Defining Interoperability: A Universal Standard

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Abstract

Interoperability is a cornerstone of modern scientific and technological progress, enabling seamless data exchange and collaboration across diverse domains such as e-health, logistics, and IT. However, the lack of a unified definition has led to significant fragmentation, with over 117 distinct definitions documented across various fields. This paper addresses the challenge of defining interoperability by tracing its historical evolution from its military origins to its current applications in sectors like healthcare and logistics. This work proposes a novel, universal definition encompassing multiple interoperability dimensions, including technical, semantic, syntactic, legal, and organisational aspects. This comprehensive definition aims to resolve the inconsistencies and gaps in current practices, providing a robust framework for enhancing global collaboration and driving innovation. The proposed definition is evaluated against key criteria such as flexibility, clarity, measurability, scalability, and the establishment of common standards, demonstrating

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its potential to unify efforts across different fields. This work highlights the profound impact a standardised interoperability approach can have on critical areas like healthcare, where streamlined patient data exchange and improved outcomes are urgently needed.

Keywords: Interoperability, standardization, cross-domain.

1 Introduction

Interoperability is vital for modern science and technology, especially in life sciences, where seamless data exchange and collaboration are crucial for innovation and efficiency [1]. Despite its critical importance, interoperability has been a longstanding challenge. Since its inception in the late 20th century [2], the concept has evolved significantly, driven by the increasing complexity of information systems and the need for more sophisticated interactions.

However, this evolution has also led to fragmentation. With over 117 distinct definitions [3] of interoperability documented across various domains, the lack of a unified understanding has created barriers to effective innovation and efficiency. Different industries and application domains, from healthcare to logistics, interpret interoperability in ways that suit their immediate needs, leading to inconsistencies that hamper effective working between users of different definitions [3]. To address the fragmentation caused by divergent definitions, we must first understand the historical evolution of interoperability.

The proposed definition of interoperability is *universal*, designed to be applicable across multiple domains, including healthcare, logistics, IT, and beyond. However, for the purposes of this study, the e-health sector has been chosen as a focal point for the case study. Healthcare serves as a compelling example because it vividly illustrates the profound impact that true interoperability can have on human lives. Achieving seamless interoperability in healthcare directly influences patient outcomes, enhances the efficiency of medical services, and reduces critical errors – demonstrating the real-world necessity of a standardized, cross-domain framework.

Moreover, interoperability in healthcare is uniquely complex due to the diversity of systems, stakeholders, and regulatory requirements. Addressing these challenges requires a clear and purpose-driven definition of interoperability, ensuring that data exchange and collaboration are not hindered by ambiguity. While the healthcare case study exemplifies the importance of interoperability, the proposed definition remains broad and adaptable to other sectors where interoperability is equally critical.

2 History of Interoperability

Interoperability is defined by the US Department of Defense (DoD) in 1977 [2] as:

> *...the ability of systems, units, or forces to provide services to and accept services from other systems, units, or forces and to use the services so exchanged to enable them to operate effectively together.*

This definition addressed critical military challenges. Military communication systems lacked compatibility, hindering joint operations. The concept of interoperability emphasised the need for standardised protocols to ensure seamless technology integration. Since then, interoperability has significantly evolved, both in its numerous definitions and the associated distinct types [2, 3]. By the 1980s, the DoD broadened the concept to include *electronic* and *logistic* interoperability, emphasizing compatible interfaces and components. In the 1990s, definitions widened to include *technical* interoperability, focusing on dynamic information exchange and operational integration.

The Institute of Electrical and Electronics Engineers (IEEE) significantly contributed to this evolution, emphasizing basic information exchange among systems from 1990 onward with the publication of the Standard Computer Dictionary [4]. By 2000, the IEEE's definitions included the ability of equipment to work together in networks, stressing the importance of standards for interoperability. Concurrently, other definitions highlighted the effort required to couple systems (1980, [5]), the quality of information exchange (1987, [6]), and the ability of large-scale distributed systems to exchange services and data (1995, [7]).

In the 2000s, the concept of interoperability evolved from a containerised focus to broader applications, incorporating semantic, structural, and syntactic aspects to address the growing complexity of information systems. The European Interoperability Framework (EIF, [8]) expanded this understanding by emphasizing seamless data, business process, and organizational interactions. Similarly, projects like IDEAS (2005, [9]) highlighted the need for interoperability across data, application, and business process levels in enterprise software.

