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Interoperability

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Abstract: Interoperability describes the ability of systems to share services and resources with other systems. It is used in many fields — in the law, in communications and payments systems, in healthcare systems and in military alliances, to name a few — and describes a large number of characteristics from technical standards, to information architecture, to organisational governance. This glossary entry presents a topology of interoperability layers and presents some of the key economic and socio-technical concerns faced by interoperable systems.

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Definition

Interoperability in socio-technical systems describes the ability of discrete and technically or organisationally heterogeneous systems to share services or resources with other systems. Systems that are fully interoperable are experienced by the relevant group of stakeholders as a single ‘integrated’ system (Cooling & Hixson, 1978) or as a sense of ‘seamlessness’ between systems (Lawson & Herrada, 2022), although this experience can disguise considerable effort on behalf of those who design and maintain these systems. Interoperability can be achieved through particularised work to connect two systems together through the development and adoption of standards that allow an arbitrary number of systems to interface with each other, or through integrative approaches that build generalisable interoperability at the design and implementation of systems themselves.

Origin and scope

The study of interoperability *per se* is highly domain-specific and used in many fields to describe a variety of system characteristics. For example, healthcare interoperability describes the ability of systems to pass patient information between each other (Iroju et al., 2013). Payment system interoperability refers to the ability of diverse payment platforms (such as credit card networks and bank accounts) to interact, thus facilitating transactions across networks (Lawson & Herrada, 2022). Blockchain interoperability refers to the ability for blockchain networks to pass information to each other in a manner that allows (for example) users to experience the movement of 'digital assets' between chains. Although much of the discourse on interoperability across domains tends to focus on the interoperability of communication systems and data, the concept is frequently extended to a broader context. For example, the domain of enterprise interoperability (Archimède & Vallespir, 2017) describes both technical barriers to interoperability but also barriers of meaning and barriers of organisation and coordination. This wider perspective emphasises the sociotechnical structures which influence the interaction between systems.

This broader vision of interoperability is evident in the domain in which interoperability first emerges as a significant concern. The interoperability between military systems was a central focus of allied warfare during the Second World War. For the Allies, the experience of a long-term engagement between multiple allied armies in single theatres of war allowed interoperability to develop as a process of trial and error, with the ultimate goal of integrated operations (Cooling & Hixson, 1978). Contemporary military interoperability describes the capability of military units from different nations to share services and thereby benefit from efficient joint operations, which spans everything from strategic interoperability (such as objective setting processes) to technical interoperability (such as the sharing of equipment standards and communications systems) (Moon et al., 2008; Pernin et al., 2020). Thus, while it should be noted that early discussion around interoperability focused on the interface between computational systems or communications systems (see for example Zakanycz & Betts, 1978; LaVean, 1980), from its earliest conception, interoperability in specific fields has always been concerned with the institutions and infrastructure to allow two systems that might interface for integrated behaviour.

Topology

There exist a number of multilayered models to understand interoperability which variously seek to generalise or particularise approaches to interoperability. For example, Chen's (2017) enterprise interoperability framework distinguishes between interoperability of data (how data is shared and interpreted), of services (how discrete applications interface), of process (how business processes connect), and of business (how decisions, rules, cultures, practices, and legislative and regulatory governance interact). The European Interoperability Framework for e-government services distinguishes between legal, organisational, semantic, and technical interoperability (European Commission, 2017). This entry is motivated by a belief that interoperability should be understood from a generalisable socio-technical and economic lens prior to applying a particular policy or operational lens. Hence this entry first describes a topology of interoperabilities, expanding in scope from technical, syntactic and semantic, and organisational interoperability.

To explore this topology we use as an example the field of interoperability between blockchain networks. Blockchains are distributed databases that use consensus mechanisms to maintain state without the need for a single authority. There are a large number of blockchains, each with usually at least one but in some cases thousands of different digital assets implemented upon them. One prominent goal for blockchain interoperability is to give users of those blockchains the experience of being able to transfer assets from one blockchain to another blockchain (Belchior et al., 2022). Such a problem requires efforts to establish interoperability at all levels, technical, syntactic and semantic, and organisational.

