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RESEARCH

Relational Information Towards a New *Kind* of Information in Quantum Mechanics

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Abstract

This paper argues that von Neumann entropy plays two conceptually distinct roles in quantum theory. When applied to global mixed states, it expresses the quantum analogue of the informational entropy. But when applied to reduced states of entangled systems, it measures objective physical correlations. We propose that this second usage realizes a new informational *kind*, which we call *relational information*. Unlike information in communication theory, it reflects structural interdependence between systems, not probability about a certain outcome. We further suggest that this informational *kind* has ontological significance: relational information is a physically instantiated feature of entangled systems, and not merely an agent-relative concept.

Keywords Relational information · Quantum entanglement · Information theory · Quantum foundations · Philosophy of physics

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1 Introduction

The concept of information has become increasingly central in contemporary physics, appearing in contexts as diverse as thermodynamics, quantum mechanics, and black hole physics. Yet, despite its widespread use, the term often lacks conceptual clarity. In particular, it is not always evident whether "information" refers to something epistemic—linked to what an observer can infer through a communication channel—or to something physical—part of the fabric of the world itself. This ambiguity is especially pressing in quantum mechanics, where information is routinely associated with quantities such as von Neumann entropy, quantum correlations, and entanglement.

The standard framework for understanding information in physics derives from [39]'s mathematical theory of communication. In this setting, information is treated quantitatively: the theory measures the generation and reproduction of messages, chosen from a probabilistic ensemble, along with the resources required for their transmission. Crucially, Shannon information presupposes two agents (a source and a receiver) and a message that is to be reproduced. This interpretation aligns well with classical systems and communication scenarios, in which states encode pre-existing properties and receivers decode them. However, we contend that quantum theory challenges this classical paradigm. In particular, the behavior of von Neumann entropy—a quantum analogue of Shannon entropy [38]—reveals a tension. When applied to a global mixed state, von Neumann entropy behaves much like Shannon's: it characterizes the information source and can be exploited to optimize quantum informational protocols. By contrast, when applied to the reduced density matrix of a subsystem—an improper mixture obtained by tracing out the rest of a larger composite system—the very same function acquires a different meaning. Adopting the pluralist account of information advocated by [14], we examine the difference in physical status between global states and reduced states. Our proposal is to articulate this physical distinction in informational terms: the two standard uses of von Neumann entropy correspond to two conceptually distinct kinds of information. Hence, when applied to a reduced subsystem of an entangled state, the very same function, the von Neumann entropy, acquires a different meaning: it quantifies the strength of quantum correlations that cannot be attributed to either subsystem alone. These correlations are not reducible to ignorance [47] or communication, and while they may be accessed differently by different observers, the relational structure they instantiate is the same for all observers who are part of the entangled system. This suggests that the concept of information in quantum physics may not be unified. Rather, it may bifurcate into (at least) two conceptually distinct *kinds*: an epistemic one, grounded in communication (as in the classical case), and a structural one, grounded in physical interdependence (fully quantum). We refer to this novel informational kind as *relational information*.

Our goal is not merely terminological. By clarifying the nature of relational information, we aim to address a latent conceptual tension in the foundations of quantum theory and in the broader use of information in physics [22, 32, 48]. The central thesis is that information, as it appears in physical theory, is not always reducible to ignorance [47] or communication. Some forms of information are ontological: they pertain not to what agents know or transmit, but to how physical systems are

related. Entanglement provides a paradigmatic case of this kind of information, and its recognition invites a broader rethinking of the role of information in the ontology of physics. Furthermore, by distinguishing between kinds of information, we aim to clarify the ambiguity surrounding the notion of information, thereby contributing to the ongoing debate on its nature in physics. For these reasons, our proposal identifies two functionally distinct informational roles within a pluralist framework—echoing the spirit of [23].

The structure of the paper is as follows. In §2, we examine the conceptual foundations of classical information theory, as developed by Shannon, and clarify how information can be understood in two complementary ways: as a property associated with the source and as an abstract entity—the message produced by a source. In §3, we introduce von Neumann entropy as the quantum analogue of Shannon entropy and discuss its formal properties and physical significance within quantum theory. Section §4 analyzes two distinct uses of von Neumann entropy in quantum mechanics: first, as a measure that characterizes a source in a communication channel when applied to global states; and second, as a measure of quantum correlations when applied to subsystems. In §5, we introduce an abstract definition of relational information as a new informational kind. Finally, §6 offers our conclusions.

2 State of the Art in Information Theory

Information theory, as founded by [39], provides a mathematical framework for analyzing communication systems. In Shannon's model, three key components define the structure of communication: a transmitter, a channel, and a receiver. Crucially, the theory abstracts away from the semantic content of messages: information is quantified not by meaning on the basis of its content, but by statistical structure. In this section, we analyze one of the most prominent views on the interpretation of information theory, developed in various works by [43–45] and [26], but also endorsed by [11]. This perspective has had a significant impact on foundational studies of information, particularly among those interested in interpreting communication theory directly in terms of Shannon's original formulation, without invoking additional metaphysical commitments or alternative interpretative frameworks.[1]

The formal framework presented by Timpson has its roots in the type/token metaphysical distinction introduced by [30].[2] According to this distinction types are abstract and unique entities, while tokens are concrete particulars—that is, occurrences of types.

Timpson generalizes this distinction and applies it to Shannon's theory, thereby articulating what has come to be known as the deflationary account of information.

[1] We regard Timpson's formal framework as an outstanding contribution to the foundations of information theory, providing one of the clearest analyses of the Shannon notion of information. It remains a key reference in foundational debates, and our use of it here is strategic rather than wholesale: we draw on it to highlight what is conceptually novel in the quantum case, without endorsing every aspect of the associated deflationary account.

[2] For a more complete analysis, see [50]; here we only sketch the basic concepts necessary to understand Timpson's framework.

He distinguishes between *piece of information*. The type to be transmitted, and the actual physical instantiations of the message —e.g., sound waves, electrical signals— which can be regarded as tokens of the informational type.[3]

With the type/token distinction in mind, it is possible to obtain an interpretation of Shannon's theorems and an interpretation of the communication mathematical formalism. For instance, take the Noiseless-Channel Coding Theorem[4]:

(S_1) Noiseless-Channel Coding Theorem: Let X be a discrete random variable with probability distribution $p(x_i)$. Then the *Shannon entropy*

$$H(X) = -\sum_i p(x_i) \log p(x_i) \ , \tag{1}$$

gives a lower bound on the average length L of any lossless encoding of the output of the source.[5] Thus, the entropy quantifies the minimum average number of bits required to encode messages emitted by the source.

In Timpson's interpretation, the source is conceived as a physical system that probabilistically generates tokens of informational types, where the probability distribution over these types determines the Shannon entropy of the source. Moreover, the entropy is a feature of the source: it represents the amount of information, quantifying the minimal average capacity required to transmit the messages it produces. This is because the statistical structure of the source can be exploited to compress the output, thereby reducing the resources needed for transmission.[6] Overall, in Timpson's perspective, Shannon entropy does not measure information itself, but rather a structural property of the source.If, in Timpson's framework, Shannon entropy does not measure information itself but rather a structural property of the source then a natural question arises: what, in this view, actually counts as information? Timpson's answer draws on the type/token distinction and introduces a second, complementary notion: what he calls a piece of information.

> [A Piece of information] is what is produced by an information source that is required to be reproducible at destination if the transmission is to be counted a success. [43, p.22]

[3] For the sake of exposition, consider the example of someone using a telephone: the message represents the type, while the sound waves produced by the speaker's voice are the tokens used to carry that type. In practice, the process is more complex, involving multiple layers of token substitution—digital signals, electromagnetic waves, and so on. However, for the purposes of this discussion, we restrict ourselves to a single physical token as the concrete instantiation of the informational type. In Timpson's terms, the type is the message itself, while the tokens are its physical realisations. Distinct again is the amount of information associated with the source: a quantitative measure, given by Shannon entropy, of the compressibility of its outputs.

[4] For an analysis of the theorem see [8, ch. 5].