Commonalities among these definitions include a consistent emphasis on information exchange and utilization, the importance of technical compatibility, and the role of standards. Differences emerge in the specific contexts and domains addressed: the DoD focuses on operational and logistic aspects, IEEE emphasizes technical standards and heterogeneous environments, and other definitions highlight semantic integration and enterprise applications.

While these developments mark significant progress, they also indicate the ongoing challenges in achieving true interoperability. The proliferation of definitions and standards across sectors has led to inconsistencies and gaps in implementation, particularly in complex domains like healthcare. These challenges highlight the urgent need for a comprehensive, unified approach to interoperability.

3 Proposed Definition

The proposed new definition is articulated in two propositions:

Proposition 1: A concise definition

Interoperability is the capacity of diverse systems, units, or components to seamlessly exchange information, services, and data, utilising this exchanged content in a meaningful, effective, and efficient manner.

Proposition 2: An extended definition

Interoperability encompasses several dimensions:

- **Technical interoperability** refers to the ability of diverse systems, networks, and platforms to communicate and exchange information seamlessly. This involves facilitating dynamic, interactive data and service exchanges without the need for translation or middleware, ensuring that systems speak the same language. It includes the integration of blockchain networks, cloud services, and interconnected networks, all of which must operate together efficiently to maintain expected quality levels.
- **Pragmatic interoperability** ensures that the messages exchanged between systems achieve their intended effects and are correctly understood by collaborating systems. This requires systems to be syntactically and semantically aligned and dynamically adaptable to changes in context over time.

- **Semantic interoperability** enables systems to exchange information with a shared understanding of meaning, context, and purpose. It ensures that data, concepts, and knowledge are interpreted consistently across different systems, cultures, and domains. This includes the alignment of conceptual models, the shared understanding of data within ecosystems, and the ability to transfer knowledge across heterogeneous environments.
- **Syntactic interoperability** ensures that data exchanged between systems follows a compatible format, allowing it to be processed and understood without requiring additional transformation. This involves defining clear data structures and formats that facilitate seamless communication between diverse systems – also known as *structural* interoperability.
- **Legal interoperability** ensures effective collaboration across organisations with different legal frameworks. It involves adapting legislation to support cross-border services and establishing clear agreements to address legal differences, promoting flexibility and scalability in diverse legal environments.
- **Organisational interoperability** involves the alignment and integration of business processes, policies, and information exchanges across different entities to meet user needs effectively. It encompasses the ability of enterprises to cooperate with partners, conduct IT-supported business relationships, and align their processes seamlessly, enabling businesses to achieve their objectives automatically and efficiently.
- **Operational interoperability** enables systems, units, or organisations to provide and access services from one another, ensuring effective and coordinated operations. This type of interoperability is crucial in contexts like multinational military coalitions, where diverse forces must work together cohesively in real time.
- **Enterprise interoperability** is the ability of an enterprise – a company or other large organisation – to functionally link activities, such as product design, supply chains, and manufacturing, efficiently and competitively.
- **Constructive interoperability** uses common architecture, standards, data specifications, and communication protocols to build and maintain interoperable systems.
- **Programmatic interoperability** manages the interaction of one program within the context of another, ensuring coherent program management.

- **Electronic interoperability** facilitates the effective and secure exchange of information among devices, systems, and platforms through common interface characteristics. This includes the integration of Internet of Things (IoT) devices, ensuring they can work together within the same ecosystem, and the ability of electronic devices to communicate and control one another seamlessly.
- **Data interoperability** enables the seamless exchange, interpretation, and integration of data across different systems and organisational boundaries. It ensures that data can be merged, aggregated, reused, and processed in meaningful ways, with shared expectations for content, context, and quality. This interoperability is critical for supporting clarity, scalability, and innovation across various domains.