Technical interoperability

Technical interoperability refers to the ability of different technological systems, platforms, or devices to communicate and exchange information. It involves the compatibility of hardware, software, network protocols, and interfaces allowing for the smooth transfer of information between systems. We can understand this as a characteristic of the infrastructure on which interoperable systems are built, whereby technical systems are capable of transmitting data to each other. Technical interoperability in blockchain networks describes the ability of those networks to receive data from another separate blockchain that may otherwise be governed by different consensus algorithms, validated by different nodes or servers, or have different data formats. The ability to receive that data is distinct from the ability to interpret or act upon that data. However, such a technical interoperability is a base requirement for interoperability but using and acting on shared services and resources requires interoperability at higher levels of abstraction. For example, being able to pass data between blockchain networks does not mean that those networks will mutually recognise that data as ‘digital assets’ — for such interoperability to be achieved they need interoperability at the semantic and syntactic level.

Semantic interoperability

Syntactic interoperability deals with the structure and format of data exchanged between systems. It ensures that data conforms to a common syntax or set of rules, facilitating its exchange and processing. This includes standard data formats, encoding schemes, and message protocols to enable interoperability between different systems. Semantic interoperability describes the ability for information to be *understood* — that is, the ability of different systems to understand information accurately and meaningfully, despite variations in their structure, format, or vocabulary across systems (Heiler, 1995). Semantic interoperability focuses on ensuring that data can be interpreted and utilised correctly across systems. It involves the use of standardised and well-defined vocabularies, ontologies, and data models to enable the accurate interpretation, integration, and utilisation of data across diverse domains and applications.

For blockchain interoperability the syntactic and semantic requirements for interoperability require each blockchain to recognise the data they have received as an “asset” which can be represented on the receiving blockchain. An asset on the

Ethereum blockchain is coded as a standardised smart contract (such as an ERC-20). A receiving chain needs to interpret that contract as an asset, recognise that the asset has been locked on the sending blockchain, and mint the asset on its own blockchain according to its own semantic model of asset specifications. Thus while assets are never "sent" from one blockchain to another, the semantic transformation (the locking of a syntactically discrete asset on one chain and the minting of a syntactically discrete asset on another) provides the effect of a transfer.

Organisational interoperability

Organisational interoperability refers to the ability of different organisations or entities to collaborate, share resources, and align their processes and goals (Kubicek & Cimander, 2009). It involves establishing common frameworks, protocols, and practices to enable effective coordination, communication, and cooperation between diverse entities, fostering seamless collaboration and integration. Goldkuhl (2008) notes that organisational interoperability is often used as a catch-all for interoperability requirements that do not fall within other categories, and decomposes the concept further between *axeological* (coordination around values and goals), cognitive (shared organisational reasoning and knowledge), intra-processual (the ability for work processes internal to each organisation to connect), and interactional (structural characteristics that facilitate organisational interactions between systems). The organisational layer is what Palfrey and Gasser (2012, p. 6) call the "human layer", writing that interoperability "often succeeds or fails based on whether we are willing to put effort into working together as human beings". In the case of blockchain interoperability, such organisational interoperability describes a variety of characteristics, such as the ability of blockchain explorers and wallets to represent to users the assets in a manner consistent with the experience of the cross-blockchain transfer, or the experience of interacting with those transferred assets in other smart contract or business systems (such as digital asset exchanges).

Paths to interoperability

Interoperability and governance

Not all approaches to achieving interoperability are uniform. ISO 14258 describes three approaches to achieve interoperability: discrete connections between systems (*federated*), shared standards between otherwise heterogeneous systems (*unified*), or harmonisation from the ground up (*integrated*), emphasising the distinct governance of paths to interoperability (Chen, 2017; Fernandes et al., 2020).

Federated interoperability refers to a distributed and decentralised approach to achieving interoperability. In this mode, individual systems or components maintain their autonomy while establishing communication channels and protocols to enable data exchange and collaboration. Each system retains its own decision-making capability — a form of system sovereignty. Federated interoperability allows for a loosely coupled integration where different systems can interact and share information while maintaining their independence. It provides flexibility and scalability as new systems can join or leave without affecting the overall integration. However, it may introduce complexities in managing coordination and ensuring consistency across interoperability systems, as well as high costs relative to other modes as heterogeneous links between systems may have to be developed in a federated approach (Fernandes et al., 2020). One open question for researchers is how autonomous systems — such as those underpinned by machine learning and artificial intelligence — might be able to implement such "on the fly" interoperability where other modes of coordination have so far failed.

Unified interoperability, on the other hand, aims to coordinate heterogeneous systems. It involves establishing a common data model, a shared infrastructure, and standardised processes. Typically referred to as the process of 'standardisation', unified interoperability focuses on achieving seamlessness by adopting shared protocols or rule-sets that can be adopted by existing and future market participants to achieve interoperability. However, it may require significant effort in standardisation and coordination among diverse systems and it may be less flexible in accommodating new systems or changes in requirements.