[5] More precisely, for any prefix-free binary code, $H(X) \leq L < H(X) + 1$, where $L = \sum_i p(x_i)\ell(x_i)$, and $\ell(x_i)$ is the length of the codeword assigned to symbol x_i.

[6] By way of analogy, one might think of radio transmission, where a continuous variation of frequency carries the information of the message; similarly, in Shannon's framework, variations in code length reflect the probabilities of the signals.

This concept captures the idea of information as a reproducible content—that is, a type produced by the source and required to be reconstructed at the destination for communication to count as successful. In this light, Timpson's account draws a crucial distinction: Shannon entropy measures the *amount of information*, reflecting the statistical structure of the source, while the *piece of information* refers to the reproducible type generated by the source and expected at the destination. This distinction helps clarify the conceptual terrain, especially given that Shannon's formalism remains silent about the physical nature of the communication system. Whether a transmission counts as successful depends not on abstract quantities alone, but on whether a token of the same informational type can be reconstructed at the destination. Although Timpson and many others, such as [11], characterize this as the goal of communication, namely the reproduction at the destination of a token of the same type produced by the source. Indeed, as Duwell notes,

> The most natural way to think about success internal to the Shannon theory is to have a one–one mapping from the set of symbols that characterize the source to the set of symbols that characterize the destination. [11, p.200]

However, this characterization captures only part of the picture and adequately represents communication only in the idealized case of a perfectly noiseless channel.[7] Accordingly to Timpson information transfers are the establishment of a structural correlation between system components, and identifies informational success with the receiver's ability to reproduce the intended type. Under this view, it is not the entropy that constitutes the information, but the abstract type instantiated by the source and transmitted through physical tokens.

Timpson's interpretation of Shannon's framework culminates in a stronger ontological claim: information is not a physical object, but an abstract entity defined independently of the concrete tokens used to transmit it. Information is not a physical object transmitted through the channel. It is an abstract entity, whose identity is independent of the specific physical tokens (e.g. , sound waves, electrical signals) used to instantiate it. The communication system does not transmit the type itself, but rather physical tokens from which the receiver may infer and reproduce the type. Mutual information thus measures the statistical success of this token-based reconstruction of an invariant abstract structure. Mutual information does not measure how much of a "substance" called information has passed through the channel, but rather how well the receiver can recover the type generated at the source, using the correlations made available by the physical process of transmission.

To support this claim, Timpson appeals to the second major result of Shannon's theory, i.e. the Noisy-Channel Coding Theorem:

(S_2) Noisy-Channel Coding Theorem: Let X be a random variable representing the input of a discrete *memoryless* channel, and let Y be the corresponding output variable. Then, for any rate $R < I(X;Y)$, where $I(X; Y)$ is the mutual information between X and Y, there exists a coding scheme such that the probability of decoding

[7] When noisy channels are taken into account, physics and engineering typically adopt a more nuanced view of what successful communication involves.

error can be made arbitrarily small as the block length tends to infinity. Conversely, for any $R > I(X;Y)$, reliable communication is not possible.

This formulation highlights the role of mutual information as a capacity threshold: it is the maximum rate of reliable transmission through the channel, even in the presence of noise.On this basis, Timpson draws a crucial interpretive conclusion: even when the communication process is affected by noise, so that the received signal may differ from the transmitted one, the notion of a piece of information, or informational type, remains unique.[8] That is, communication is successful to the extent that the receiver can reconstruct the same abstract type originally generated by the source. The mutual information $I(X; Y)$ quantifies the degree to which this reconstruction is possible on average, but what is being reconstructed is always the same kind of entity: an abstract type, a piece of information. Hence, gives rise to three distinct but interrelated aspects of information:

(i) *Amount of information* that is quantified by Shannon entropy $H(X)$, and it measures the statistical structure of the source and reflects how compressible its output is. This is a property of the ensemble of possible tokens and not of any specific message.
(ii) *Tokens* that are the physical carriers used to instantiate and transmit the type across the channel. Communication succeeds when the receiver reconstructs a token of the same type as that produced by the source.
(iii) *Piece of information* that is the information-qua-type produced by the source and intended to be reproduced at the destination. It is an abstract entity, defined independently of any particular token.

From a different perspective, a communication system can be understood to be not analogous to the flow of physical objects. The source does not generate information about types—it generates the types themselves. What passes through the channel are tokens, not types. It is therefore a mistake to treat the amount of information as a quantity of some material substance. Information, as Timpson emphasizes, is an abstract noun: not a physical quantity that flows like energy or heat, but a structural property of the source that reflects how compressible its output is. When we speak of a "flow of information," we are referring to something quite different from the everyday sense of information as shared knowledge. In Shannon's theory, what flows are tokens that allow the reproduction of a type—nothing more. Indeed, as Timpson emphasizes:

[8] This step is conceptually delicate. In many realistic communication scenarios, the goal of communication is not the reproduction of a token of the same type, but rather the successful identification at the destination of the state produced at the source, even when the states of source and destination are physically very different and cannot straightforwardly be conceived as tokens of the same type. This is particularly evident in noisy channels, where there need not be a one-to-one mapping between the set of source states and the set of receiver states. Timpson's framework does not explicitly accommodate this possibility, as it preserves the uniqueness of the informational type even in the presence of noise. This idea is controversial when the deflationary account is applied to telecommunication engineering; for a detailed analysis, see pp. 13–14 of [23].

> Forcing one set of concepts to walk in shoes that don't fit, as they were designed for other feet, gives rise to strangely shaped bunions: the postulation of odd ontology. [43, p.36]

Timpson's point underscores a broader lesson: information, in the Shannon framework, is not something that is physically transported or possessed. It is a relation between types and tokens within a statistical structure. Recognizing this helps prevent ontological confusion and sets the stage for our next step: the role of information in quantum theory.

3 A (New) Concept in Information Theory: von Neumann Entropy

We have seen that Shannon's information theory is largely silent on the nature of information.[9] By drawing on the interpretation developed by [43], it can be understood as an abstract entity carried by different tokens through a channel of communication.[10] In this section, following Timpson we extend the deflationary account to quantum information theory (§3.1). We also provide a brief analysis of the concept of entropy in the context of quantum mechanics (§3.2), where the same quantity has two distinct uses, unlike Shannon entropy, whose meaning varies depending on the interpretation and context applied to Shannon's original framework.[11]

3.1 Quantum Information Theory in a Nutshell

Quantum information theory lies at the intersection of quantum physics and communication theory. The advent of quantum mechanics raises new doubts about the ontology of information, since the peculiar features of its formalism appear to provide fresh insights into the nature of information. In what follows, we adopt the type/token framework developed by Timpson as a conceptual tool for interpreting quantum information theory in continuity with Shannon's classical account. While several other approaches have been proposed—such as those by [22, 32, 51], and [20]—we focus here on Timpson's deflationary account, which seeks to understand quantum information within the same structural framework as classical communication theory.

Schumacher [38] introduced quantum information as an extension of Shannon's framework, incorporating new elements of communication such as the qubit, novel protocols, and the notion of a quantum source. In classical communication theory, bits are the basic units used to characterize the quantity of information produced by a source and reproduced at a destination. By contrast, qubits are the basic units of

[9] In other words, Shannon's framework was never intended to provide a metaphysics of information, but only a formal calculus for quantifying its transmission under well-defined physical and probabilistic conditions.

[10] The same conclusion is now widely accepted by several authors [10, 11, 24, 25], both with and without Timpson's deflationary account.

[11] For a classic discussion of this point, see [42]. Timpson argues that the Shannon information, properly understood, remains conceptually adequate in quantum contexts and that its interpretative variability does not reflect any intrinsic ambiguity in the definition of entropy itself.

quantum information theory introduced, for instance, by the *Quantum Noiseless Coding Theorem*, which is the quantum analogue of the classical source coding theorem.

(Q_1) **Quantum Noiseless Coding Theorem** [38]**:** Let a quantum source emit pure states $|\psi_i\rangle$ with probabilities p_i , and let $\rho = \sum_i p_i |\psi_i\rangle\langle\psi_i|$ be the average density matrix. Then, for large *n*, it is possible to faithfully compress the quantum information from *n* emissions of the source into approximately *n* $S(\rho)$ qubits, where $S(\rho)$ is the von Neumann entropy of the source. This is asymptotically optimal: fewer than *n* $S(\rho)$ qubits will not suffice to reconstruct the original states with high fidelity.