These novel definitions provide a robust foundation for addressing the core challenges of fragmentation, lack of consensus, and limited applicability, offering the scientific community a unified and adaptable framework. By encompassing a wide spectrum of interoperability dimensions – from technical to legal – it aims to resolve inconsistencies and gaps in current practices. For instance, semantic interoperability ensures that exchanged information is interpreted consistently across systems, reducing the misunderstandings that frequently plague current implementations. Additionally, operational and programmatic interoperability facilitate cross-domain collaboration, ensuring that sectors ranging from healthcare to logistics can communicate and operate effectively within a cohesive framework.

Interoperability is a multilayered concept, and distinguishing between different levels is critical for ensuring practical implementation. Three closely related but distinct types of interoperability – organisational, operational, and enterprise interoperability – play key roles in enabling efficient collaboration across systems and institutions. Their relationships can be defined as follows: enterprise interoperability is an internal prerequisite for operational and organisational interoperability (a company cannot effectively interact with partners (organizational interoperability) or external service providers (operational interoperability) if its own internal processes (enterprise interoperability) are fragmented), while it also enables operational interoperability. If organisations cannot agree on policies, standards, or data exchange methods, seamless real-time service exchange at the operational level becomes impossible.

Our proposed unified definition consolidates the most stable and widely accepted types of interoperability, while clarifying and addressing previous misunderstandings [3]. This approach simplifies the interoperability landscape, offering a clear, comprehensive foundation that supports the seamless integration of new technologies and domains, ensuring future advancements can be adopted effectively.

The adoption of these comprehensive definitions could impact multiple fields. In healthcare, a universal understanding of interoperability will streamline patient data exchange, reduce errors and improve outcomes. In logistics, it will enhance coordination between supply chain systems, boosting efficiency and cutting costs. In information technology, it will provide a solid framework for integrating emerging technologies like AI and IoT into existing systems, fostering innovation and ensuring long-term scalability.

4 Methodology

To develop a comprehensive understanding of interoperability, a bibliographic analysis was conducted to identify and evaluate definitions across various domains. This analysis revealed significant heterogeneity in how interoperability is conceptualised [3]. Some types (e.g., technical, semantic, syntactic, legal) have stable, widely accepted definitions, while others (e.g., operational, enterprise) are still evolving. The methodology followed a structured approach based on the maturity and stability of definitions:

1. **Stable dimensions:** definitions for well-established types (e.g., *technical* [1, 10–17], *pragmatic* [13, 17], *semantic* [10, 11, 13, 15–17], *syntactic* [10, 11, 13, 17], *legal* [13, 15, 16], *organisational* [10, 11, 14, 15]) were directly incorporated from widely accepted sources.
2. **Evolving dimensions:** definitions for types still under conceptual development (e.g., *operational* [1, 13, 14], *enterprise* [1, 12, 14]) were synthesised by reconciling differences across sources.
3. **Emerging dimensions:** new definitions were proposed for nascent or poorly defined types (e.g., *constructive* [1, 13], *programmatic* [1, 14], *electronic* [10, 11]), based on current cultural and technological contexts, to provide a foundation for further refinement.
4. **Misunderstood dimensions:** a new definition was proposed for highly misunderstood types, such as *data interoperability*, which suffers from confusion due to the lack of a single, universally accepted definition for both *data* and *interoperability* [18]. The concept of data is often described based on its specific characteristics, contexts, and intended purposes, which leads to varying interpretations. Similarly,

interoperability is frequently defined differently depending on the specific domain, application, and technological constraints.

This process revealed significant gaps in the literature: of the 36 identified types of interoperability, only 8 had well-established and consistently used definitions, while the remaining types were still in early conceptual stages – used inconsistently or vaguely – highlighting a need for greater definitional clarity and scholarly agreement.

To ensure the proposed definition incorporates the latest advancements in interoperability research while maintaining a connection to its historical evolution, this study refers to the most recent tertiary study on interoperability definitions [3]. This approach ensures relevance and applicability in today's technological landscape while examining historically significant definitions. By balancing recent advancements with foundational perspectives, the study ensures that the proposed definition is both forward-looking and grounded in well-established principles.

The sources were selected based on the following criteria:

- **Recency:** priority was given to definitions and frameworks published in the last decade to ensure relevance in modern interoperability challenges.
- **Authority:** highly cited works and definitions from standard-setting bodies (e.g., IEEE, DoD) were emphasised.
- **Cross-domain applicability:** only definitions that apply to multiple sectors were included, ensuring the proposed definition remains universal rather than domain-specific.

