Status value “Bidikmisi” and Achievement Level value “International”	Ainun Nisa Fitri, Alwy Herfian, Mradipta Lintang Alifcanta Moktikanana
Who are the high-achieving students from Telkom University?	Student that Institution value “Telkom University”	Danu Sofwan, Espinal Adrinaldi, Fajrul Falakh, Iqbal Kamal Fasya
Who are the students with non-competition achievements in 2025?	Student that Recognition As some “Non-Competition” and Achievement Year value “2025”	Alwy Herfian, Danu Sofwan, Gita Indraswari, Meilani Adriyati
Who are the Bidikmisi students with international-level achievements in the Science and Technology field?	Student that Status value “Bidikmisi” and Achievement Field some “Saintek” and Achievement Level value “International”	Meilani Adriyati
Who are the students who became entrepreneurs?	Student that Recognition As value “Entrepreneur”	Alwy Herfian, Danu Sofwan
Who are the Bidikmisi students from UGM who won 1st place in the Science and Technology field?	Student that Status value “Bidikmisi” and Institution value “UGM” and Recognition As value “Winner 1” and Achievement Field some “Saintek”	Mradipta Lintang Alifcanta Moktikanana
Who are the students from UGM with non-competition achievements?	Student that Institution value “UGM” and Recognition As some “Non-Competition”	Alwy Herfian, Gita Indraswari, Meilani Adriyati
Who are the students who participated in student exchange programs in 2025?	Student that Recognition As value “Exchange” and Achievement Year value “2025”	Meilani Adriyati
Which students achieved in the Science and Technology field in 2024?	Student that Achievement Year value “2024” and Achievement Field some “Saintek”	Anas Saifurrahman, Espinal Adrinaldi, Fajrul Falakh, Meilani Adriyati, Vincentius Michael
Which regular students from private universities achieved at the national level in 2025 in the Science and Technology field?	Student that Institution some “Private” and Achievement Level value “National” and Achievement Year value “2025” and Achievement Field some “Saintek”	Espinal Adrinaldi, Fajrul Falakh

Furthermore, the table includes more advanced queries that combine multiple conditions across different dimensions of student data. For example, it is possible to query for students who participated in entrepreneurship programs, students from specific universities who won first place in science and technology fields, or those who engaged in student exchange activities in a particular year. These extended examples showcase the flexibility of the ontology to support complex reasoning and filtering, making it a valuable foundation for developing intelligent academic information systems or decision support tools.

F. Advantages of Ontology vs. Relational Database

Compared to traditional relational database systems, the use of an ontology offers several key advantages in the management and analysis of student achievement data. Firstly, ontologies enable semantic interoperability, allowing data to be shared and integrated across different institutions and systems with consistent meaning. Secondly, ontologies support automated inference, which enables the system to deduce implicit relationships or classifications, such as identifying outstanding achievers or detecting overlapping roles without explicit coding. Thirdly, ontologies facilitate semantic querying, allowing users to retrieve information based on meaning rather than rigid schema-based structures. This semantic richness and reasoning capability are difficult to achieve in standard relational models, especially when handling complex hierarchical or rule-based knowledge.

G. Practical Implications and Transformative Potential

The practical implications of this ontology are significant. It offers a foundational framework for developing intelligent academic information systems that go beyond static data storage. For institutional stakeholders, such as universities and government agencies, this ontology can streamline policy formulation, scholarship targeting, performance tracking, and strategic planning. Enabling structured, dynamic, and rule-aware access to achievement data transforms the way institutions analyze trends, identify talent, and evaluate non-academic contributions. Moreover, the ability to integrate this ontology with external vocabularies or linked data sources could pave the way for national or even global benchmarking of student achievements, aligning local education insights with international standards.

CONCLUSION

This study demonstrates that the development of an ontology for modeling national-level student achievements can effectively support knowledge inference and semantic querying. By conceptualizing key components such as student status, institutional affiliation, achievement category, field, year, and recognition level, the ontology enables structured representation and retrieval of data. The use of Description Logic (DL) queries and rule-based reasoning confirms that the ontology is logically consistent and functionally aligned with the intended competency questions, allowing for accurate data extraction and automated classification of individuals.

The implementation of object property restrictions, data properties, and DL queries in Protégé, combined with the use of dummy data for testing, validates the ontology's capacity to serve as a foundation for Semantic Web applications in the educational domain. Although the data used was simulated, the framework proved capable of producing meaningful inferences and supporting various scenarios related to student achievement tracking.

However, the study also acknowledges certain limitations. The domain scope is still relatively narrow and focused primarily on national-level academic and non-academic achievements. Future work could enhance this ontology by expanding its coverage to broader educational domains, incorporating real-world datasets, and linking it with external ontologies for increased interoperability. Ultimately, this research underscores the transformative potential of semantic technologies in reshaping educational information systems, enabling more intelligent, interoperable, and insight-driven approaches to managing student achievement data.

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