This result introduces the qubit as the basic unit of quantum information, analogous to the classical bit, but defined within the richer mathematical structure of Hilbert space, where quantum superposition plays a central role:

> Two possible states for a qubit are the states $|0\rangle$ and $|1\rangle$, which as you might guess correspond to the states 0 and 1 for a classical bit. [...] The difference between bits and qubits is that a qubit can be in a state other than $|0\rangle$ or $|1\rangle$. It is also possible to form linear combinations of states, often called superpositions [29, p.13]:
>
> $$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle. \tag{2}$$

This marks a possible first important difference between classical and quantum information theory. At first sight, a qubit appears to be able to store more information than a classical bit, since it can be prepared in infinitely many distinct states.[12] In practice, however, these states cannot all be distinguished from one another. An important conceptual distinction hence emerges in quantum information theory: the difference between specification information and accessible information. The former refers to the amount of information needed to fully specify the quantum state of a system, while the latter captures the amount of information that can actually be extracted or encoded through measurement. In classical systems, these two quantities coincide—what can be specified can also be accessed. In quantum systems, however, they diverge: although a quantum state may require a large amount of information to be fully specified, only a limited portion of that information is operationally accessible. For a qubit in an unknown state, for instance, the specification information requires two continuous parameters to be defined, whereas the accessible information is limited to a single bit, just as in the classical context. This distinction highlights a broader theme: while quantum systems may seem to encode "more" information, the accessible content is in fact bounded as in classical information theory. According to the Holevo bound [18], the amount of accessible information that can be extracted from an ensemble of quantum states through measurement is limited by $\chi \leq S(\rho)$, where $S(\rho)$ is the von Neumann entropy of the ensemble. This bound ensures that quantum systems, despite their richer state space, cannot yield more information than

[12] Here α and β are complex amplitudes subject to the normalization condition $|\alpha|^2 + |\beta|^2 = 1$. Up to a global phase, this leaves two real parameters.

allowed by classical communication capacities. As a result, quantum systems can still be analyzed as communication systems within the framework of Shannon's theory.

These conceptual distinctions naturally lead to the introduction of the quantum analogue of Shannon entropy: the von Neumann entropy [49]. For a quantum system described by a density matrix ρ, the entropy is defined as

$$S(\rho) = -\mathrm{tr}(\rho \ln \rho). \tag{3}$$

Here, ρ is a positive semi-definite, Hermitian operator with unit trace, known as the density operator. This definition extends the classical notion of Shannon entropy by replacing classical probability distributions with the spectral properties of ρ. To make this analogy explicit, one can consider the spectral decomposition of the density matrix. Since ρ is Hermitian, it can be diagonalized in an orthonormal basis, so there exists a unitary transformation that brings it to the form

$$\rho = \sum_i \lambda_i |\psi_i\rangle\langle\psi_i|, \tag{4}$$

where λ_i are the eigenvalues of ρ and $|\psi_i\rangle$ are the corresponding eigenvectors. Because ρ is a density matrix, its eigenvalues satisfy $\lambda_i \geq 0$ and $\sum_i \lambda_i = 1$, meaning that they behave mathematically like a probability distribution. Using this decomposition, the von Neumann entropy simplifies to $S(\rho) = -\sum_i \lambda_i \ln \lambda_i$. This expression makes the analogy with Shannon entropy explicit: the eigenvalues of ρ play the role of probabilities in a classical probability distribution. If ρ is diagonal in a fixed basis, meaning that it represents a statistical mixture of orthogonal quantum states without coherences, then its entropy reduces exactly to the Shannon entropy of its eigenvalues. However, in general, ρ can have off-diagonal elements in certain bases, capturing quantum coherence, which has no direct classical analogue.

As in the classical case, Timpson interprets this quantity as capturing the statistical structure of the source—now a quantum source—and as measuring the degree to which its output can be compressed. In this sense, the von Neumann entropy functions as the measure of *amount of quantum information*. However, this quantity is structurally analogous to its classical counterpart: it plays the same conceptual role in quantum information theory that Shannon entropy plays in classical communication. What changes is not the conceptual structure of the measure, but the underlying mathematical framework: instead of probability distributions over classical states, quantum sources are described by density operators over Hilbert spaces. For this reason, the account offered by [43, 46] also fits well in describing von Neumann entropy as characterizing the statistical structure of a quantum source.

Yet to understand what is distinctive about quantum information, we need to look more closely at the nature of quantum sources themselves. The structure of a quantum communication system is almost the same as in Shannon's theory, consisting of a source, a message, and a destination. But in 1995, Schumacher distinguished two kinds of sources in quantum communication theory. The first is a quantum source that produces a sequence of systems in pure states. In Timpson's framework, these outputs may be regarded as *pieces of quantum information*: they represent the infor-

mation produced by the source, that is, the sequence of types it generates. Of course, such a sequence differs from the one produced by a classical source, since it is represented by Hilbert space states. Nevertheless, following the ideas developed in the classical context by [43], the same notion can be applied here.

> Just as before, what will be required for a successful transmission to be effected is that another token of this type be reproduced, or reproducible, at the desired destination.

As in the classical case, communication channels involving a quantum source transmit tokens that instantiate the types generated by the source. Consequently, the outputs of quantum sources also conform to the definition of information proposed in the classical setting.

The second type of quantum source, as identified by Schumacher, emerges when a distinctly quantum-mechanical feature is considered: entanglement. In this case, the source produces as its output a particular mixed state ρ. In this case as well, the pieces of quantum information can be represented as sequences of Hilbert space states, which may consist either of individual pure states or of reduced states of entangled systems. However, in this case, transmitting a token of the local state is no longer sufficient to preserve the full informational structure. Because the output is entangled with other, possibly inaccessible, systems, the information it carries depends crucially on these non-local correlations—quantified, for instance, by entanglement entropy. Consequently, the source's informational output must be supplemented by the corresponding states of the entangled systems, in order to reproduce not merely a local token, but the full type instantiated by the global entangled structure.

According to Timpson, these pieces of information are analogous to those produced by a classical source: in both cases, they are what is generated by the respective information sources and can be analyzed in terms of sequences of types. In [43]'s words:

> both fall under the general definition of [pieces of information]

In his view, these pieces of information are not physical objects but abstract types, defined by their reproducibility at the destination and independent of the specific physical systems used to instantiate them. This conceptual continuity reinforces, for Timpson, the applicability of the type/token framework even in the presence of genuinely quantum features such as entanglement.

However, it is important to clarify that the quantum type should not be identified with the quantum state of the system—whether pure, mixed, or entangled. Rather, the type corresponds to the abstract informational message that the source intends to transmit and that must be successfully reproduced at the destination. The quantum state may serve as a token of this type, but it need not be preserved or reconstructed in its exact form. What matters, in Timpson's framework, is not the state itself, but the ability to establish a reliable correlation between sender and receiver by reproducing the intended message. In this way, the type/token framework can accommodate genu-

inely quantum phenomena, such as entanglement, without requiring that the quantum state itself be re-identified at the end of the communication channel.