The integrated model of interoperability moves towards the integration of systems, rather than the forging connections between systems. Integrated models are a form of "bottom-up" interoperability, where systems follow patterns and standards that are consistent and harmonised. As Chen (2017) notes, this makes integration more appropriate for systems that are built from scratch with interoperability at the foundation. While the integrated approach to interoperability shares common institutions and infrastructure, this does not imply that they are integrated systems — each system retains the technical or organisational decentralisation that is characterised by independent systems (Weichhart & Wachholder, 2014).

Interoperability and policy

As this might suggest, the integrated approach to interoperability favours systems whereby a single coordinator can set the terms of the integration for all interoperable systems. A dominant market participant can impose interoperability across an industry or sector. This was evident from the earliest instances: American dominance over arms production in the Second World War meant that it set implicit standards across technical, semantic, syntactic, and organisational interoperability (Cooling & Hixson, 1978). Market dominance often determines approaches to interoperability as competitors seek to take advantage of the lead firm's network effects (Kieller, 2011). The dominance of Microsoft Windows in the operating system market, even in the context of a significant alternative provided by Apple, has meant that Microsoft was able to achieve interpretability around (for example) device drivers and file types.

The desirability of interoperability commonly leads to the evolution of standards, whereby market participants coordinate to develop shared agreements about technical and other characteristics (Farrell & Saloner, 1985; Kindleberger, 1983; Tassey, 2000). Standards and interoperability are not synonyms — interoperability can exist without standards (such as the "on the fly" approaches to interoperability common in federated modes), and standards can exist to serve purposes other than interoperability (such as minimum quality standards). Nonetheless, interoperability is frequently brought about by the development and adoption of standards. Standards can evolve from the disparate coordination of economic participants, industry associations, quasi-governmental bodies (such as the US's National Bureau of Standards), government regulators, and international coordination agencies (such as the International Standards Organization). Often interoperability standards are developed by industry participants and shift into regulatory or legal requirements as they are formalised. In the blockchain industry, for example, standards can be brought about through decentralised governance (such as Ethereum's ERC-20 token standard) or through a competitive landscape where standards compete within and between ecosystems (such as the Cosmos ecosystem's interblockchain communications protocol (Goes, 2020), Polkadot's cross-consensus message format (Burdges et al., 2020), or Chainlink's cross-chain interoperability protocol), or through standards organisations (such as the IEEE Standard for Blockchain Interoperability Data Authentication and Communication Protocol IEEE 3205-2023).

Interoperability standards are increasingly seen by competition regulators as a vehicle to reduce market dominance (Brown, 2020), and interoperability is increasingly being seen by competition law scholars through the lenses of vertical and horizontal competition dynamics (see for example Bourreau & Kraemer, 2022). The European Union's Digital Markets Act requires, for example, that end-to-end encrypted messaging applications provided by large firms in digital markets implement interoperability such that users of different services can communicate with each other while maintaining end-to-end encryption (Len, 2023). Similarly, the European common charger directive, a regulatory decision of the European Council, requires electronic devices such as mobile phones and tablets use a USB-C port for charging (Council of the European Union, 2022). Such rules potentially demonstrate, however, some of the difficulties of imposing interoperability through mandatory rule-making; critics have suggested that the common charger requirement could hamper innovation in the use of charging ports by freezing the technological status quo at the moment of regulatory rulemaking (Innocenti, 2022; Tassey, 2000). At the same time, interoperability can raise other competition policy concerns by facilitating ecosystem lock in or creating data privacy risks (Palfrey & Gasser, 2012).

Conclusion

Interoperability allows heterogeneous systems to interact and exchange — it is a binding agent for independent and semi-independent complex systems that may have diverse origins, goals, and designs. In that sense, as Palfrey and Gasser (2012) write, many of our biggest problems from healthcare information provision to clean energy transportation are fundamentally problems that need to be solved by better understanding how diverse systems can work together — how they can coordinate. However, achieving interoperability at each of the levels described above requires its own complex coordination processes. Market forces can push systems towards interoperability — where system designers or controllers identify gains that they might capture by doing so — or can prevent interoperability from being established where those same controllers might identify monopoly or quasi-monopoly benefits from preventing competitors from accessing their system (or, perhaps more saliently, the users of their system). Regulatory approaches can require interoperability in the pursuit of competition or equity goals but at the same time risk locking in particular technologies or practices in a way that might reduce technological innovation.

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