The definition developed in this study aims to resolve inconsistencies and ambiguities in existing literature. Key issues addressed include:

- ***Semantic* vs. *syntactic* interoperability:** these types are often conflated: *semantic* interoperability focuses on shared meaning and eliminating ambiguity, while *syntactic* interoperability concerns the structural format of message exchange. The proposed definitions clearly distinguish between the two, reducing confusion.
- **Data interoperability:** this type has been inconsistently defined across contexts, leading to misunderstandings [1, 3, 10–12, 18]. By synthesising various perspectives, a coherent and unified definition was created to clarify the relationship between data and interoperability by emphasizing the need for context-sensitive and purpose-driven approaches, thereby addressing these conceptual ambiguities and fostering clearer communication within the field.

The unified definition was developed by reviewing over *117* existing definitions from various fields [1–3, 10–18]. The taxonomy consolidates stable dimensions and addresses prior misunderstandings, including both technological and socio-technical aspects. Articulated through Proposition 1 (concise definition) and Proposition 2 (extended definition), the unified definition resolves ambiguities and provides a flexible foundation for ongoing research and practical applications. It addresses gaps in existing literature and facilitates the integration of emerging technologies and domains.

5 Results: Evaluation of Interoperability Definitions

In this study, the author evaluates definitions of interoperability on five key criteria:

Flexibility. The definition is adaptable to both future advancements and to different contexts than that in which it was originally proposed.

Clarity and conciseness. The definition uses simple language that is easy to understand.

Measurability. The definition allows for the assessment, benchmarking, and otherwise evaluation of interoperability efforts.

Scalability. The definition is applicable across application scales: from small-scale local applications to very large-scale global applications.

Language and standards. The definition establishes a common language and set of standards that can be universally applied.

These criteria are marked as either present (✓) or absent in Table 1. DoD definitions are clear, measurable, and use common language. The Creps et al. (2008) [19] definition, while clear, concise, and uses common language, is limited to computer systems. The definition proposed by Asuncion and van Sinderen (2010) [20], though flexible and measurable, lacks scalability. The National Interoperability Framework Observatory (NIFO) definition proposed by Kalogirou [21] is flexible and scalable but is difficult to fully comprehend. Finally, the definition proposed here addresses all criteria and so is a suitable universal definition by these criteria.

The following five criteria were prioritised in this study because they address both the practical application and the future-proofing of interoperability definitions across diverse contexts and domains:

1. **Flexibility:** Interoperability is an evolving field, influenced by rapid technological advancements and changing contexts. A flexible definition ensures that it remains relevant and adaptable to future innovations and

Table 1 Evaluation of a representative selection of interoperability definitions

Source	Definition	Criteria				
		Flexibility	Clarity and Consciences	Measurability	Scalability	Languages and Standards
DoD (1977), [2]	The ability of systems, units, or forces to provide services to and accept services from other systems, units, or forces and to use the services so exchanged to enable them to operate effectively together.					✓
DoD (1997), [2]	Technical interoperability: The condition achieved among communications-electronics systems or items of communications-electronics equipment when information or services can be exchanged directly and satisfactorily between them and/or their users. The degree of interoperability should be defined when referring to specific cases.		✓	✓		
Creps et al. (2008), [19]	Semantic interoperability is the ability of computer systems to exchange data with unambiguous, shared meaning. Semantic interoperability is a requirement to enable machine computable logic, inferencing, knowledge discovery, and data federation between information systems.		✓			✓
Asuncion and van Sinderen (2010), [20]	To ensure pragmatic interoperability, message sent by a system causes the effect intended by that system; i.e., the intended effect of the message is understood by the collaborating systems. Pragmatic interoperability can only be achieved if systems are also syntactically and semantically interoperable.	✓		✓		
Asuncion and van Sinderen (2010), [20]	To ensure syntactic interoperability, collaborating systems should have a compatible way of structuring data during exchange; i.e., the manner in which data is codified using a grammar or vocabulary is compatible.		✓			✓

(*Continued*)

Table 1 Continued

Source	Definition	Criteria				
		Flexibility	Clarity and Consciences	Measurability	Scalability	Languages and Standards
NIFO (2019), [21]	Legal interoperability is about ensuring that organisations operating under different legal frameworks, policies and strategies are able to work together. This might require that legislation does not block the establishment of European public services within and between Member States and that there are clear agreements about how to deal with differences in legislation across borders, including the option of putting in place new legislation.	✓			✓	✓
Proposed definition	**Proposition 1 and 2 above**	✓	✓	✓	✓	✓

can be applied across emerging domains and new applications. This forward-looking quality is essential for a definition that can withstand the test of time and continuous development.