Overall, from Timpson's perspective, despite the structural differences between classical and quantum information theory—such as the qubit/bit distinction, the nature of the sources, and the criteria for successful transmission[13]—both still fall within the same framework. This further supports the deflationary account: information, whether classical or quantum, consists of abstract types, differing from their tokens. Moreover, this view aligns with the idea that Shannon's theory is not tied to any particular physical substrate, but provides a general framework applicable to any underlying physical theory:

> The Shannon theory can be applied to any communication system, regardless of whether its parts are best described by classical mechanics, classical electrodynamics, quantum theory, or any other physical theory. [10, p.480]

Let us conclude this section by noting that Timpson's analysis is not the only possible account. For instance, an alternative perspective is offered by [9], which raises important questions concerning the nature of entanglement and, more fundamentally, the nature of information itself. Their proposal suggests that, even in the presence of entanglement, the global state of the system can be fully determined by the states of its subsystems together with suitable hidden variables. In this view, entanglement does not entail ontological non-separability: local operations remain strictly local, and any apparent non-local correlations are accounted for by the underlying hidden variables. Although we broadly agree with the analysis offered by [43], we hold that the position advanced by these authors may lead to a conception of information as a local property—but only at the cost of departing from orthodox quantum mechanics.[14] We do not endorse the proposal advanced by [9], which appeals to hidden variables and departs significantly from standard quantum mechanics. However, we believe it highlights a crucial intuition: quantum mechanics may involve forms of information that go beyond what is captured by classical communication theory. Even within the orthodox formalism, as we shall argue in the next section, certain aspects of quantum information—such as entanglement—seem to require an informational structure not reducible to Shannon's framework. This, in turn, calls for a cautious re-examination of Timpson's deflationary account. Following the route proposed by [23], we aim to show that the distinction at play in quantum mechanics is already anticipated in some naive sense by [40], who explicitly endorses a pluralist understanding of information.

> The word "information" has been given many different meanings by various writers in the general field of information theory. It is likely that at least a number of these will prove sufficiently useful in certain applications to deserve fur-

[13] In quantum communication theory, success is defined as the ability to reproduce a sequence of tokens corresponding to a given type, typically represented as a string of Hilbert space states.

[14] Such departures typically require hidden variable theories, which face well-known empirical and conceptual difficulties, including the violation of Bell inequalities, contextuality constraints, and challenges in reconciling locality with the statistical predictions of quantum theory. For a critical discussion, see [1, 17].

> ther study and permanent recognition. It is hardly to be expected that a single concept of information would satisfactorily account for the numerous possible applications of this general field. [40, p.105]

Taking seriously Shannon's own remarks, we argue in Section 4.2 that it is possible to recognize at least two different kinds of quantum information, rather than a single unified notion. Although this move goes beyond Timpson's original proposal, it does not amount to a merely terminological revision. Rather, it constitutes a decisive step toward clarifying a structural feature of quantum theory, namely the relational properties instantiated by entanglement. What we contest in Timpson's account is not the usefulness of the type/token distinction itself, but the idea that a single informational distinction exhausts all legitimate uses of the notion of information in physics. Our proposal is deliberately modest. We do not claim that different quantum states correspond to different informational kinds, nor do we advance a state-based ontology of information. Instead, as we will be argued in Section 4 the distinction concerns the informational role played by von Neumann entropy depending on the context in which it is applied.

3.2 A Brief Account of von Neumann Entropy in Non Relativistic Quantum Mechanics

The von Neumann entropy, as we have seen in the previous section, quantifies the amount of information associated with a source. In quantum mechanics, however, this quantity has two applications, and the aim of this section is to provide a brief explanation of its uses. First, the von Neumann entropy serves as a measure of the distinction between pure and mixed quantum states [37]. A quantum state is pure if it can be written as a projection onto a single vector, that is, if its density matrix is of the form

$$\rho = |\psi\rangle\langle\psi|. \tag{5}$$

In this case, ρ has only one nonzero eigenvalue, namely $\lambda_1 = 1$, while all others are zero. Substituting into the entropy formula, we find $S(\rho) = -(1 \ln 1 + 0 \ln 0) = 0$. Thus, pure states always have zero entropy, reflecting the fact that they carry no uncertainty: the system is in a definite quantum state, and there is no statistical mixture. In contrast, mixed states arise when the system is in a probabilistic combination of different quantum states. A maximally mixed state, such as the completely depolarized state in a d-dimensional Hilbert space,

$$\rho = \frac{I}{d}, \tag{6}$$

has eigenvalues $\lambda_i = \frac{1}{d}$ for all i, leading to an entropy $S(\rho) = -\sum_{i=1}^{d} \frac{1}{d} \ln \frac{1}{d} = \ln d$. This is the maximum possible entropy for a system of dimension d, indicating maximal uncertainty about the state of the system. The von Neumann entropy thus provides a natural way to quantify the degree of mixedness of a quantum state: pure

states have zero entropy, indicating maximal knowledge (or minimal uncertainty) about the system's state, while completely mixed states have maximal entropy, reflecting maximal uncertainty. This mirrors the formal role of Shannon entropy in classical information theory, where entropy quantifies the average uncertainty of a random variable. However, while Shannon entropy pertains to probability distributions over classical states, von Neumann entropy applies to density operators and captures both classical probabilistic uncertainty and genuinely quantum features such as coherence and entanglement.

Distinguishing between pure and mixed states is not the only role played by von Neumann entropy in quantum mechanics. Another fundamental application concerns the quantification of entanglement correlations between subsystems of a composite quantum system. This role is captured by the notion of entanglement entropy, which measures the degree to which a given subsystem is entangled with the rest of the system [33]. Importantly, this is not merely a conceptual or formal distinction. Rather, it brings into focus a substantive contrast between the notion of information defended by Timpson, understood as a purely abstract, type-based entity tied to communication and coding, and a conception of information that is physically grounded in the relational structure instantiated by entangled systems. To understand this point, consider a quantum system that consists of two subsystems, A and B, described by a joint density matrix ρ_{AB} acting on the Hilbert space $\mathcal{H}_A \otimes \mathcal{H}_B$.[15] If the overall system is in a pure state, meaning that the total density matrix satisfies $\rho_{AB} = |\Psi\rangle\langle\Psi|$ for some state $|\Psi\rangle$, we can define the reduced density matrix for subsystem A by tracing out subsystem B:

$$\rho_A = \mathrm{tr}_B(\rho_{AB}). \tag{7}$$

This operation, known as the partial trace, effectively removes information about subsystem B, leaving a statistical description of subsystem A. The von Neumann entropy of ρ_A, known as the entanglement entropy, quantifies the degree of entanglement between A and B:

$$S(\rho_A) = -\mathrm{tr}(\rho_A \ln \rho_A). \tag{8}$$

$S(\rho_A) = 0$ entails that the total state $|\Psi\rangle$ is a product state, meaning it can be written as $|\Psi\rangle = |\psi_A\rangle \otimes |\psi_B\rangle$. In this case, there are no entanglement correlations between subsystems A and B, and their joint state is simply a direct product of two independent states. Conversely, $S(\rho_A) > 0$ occurs when the total state $|\Psi\rangle$ is an entangled state. The entanglement entropy hence quantifies the amount of quantum correlations between A and B. A maximally entangled state, such as the Bell state

[15] The tensor product $\mathcal{H}_A \otimes \mathcal{H}_B$ is the mathematical structure used to describe composite quantum systems. Unlike the Cartesian product used in classical physics—which simply lists all possible state combinations—the tensor product allows for superpositions of product states. This enables the representation of entangled states, which have no classical analogue and cannot be factored into independent subsystem states.

$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}\left(|00\rangle + |11\rangle\right), \tag{9}$$

has a reduced density matrix for either subsystem[16] given by

$$\rho_A = \rho_B = \frac{1}{2}(|0\rangle\langle 0| + |1\rangle\langle 1|) = \frac{I}{2}. \tag{10}$$

Since this is a maximally mixed state in a two-dimensional Hilbert space, its entropy is

$$S(\rho_A) = \ln 2. \tag{11}$$

Thus, for a maximally entangled state, the entanglement entropy reaches its maximum value, which in the case of a two-qubit system is $\ln 2$. Here, an important difference between the value of the entanglement entropy and the Shannon entropy is highlighted. Indeed, the latter can reach a value of 1 when the states are maximally uncorrelated, whereas the former can take values between 0 and $\ln 2$.

More generally, for a maximally entangled bipartite system in a d-dimensional Hilbert space, the entanglement entropy of either subsystem is $\ln d$. In this sense, entanglement entropy quantifies non-classical correlations between subsystems—correlations that cannot be described by any classical joint probability distribution.[17] This notion plays a central role in quantum information theory, where entanglement is treated not merely as a formal feature but as a resource. A particularly significant result in this context is the so-called *area law*, which states that for many systems governed by local Hamiltonians, the entanglement entropy of a subsystem scales with the size of its boundary, rather than its volume.[18] This behavior contrasts with classical thermodynamic entropy, which is an extensive quantity and typically scales with volume.[19] In quantum field theory and gravity, entanglement entropy also plays a pivotal role. It provides a natural microscopic candidate for the Bekenstein–Hawking entropy of black holes, interpreting it as the entanglement between degrees of freedom inside and outside the event horizon.[20] These diverse applications already hint at a conceptual ambiguity: the same entropy function can describe the compressibility of a source or, in other contexts, the strength of entanglement between subsystems. To make this ambiguity precise, we now turn to analyze the two distinct uses of von Neumann entropy in quantum mechanics.

[16] This example is perfectly symmetric with respect to the two subsystems, meaning that tracing out either A or B yields the same reduced state. However, this symmetry is not essential to the phenomenon of entanglement. We have chosen a symmetric Bell state for ease of exposition, but the conceptual points hold without loss of generality for asymmetric or higher-dimensional entangled states.

[17] For a detailed discussion of the distinction between classical and quantum correlations, see [19].

[18] See [13] for a review. The area law typically holds for ground states of gapped systems and plays a central role in tensor network approaches.

[19] On the foundations of thermodynamic entropy in statistical mechanics, see [15].

[20] See [3, 41] and [36] for key developments in this line of research.

4 On Two Informational Uses of von Neumann Entropy

We have seen that von Neumann entropy plays a dual role in quantum mechanics, depending on whether it is applied to the density matrix of the entire system or to the reduced density matrix of a subsystem. This duality arises not from any ambiguity in the definition of the entropy, but from the different physical status of the states to which it is applied. Global states of closed systems can be interpreted as proper mixtures, reflecting classical probabilistic uncertainty about preparation, whereas reduced states of subsystems entangled with an environment are improper mixtures produced by tracing out external degrees of freedom. As emphasized by [14], these two classes of states have distinct physical interpretations. It is therefore unsurprising that the very same function, when applied to them, should support different informational roles. In what follows, we make this distinction explicit. Specifically, we distinguish between entropy as uncertainty (§4.1) and entropy as correlation (§4.2). While both are captured by the same formal expression—the von Neumann entropy—they correspond to two structurally distinct informational kinds. The second, entropy as correlation, emerges uniquely from quantum mechanics and departs significantly from the Shannon paradigm. It represents a novel informational kind , not reducible to the epistemic logic of uncertainty, even if its possible classical limits remain to be explored.

4.1 Entropy as Uncertainty

Let us begin with the first application of von Neumann entropy: its evaluation on a global density matrix ρ. In this case, as we will see, the von Neumann entropy plays a role that is conceptually analogous to Shannon entropy in classical information theory: it quantifies the observer's epistemic uncertainty about the system's state—that is, it does not reflect an intrinsic physical property of the system itself, but rather encodes the degree of uncertainty about which pure state the system actually occupies. In this analogy with Shannon's communication model, the quantum system functions as the information source, while the observer or measuring apparatus plays the role of the receiver.[21]

When the density matrix ρ corresponds to a pure state—meaning that the system is in a well-defined quantum state with complete information—the entropy is zero: $S(\rho) = 0$. This indicates maximal knowledge of the system. Conversely, when the system is in a mixed state, representing a probabilistic ensemble of pure states, the entropy is positive. The more mixed the state (i.e. , the more evenly distributed the probabilities in the ensemble), the higher the entropy and, accordingly, the greater the uncertainty about the actual state of the system. In the extreme case, a maxi-

[21] In Shannon's model, a source emits messages that are received and decoded by a receiver through a channel. When applied to quantum theory, this structure is metaphorical: the quantum system "emits" a statistical distribution (represented by the density matrix), and the receiver is the entity that acquires information through interaction. Depending on the interpretive stance, the receiver may be conceived as a classical measurement device (instrumentalist views), an epistemic agent (as in QBism), or a physical system (as in some relational or objective collapse interpretations). In all these cases, the key point is that entropy reflects the receiver's uncertainty, not an ontological feature of the system itself.

mally mixed state—where all possible outcomes are equally probable—yields the maximum entropy allowed by the dimension of the Hilbert space, and corresponds to complete ignorance within that framework. In the language of Shannon's theory, we can think of the quantum system as the source of information, emitting a probabilistic distribution over possible messages (pure states), while the observer functions as the receiver, attempting to infer which state was prepared or transmitted. The von Neumann entropy then plays the role of measuring the expected number of qubits needed to identify the state, or equivalently, the degree of uncertainty the observer faces in the absence of further interaction. In the extreme case of a maximally mixed state—where all outcomes are equally probable—the entropy reaches its maximum value given by $\ln d$, where d is the dimension of the Hilbert space. This corresponds to complete ignorance, in analogy with a uniform distribution in Shannon's framework, where each message is equally likely and no compression is possible.

To illustrate this, consider the case of a single qubit described by a diagonal density matrix:

$$\rho = p|0\rangle\langle 0| + (1-p)|1\rangle\langle 1|. \tag{12}$$

This represents a statistical mixture of the two basis states $|0\rangle$ and $|1\rangle$, with probabilities p and $1-p$, respectively. The von Neumann entropy for this state is given by the binary entropy function:

$$S(\rho) = -p\ln p - (1-p)\ln(1-p). \tag{13}$$

As expected, this function behaves as follows. When $p = 0$ or $p = 1$, the state reduces to a pure state ($\rho = |0\rangle\langle 0|$ or $\rho = |1\rangle\langle 1|$), and entropy vanishes: $S(\rho) = 0$. The observer knows with certainty which state the system is in. When $p = 0.5$, the state is maximally mixed, and entropy reaches its peak value $\ln 2$, signaling maximal uncertainty. The entropy curve is concave and symmetric about $p = 0.5$, which reflects the fact that both p and $1-p$ contribute equally to the uncertainty when the state is fully mixed.

To visualize the inverse relationship between entropy and epistemic knowledge, we can introduce a normalized information-like quantity:

$$I_{\text{norm}}(\rho) = 1 - \frac{S(\rho)}{\ln d}, \tag{14}$$

where $S(\rho)$ is the von Neumann entropy of the quantum state and d is the dimension of the Hilbert space on which ρ acts. This expression ranges from 0 (maximally mixed state, complete ignorance) to 1 (pure state, maximal knowledge). Although not a standard measure of information in either classical or quantum information theory, this normalized complement to entropy captures, in heuristic terms, the degree of knowledge an observer has about the actual state of the system. The intuition behind this quantity reflects the Shannon-like idea that lower entropy corresponds to a more

informative (i.e., less uncertain) state description.[22] The nonlinearity arises because entropy itself is a nonlinear function of the parameter p. This plot confirms that even in this classical-like scenario, the relation between physical parameters (in this case, p) and information is not linear, and care must be taken not to conflate the shape of the entropy function with a direct interpretation of the underlying informational content. The key point is that, in this context, the von Neumann entropy plays a role analogous to that of classical Shannon entropy: it decreases as the probability distribution over the source's possible outcomes becomes more concentrated—that is, as uncertainty diminishes and knowledge about the system's output increases. In this scenario information is understood as a quantifiable reduction in epistemic uncertainty about which state a system occupies. The von Neumann entropy, when applied to a global quantum state, preservs the fundamental logic of Shannon's framework. In this view, the density matrix represents a probabilistic source (analogous to Shannon's transmitter), and the observer functions as a receiver whose ability to reproduce the message is incresed through measurement. What we have, then, is not a new concept of information, but a quantum implementation of an existing kind of information. In the next section, however, we will see that when the same function is applied to subsystems of entangled states, an entirely different kind of information emerges—one that cannot be captured within the epistemic paradigm. This poses a challenge to Timpson's assumption that quantum theory can be fully contained within the single informational kind inherited from the classical framework (Fig. 1).