2. **Clarity and conciseness:** A definition that is simple and easy to understand is fundamental for fostering a shared understanding of interoperability across various disciplines and stakeholders. Clear and concise language eliminates confusion and ensures that the definition can be effectively communicated to both technical and non-technical audiences, which is crucial for widespread adoption and implementation.
3. **Measurability:** To evaluate the effectiveness of interoperability efforts, a definition must allow for the measurement and assessment of progress. Measurability ensures that interoperability initiatives can be benchmarked, evaluated, and refined over time, providing a framework for continuous improvement and comparison. This is achieved through quantifiable metrics, including:
    - **Response time:** measuring the time taken to exchange and process data between systems.

  - **Data accuracy:** assessing the reliability and consistency of exchanged data.
  - **Error rates:** the frequency of errors occurring during interoperability events.
4. **Scalability:** Interoperability needs to be applicable across different scales, from small-scale, localised systems to large-scale, global applications. This criterion ensures that the definition can support a wide range of use cases, making it practical for diverse real-world scenarios and supporting the integration of systems from small organisations to global networks.
5. **Language and standards:** Establishing a common language and set of standards is essential for interoperability to function seamlessly across systems, sectors, and geographic boundaries. This criterion ensures that the definition supports the development and implementation of consistent terminologies and protocols, which are critical for enabling smooth communication and interaction across diverse systems and organisations.

By addressing all five criteria, the proposed definition in this study offers a robust, universal framework for interoperability, capable of adapting to diverse domains and facilitating meaningful, measurable outcomes. These comprehensive evaluation criteria highlight the potential of the proposed universal definition to streamline interoperability efforts across industries.

6 Case Study: Healthcare Interoperability

The extensive challenge of interoperability is easily illustrated within the healthcare sector, where the intricate nature of data and the heterogeneity of systems have long hindered seamless integration [22, 23]. The healthcare ecosystem encompasses a diverse array of professionals – such as doctors, nurses, and pharmacists – as well as various computing systems and specialised domains, all of which generate and process a wide range of data, including clinical records and laboratory results. The absence of standardised definitions and protocols for data exchange has precipitated significant interoperability issues [24]. For instance, inconsistencies in how electronic health records (EHRs) define “medical records” can result in fragmented data exchanges, severely impacting patient care [25]. Such discrepancies can manifest as incomplete patient histories, diagnostic errors, medication mishaps, inconsistent treatment plans, fragmented care coordination, and flawed data reporting. These issues collectively and systematically undermine the quality of care by depriving healthcare providers of essential, comprehensive information.

While standards such as HL7 [26, 27] and DICOM [28] have been established, they have not resolved the underlying fragmentation, characterised by persistent inconsistencies and divergent interpretations. This fragmentation can lead to critical information being lost or misinterpreted, particularly during transitions of care between providers [29, 30].

The lack of a universal foundation in the form of a definition of interoperability that is *flexible*, *clear and concise*, *measurable*, *scalable*, and *standardised* leads to persistent communication inconsistencies, resulting in inefficiencies and potential risks to patient care. This underscores the urgent need for a comprehensive and universally applicable definition of interoperability.

The proposed definition addresses these challenges by providing a framework for scalability, semantic alignment, and integration across heterogeneous systems. In healthcare, this definition can:

- **Facilitate EHR interoperability:** By aligning with standards such as HL7 [26] and SNOMED CT [27], it ensures accurate and consistent data exchange between diverse systems.
- **Enable patient-centric data sharing:** It supports decentralised, patient-driven models for managing health data, such as blockchain-enabled systems [31, 32].
- **Support federated healthcare models:** By addressing organisational and technical interoperability, it enables real-time data access and privacy compliance in initiatives like JA-InfAct [33].