4.2 Entropy as Correlation

A very different perspective on entropy and information emerges when we shift our attention from global quantum states to reduced density matrices—that is, when we consider a subsystem of an entangled system. In this context, the density matrices we consider are improper mixtures: they represent the local states of subsystems entangled with other systems, rather than proper statistical mixtures of pure states prepared with given probabilities. For such reduced states, von Neumann entropy no longer quantifies an observer's probabilistic uncertainty (destination) about which pure state has been prepared (source). Instead, it measures the entanglement correlations between subsystems and thereby captures a distinct, genuinely quantum kind of information: one that departs from the framework proposed by Timpson and discussed in §2. We refer to this informational kind as relational information. To illustrate this point concretely, consider a simple bipartite system consisting of two spin-$\frac{1}{2}$ particles, conventionally assigned to two observers, Alice and Bob. Suppose the total system is in the singlet state:

[22] This definition is not meant to propose a new formal measure of information, nor to replace established quantities such as mutual information. Rather, it serves a purely interpretive and illustrative purpose, highlighting how epistemic uncertainty and "information" can be understood as complementary in a classical-like setting. The normalization by $\ln d$ ensures that this heuristic measure varies between 0 and 1 for finite-dimensional systems, and allows for intuitive graphical representations.

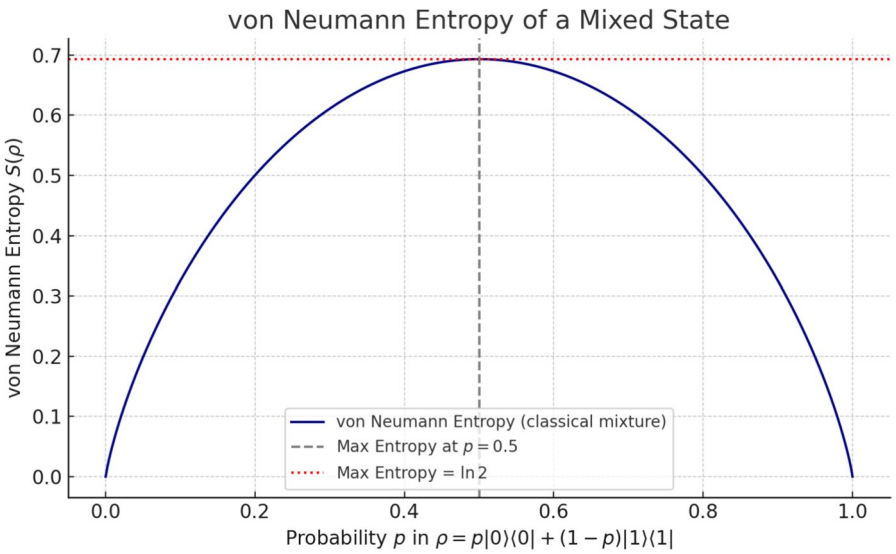


Fig. 1 Classical information as a function of the probability parameter p in a diagonal density matrix of the form (13). The vertical axis represents classical information, defined as $1 - \frac{S(\rho)}{\ln 2}$, where $S(\rho)$ is the von Neumann entropy. The curve shows that information is maximal when the system is in a pure state (i.e., $p = 0$ or $p = 1$), and minimal when the system is maximally mixed ($p = 0.5$). This illustrates the epistemic interpretation of entropy: it measures an observer's uncertainty about the state, and thus information decreases as entropy increases. The concave, symmetric shape reflects the non-linearity of entropy as a function of the state parameter p

$$|\Psi^-\rangle = \frac{1}{\sqrt{2}} \left(|\uparrow\rangle_A |\downarrow\rangle_B - |\downarrow\rangle_A |\uparrow\rangle_B \right), \tag{15}$$

a maximally entangled state. To analyze the local properties of Alice's subsystem, we consider its reduced density matrix, obtained by tracing out Bob's degrees of freedom. While the global system is in a pure state, the reduced state is mixed, reflecting the entanglement between the two subsystems. The resulting reduced density matrix for Alice is

$$\rho_A = \mathrm{tr}_B(|\Psi^-\rangle\langle\Psi^-|) = \frac{1}{2} \left(|\uparrow\rangle\langle\uparrow| + |\downarrow\rangle\langle\downarrow| \right). \tag{16}$$

This reduced state is indeed maximally mixed, with von Neumann entropy

$$S(\rho_A) = -\mathrm{tr}(\rho_A \ln \rho_A) = \ln 2. \tag{17}$$

As we saw in the previous section, a maximally mixed state is usually associated with maximal ignorance about the system's state. In this sense, the reduced density matrix for Alice might seem to reflect complete uncertainty about her spin. However, in the context of entanglement, this interpretation—while not incorrect—is incomplete. The mixedness of the reduced state also encodes nonlocal correlations with Bob's

subsystem. What appears as local ignorance is, in fact, a manifestation of new relational structure. In fact, while the high entropy of the reduced state indicates maximal uncertainty about the local properties of the subsystem, this is only part of the story. Crucially, it also reflects the presence of strong quantum correlations between the two subsystems. When Alice measures her spin and obtains a definite outcome, she can infer with certainty the outcome that Bob would obtain, despite each local state being maximally mixed. This suggests that the information is not encoded in the subsystems individually, but in their joint correlations. The entropy of the reduced state therefore quantifies the amount of relational information accessible between the subsystems—not what either observer knows about their own system, but what the structure of their entanglement allows each to infer about the other.

More precisely, the decrease in information regarding the local properties of a subsystem is accompanied by a corresponding increase in information about the correlations between subsystems. In separable (product) states, such as

$$|\psi\rangle_{\text{prod}} = |\uparrow\rangle_A \otimes |\uparrow\rangle_B \ , \tag{18}$$

the composite system is in a pure, unentangled configuration. The reduced density matrix associated to A, computed tracing out B degrees of freedom, is given by

$$\rho_A = |\uparrow\rangle_A \langle\uparrow|_A \ , \tag{19}$$

which is a pure state and thus its von Neumann entropy is zero. The fact that the entropy of ρ_A is zero means that there is no uncertainty about the state of subsystem A: it has well-defined, sharp properties that can, in principle, be fully known. Indeed, in the example provided, the system A has the property of having spin-up along a given axes. This aligns with the classical notion of complete information, as discussed in the previous section. But more importantly for our purposes, this zero entropy also tells us that there is no entanglement between A and B. The two subsystems are statistically independent: there are no nonlocal correlations, and no information about one can be inferred by measuring the other. In terms of "information content", then, everything is "local": the state of A fully specifies its own properties, the state of B is similarly independent, and there is no mutual constraint or connection between the two. In this sense, the information in the system resides entirely in the individual subsystems, and no relational information is present. The zero entropy of the reduced state is not just a sign of epistemic certainty, but also of ontological separability: the properties of the parts are defined independently of each other. This contrasts sharply with the case of entangled states, where—as we shall see—the entropy of reduced states is nonzero, and the information resides primarily in the correlations between the parts rather than in the subsystems themselves. Indeed, take, for instance, he case of a maximally entangled state $|\psi^-\rangle$ described in (15). When we compute the reduced density matrix of the subsystem A by tracing out the degrees of freedom of B, one gets:

$$\rho_A = \frac{\mathbb{I}}{2} \ . \tag{20}$$

This is, as already discussed in §4.2, a maximally mixed state with von Neumann entropy $S(\rho_A) = \ln 2$. At first glance, this high entropy might suggest maximal ignorance about the state of subsystem A, as in the classical interpretation. But in this entangled setting, that interpretation is incomplete. What appears as local ignorance is, in fact, the manifestation of maximal quantum correlation. That is, although subsystem A by itself has no definite properties, its joint behavior with B is perfectly constrained. For instance, if a measurement on A reveals the state $|\uparrow\rangle$, we instantly know that B must be in $|\downarrow\rangle$, and vice versa. This knowledge does not arise from learning something about A alone, but from the structure of the entangled pair. The entropy of the reduced state ρ_A thus quantifies the strength of these nonlocal correlations—what we call *relational information*. Unlike in the product state, where zero entropy indicated fully local and separable information, here the high entropy of the part reflects the completeness of the whole. Thus, in the example just provided, the local subsystems are maximally mixed, i.e. $S(\rho_A) = S(\rho_B) = \ln 2$, and all the informational content lies in the correlations between A and B. This mutual constraint defines a kind of information that is not reducible to knowledge about parts, but exists only in the relational structure between them. This behavior is emblematic of entanglement entropy[23]: it does not measure ignorance, but rather the extent to which subsystems are entangled. The more mixed the reduced state, the more entangled the whole system is, and the more relational information is physically instantiated.

To illustrate this behavior more generally, consider a bipartite pure state written in its Schmidt decomposition:

$$|\psi\rangle = \sqrt{\lambda}\,|00\rangle + \sqrt{1-\lambda}\,|11\rangle, \tag{21}$$

where $\lambda \in [0, 1]$ is the so-called *Schmidt coefficient*. The entanglement entropy of the subsystem A, given by the von Neumann entropy of the reduced density matrix associted with the system A, is given by:

$$S(\rho_A) = -\lambda \ln \lambda - (1-\lambda)\ln(1-\lambda). \tag{22}$$

This function is nonlinear, symmetric around $\lambda = 0.5$, and concave. It reaches its maximum at $\lambda = 0.5$, corresponding to a maximally entangled state, and vanishes at the extremal points $\lambda = 0$ and $\lambda = 1$, which represent product states. Crucially, this curve quantifies a distinct kind of information. As entanglement increases, so does the entropy of the reduced states, even though each subsystem becomes locally more uncertain. What grows is not only classical (local) ignorance, but, more importantly for our discussion, relational constraint. The reduced density matrices encode no local knowledge (on the properties of the subsystem), yet the global system displays precise and predictable correlations. This is the signature of what we call relational information: a kind of information not reducible to local properties or classical probability distributions. In other words, although each subsystem by itself appears maximally uncertain, their joint behavior is maximally constrained. From the perspective

[23] Mutual information characterizes what is called an external relation: the properties of the subsystems are not sufficient to know the entanglement relation [4, 27].

of the observers, entanglement entropy provides a measure of how much they can know about one another's subsystem just by observing their own. Unlike classical information, which is additive and reducible to properties of individual systems, relational information encoded in entanglement is intrinsically nonlocal and cannot be assigned to either subsystem independently (Fig. 2).

5 One Function, Two Kinds of Information?

The preceding analysis has shown that a single mathematical function—the von Neumann entropy $S(\rho) = -tr(\rho \ln \rho)$—can play multiple conceptual roles depending on the physical context in which it is applied. When evaluated on the global density matrix of a quantum system, its interpretation depends on the nature of the state: for pure states, the entropy vanishes and carries no informational significance; for mixed states, by contrast, the entropy quantifies epistemic uncertainty about which pure state the system occupies, much like Shannon entropy in classical probability theory. In this latter case, entropy is inversely related to information: the more mixed the state, the less knowledge an observer has. In this first case, the relevant density matrices are global states of closed systems or sources, which can be interpreted as proper mixtures of pure states. By contrast, when the same function is applied to reduced density matrices describing subsystems of an entangled whole, we are deal-

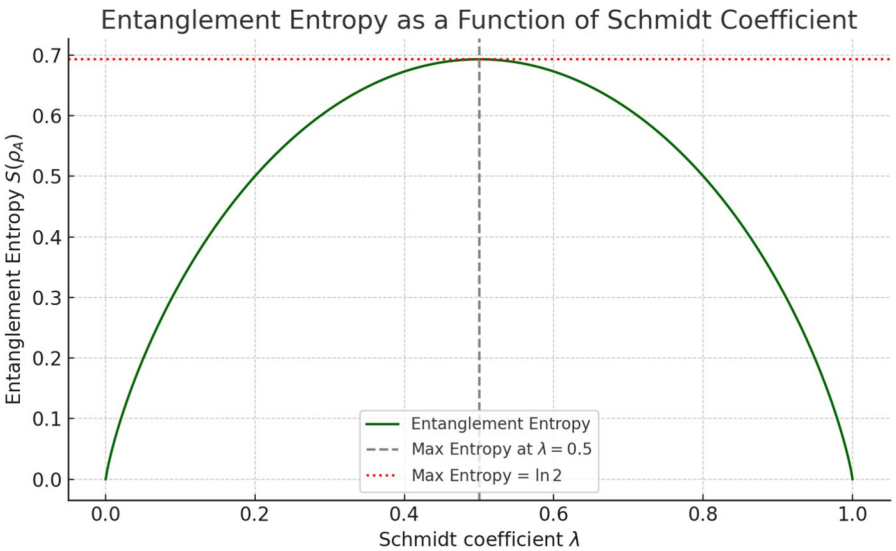


Fig. 2 Entanglement entropy $S(\rho_A)$ of a bipartite pure state (21) as a function of the Schmidt coefficient λ. The entropy quantifies the degree of quantum correlation (entanglement) between subsystems. It reaches its maximum $\ln 2$ at $\lambda = 0.5$, indicating maximal entanglement and maximal relational information. The entropy is zero at the extremal points $\lambda = 0, 1$, where the state is separable and no shared quantum information exists. This behavior reveals the nonlinear nature of quantum correlations and distinguishes entanglement entropy from classical measures of uncertainty

ing with improper mixtures: states that result from tracing out external degrees of freedom and that encode the influence of those degrees of freedom on the subsystem. This difference in physical status is crucial. It is not just that we apply the same formula to different arguments: the two classes of density matrices support two distinct informational roles for $S(\rho)$.

Once this distinction is drawn, the informational profile of entropy in the reduced case can be characterized more precisely. While von Neumann entropy still captures local uncertainty, it also encodes the presence of quantum correlations between subsystems, and thereby tracks an entirely different informational role. In this context, entropy and information become directly proportional: the greater the uncertainty about the local properties of each subsystem, the stronger the correlations embedded in the global state—a signature of genuinely non-classical structure. The same mathematical expression, therefore, quantifies both lack of information about a system's intrinsic state (in the global case) and the presence of relational constraints between parts (in the reduced case). This duality illustrates the context-sensitivity of the von Neumann entropy: its informational meaning is not determined solely by its formal definition, but depends crucially on the physical system to which it is applied and on the interpretive framework in which it is embedded.

A further clarification concerns the role played by subsystem structure. If one adopts the standard bipartite conception of entanglement, the informational contribution of the entropy of a reduced state is indeed relative to a chosen decomposition of the Hilbert space: the mutual information associated with a subsystem depends on the tensor-product partition used to model the composite system.[24] This "relativity", however, is not epistemic. It reflects the physical way in which different groups of degrees of freedom interact with each other rather than any agent-dependent perspective. Alternatively, on a genuinely multipartite understanding of entanglement, the correlation structure is global and encoded in the mutual constraints among all dynamical degrees of freedom jointly; in this setting, relational information is not tied to any particular subsystem decomposition, but measures the structural interdependence instantiated among all degrees of freedom of the composite system.[25] Our analysis is compatible with both ways of understanding entanglement. If one adopts the standard bipartite framework, the correlational contribution of the entropy is relative to the physically motivated bipartition chosen to represent the system: it captures how much the properties of one subsystem constrain those of another across that specific cut. If, instead, one adopts the multipartite perspective—on which entanglement

[24] The "relativity" of bipartite entanglement to a chosen tensor-product decomposition is well established in the literature. Questions such as "is this state entangled?" are only meaningful relative to a specified partition of the Hilbert space, since different factorizations can yield different entanglement properties. Earman [12], indeed, emphasizes that the very definition of bipartite entanglement presupposes a fixed subsystem structure, and that no unique or privileged decomposition is supplied by the quantum formalism itself.

[25] This multipartite perspective follows the analysis developed in [4], where entanglement is treated as an *external* and *multigrade* physical relation: a structural constraint instantiated by the global quantum state and holding among *all* dynamical degrees of freedom jointly, rather than a relation between pregiven subsystems. Consequently, what we call relational information tracks the objective pattern of mutual constraints encoded among all degrees of freedom, and thus independently of how one chooses to group degrees of freedom into subsystems.

is a single external multigrade relation instantiated by the global state—the same correlational contribution becomes a global invariant, quantifying the pattern of mutual constraints among all dynamical degrees of freedom taken together, independently of any particular subsystem decomposition.