These applications demonstrate how the new definition directly addresses the complex interoperability challenges within the healthcare sector. For a more comprehensive understanding of the various contexts in which interoperability is applicable, please refer to the Supplementary Material, which provides a detailed history of the term and its evolution, along with additional examples of its applications.

7 Discussion

Interoperability is a multidimensional concept encompassing technical, operational, organisational, and semantic aspects, as highlighted in Proposition 2.

While the proposed definition effectively addresses these core dimensions, it does not explicitly consider social or ethical interoperability. These aspects, which involve aligning societal values, cultural norms, and ethical frameworks, are increasingly relevant, particularly in domains such as healthcare. For instance, ensuring that interoperability frameworks respect patient consent, promote equity, and adhere to ethical standards for data usage is critical for fostering trust and long-term sustainability.

The proposed definition is designed as a universal framework, balancing conciseness and extensibility. Its structure, with Proposition 1 as the core concise definition and Proposition 2 as the extended framework, ensures adaptability to emerging needs and domains. This adaptability allows extensions to incorporate dimensions such as social and ethical interoperability while retaining the integrity of the core definition. By establishing a clear and comprehensive foundation, the proposed definition enables ongoing refinement and ensures its relevance in an evolving technological and societal landscape.

The practical implementation of the proposed definition is essential for its adoption and impact across various industries. To facilitate this, the following steps are recommended:

1. **Adoption of standards:** Aligning with established interoperability standards, such as HL7 [26], SNOMED CT [27], or openEHR [34], ensures consistency in semantic and syntactic data exchange. These standards provide the necessary foundation for seamless communication across heterogeneous systems.
2. **Framework integration:** Operationalising the definition requires leveraging advanced frameworks, including federated architectures and blockchain-enabled systems. These technologies enable interoperability across diverse environments by addressing challenges such as data fragmentation and privacy concerns.
3. **Stakeholder collaboration:** Effective interoperability cannot be achieved in isolation. Collaboration among technical experts, policymakers, and end-users is essential to address technical, organisational, and ethical dimensions comprehensively. Building consensus among stakeholders ensures that solutions are practical and widely accepted.
4. **Training and education:** Building organisational capacity through training and education is crucial for successful implementation. Ensuring that teams understand and can apply interoperability principles empowers organisations to transition from theoretical frameworks to practical solutions effectively.

By addressing these practical steps, the proposed definition can be implemented across diverse industries, transitioning from a theoretical construct to a functional framework with tangible benefits. These measures will not only enhance the technical feasibility of interoperability but also strengthen its relevance and applicability in addressing real-world challenges.

8 Conclusion

A single, universally accepted definition of interoperability is crucial for unifying efforts across diverse domains and improving outcomes in critical areas such as healthcare. To address the challenges posed by fragmented systems, a consistent and comprehensive approach is essential. This chapter proposes a universal definition of interoperability that meets all key criteria, providing a cohesive framework adaptable to various contexts. By standardising efforts, reducing inefficiencies, and fostering global innovation, this definition offers a clear path forward for enhancing collaboration and effectiveness across fields, from healthcare to logistics.

While the full impact of this definition will depend on its adoption and implementation, its potential is significant. By consolidating diverse dimensions of interoperability into a universal framework, it establishes a robust foundation for ongoing research, standardisation, and innovation. This structured approach ensures that the definition can evolve alongside emerging challenges, maintaining its relevance and utility across domains.

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Biography

Giada Lalli received her Bachelor's degree in Clinical Engineering from La Sapienza University of Rome in 2017 and her M.Sc. degree in Biomedical Engineering – Cells, Tissues and Nanotechnologies from Politecnico di Milano in 2019. From 2020 to 2023, she was an Early Stage Researcher within the MSCA ITN TranSYS, funded by the EU Horizon 2020 programme, and obtained her Ph.D. in Biomedical Sciences from KU Leuven in 2024. She is currently a Clinical Researcher at Therapixel, focusing on the application of advanced computational methods to medical imaging and healthcare data. Her research interests include interoperability, computational genomics, machine learning for health data, and personalized medicine. In addition to her research, she is actively engaged in science outreach for diverse audiences, with the aim of making science and research accessible and understandable to all, participating in initiatives such as Skype a Scientist.