We argue that the von Neumann entropy applied to the reduced density matrix realizes a kind of information grounded in structural interdependence rather than epistemic uncertainty. What justifies treating entanglement entropy as a form of information, rather than merely a formal quantity? The key lies in the operational content of quantum correlations: the entropy of a reduced state quantifies how much a subsystem A can reveal about another subsystem B, simply through local measurements. That is, even without accessing B, the measurement outcomes on A constrain, in a non-trivial and quantifiable way, the possible properties of B.[26] This notion of information is not epistemic in the classical sense—where information tracks the observer's probabilistic uncertainty about pre-existing properties—but structural and relational. It measures the extent to which two quantum systems are nonlocally constrained by their entangled joint state. In this sense, entanglement entropy encodes the amount of relational information: not knowledge about a system's own state, but about the interdependence between systems. This contrasts with the classical case, where correlations between subsystems can always be explained in terms of shared causes or statistical dependencies. In quantum mechanics, entangled correlations cannot be reduced to such explanations, and thus represent a fundamentally new form of physical information.

In light of the foregoing discussion, we are now in a position to articulate a more general and abstract definition of the kind of information instantiated by entanglement entropy. Our aim is to isolate the conceptual core of this notion independently of its specific quantum realization. Just as classical information theory—most notably in Shannon's framework—abstracts away from physical details to characterize information as uncertainty reduction, we seek to characterize relational information as a distinct kind of information, grounded in structural constraints rather than in probabilistic uncertainty about underlying local states. The following definition captures this idea.

(I_{rel}) **Relational Information.** Relational information is a kind of information that quantifies the degree to which the physical properties of one system are constrained by those of another, in a way that is both independent of any observer and irreducible to the intrinsic properties of the individual systems. It captures an objective interdependence that does not supervene on the local states of the relata, but is instantiated only at the level of their joint physical structure.

This abstract definition is intended to capture the structural and ontological dimension of a form of information that arises when two or more physical systems are not merely co-existent, but mutually constrained in a way that cannot be reduced

[26] This apparent influence of measurements on subsystem A over the predicted outcomes for subsystem B does not imply any violation of relativistic causality or superluminal signaling. As shown by [21], the condition violated by quantum mechanics is not *parameter independence* (which would imply faster-than-light causation), but *outcome independence*. The correlations in entangled states do not allow for the transmission of usable information between spacelike separated regions, preserving the "peaceful coexistence" between quantum mechanics and special relativity. See also [28] on this point.

to their individual states. Unlike epistemic notions of information, which depend on what an observer knows or can infer, relational information refers to an objective physical structure: a set of constraints that exist between systems regardless of observation, and that are not recoverable from the properties of the subsystems in isolation.Quantum entanglement offers the clearest and most studied realization of the informational kind we have called relational. In bipartite entangled systems, the local subsystems can be in maximally mixed states—possessing no definite properties on their own—while the composite system exhibits highly constrained, nonclassical correlations. These correlations are not reducible to any statistical mixture of separable states, nor can they be explained by shared classical causes. Rather, they instantiate a new kind of interdependence, irreducible to the properties of the parts and located in the structure of the whole. This is precisely what entanglement entropy captures: a quantifiable measure of this structural relation. Far from being a mere bookkeeping device, it operationalizes the presence of relational information in quantum theory, serving as the empirical and formal signature of a deeper ontological feature of quantum systems.[27]

Relational information, as exemplified by entanglement entropy, satisfies three key conditions that justify treating it as a distinct kind of information—one that is ontologically different from the classical epistemic conception exemplified by Shannon. First, it has a well-defined quantitative structure: given two subsystems of a bipartite quantum system in a pure state, the von Neumann entropy of the reduced density matrix of either subsystem provides a precise scalar measure of the degree of quantum correlation between them. This quantity is a continuous, concave, and symmetric function of the Schmidt coefficients of the global state, and it offers a clear parametrization of how the properties of the systems are physically constrained. Second, relational information has operational significance: it determines the extent to which local measurements on one subsystem allow inference about the other. It underlies empirically observable phenomena such as the violation of Bell inequalities, quantum teleportation, and entanglement-based communication. These effects cannot be explained in terms of classical probabilistic uncertainty or probabilistic dependence alone—they require a nonlocal form of information that is physically realized through entanglement.[28] Third, this kind of information is observer-independent: the correlations between subsystems exist objectively in the quantum state,

[27] While our discussion has focused on bipartite systems to illustrate clear instances (tokens) of relational information, the underlying kind generalizes naturally to multipartite entangled systems. In such cases, quantum correlations exhibit richer patterns of nonlocal constraint—such as GHZ states—that cannot be decomposed into sums of bipartite entanglement. These structures instantiate the same kind of relational information: a physical interdependence that is not reducible to the properties of the individual subsystems. Quantifying relational information in the multipartite case may require measures beyond bipartite entanglement entropy—such as the so called *(quantum) mutual information*—but the conceptual point remains: what matters is the structural relation among systems, not their isolated states. Notably, in the bipartite case of a pure state, entanglement entropy and quantum mutual information coincide (if the composite system state is pure). The thesis defended in this paper can therefore be equivalently reformulated in terms of (quantum) mutual information as an indicator of relational constraints.

[28] This argument does not contradict the claims made by [44], according to which teleportation must be regarded as something entirely distinct from Shannon's communication theory. Rather, we reinforce their view by establishing a new correlation with the kind that we have termed Relational Information.

regardless of whether any agent accesses them. The entanglement entropy quantifies a real, measurable feature of the system's structure that remains in place even in the absence of external observation or measurement.[29] These three features—quantifiable structure, empirical relevance, and objectivity—are sufficient to treat relational information not as a reinterpretation of classical information, but as a genuinely new informational kind . It expands the conceptual landscape of information in fundamental physics.

These considerations suggest that epistemic and relational information should not be seen as rival interpretations of a single concept, but as distinct kinds of informational structure that operate at different explanatory levels. While classical information theory—exemplified by the Shannon framework—captures uncertainty reduction in communication channels or probabilistic ensembles, relational information captures objective interdependence in the structure of physical systems. These two kinds of information are not incompatible; they reflect complementary aspects of the quantum formalism. Adopting this perspective allows us to resist views that seek to assimilate all forms of information into a single paradigm. Instead, it supports a pluralist approach, along the lines advocated by [23]. On our proposal, the theory of information in physics must be broadened to accommodate at least two context-dependent notions, each grounded in distinct physical and conceptual features. Importantly, this pluralism does not rest on a state-based ontology of information, nor does it posit fundamentally different kinds of quantum states. Rather, it concerns the different informational roles played by the same formal quantity, von Neumann entropy, depending on the physical context in which it is applied. Relational information, in this sense, is not a refinement of classical ideas nor a merely terminological extension, but a genuine conceptual extension required by the non-classical, relational structure instantiated by entanglement.

If one accepts that quantum entanglement is a genuine physical phenomenon—not merely an artifact of the mathematical representation—then the information it gives rise to must also be granted ontological significance. Entanglement entropy does not merely reflect an observer's limited access to subsystems; rather, it quantifies an objective structural feature of the world: the non-separability of quantum systems. The correlations captured by entanglement entropy are thus not incidental byproducts of incomplete knowledge, but irreducible aspects of the physical structure of reality—features that resist reduction to local properties and persist independently of observers or interpretative choices. In this light, relational entropy should not be viewed merely as a calculational tool, but as the formal expression of an objective physical relation instantiated between systems. This, in turn, lends further support to treating it as a distinct and irreducible informational kind within the ontology of quantum theory.

[29] Indeed, the entanglement entropy is basis-independent in the following sense: for a bipartite system in a pure state, the von Neumann entropy of the reduced density matrix is invariant under local unitary transformations. That is, applying any unitary operator U_A on subsystem A and U_B on subsystem B leaves the entanglement entropy unchanged. This invariance ensures that entanglement entropy reflects a structural feature of the global state, not an artifact of a particular representation or measurement basis. For more on this property, see [4].

6 Conclusions and Outlooks

In this paper, we have argued that the standard notion of information, modeled on Shannon's theory and rooted in epistemic uncertainty, is insufficient to capture all conceptually legitimate uses of the term in contemporary physics. While Shannon information provides a robust and widely applicable framework—especially in contexts involving communication, compression, and statistical uncertainty—it does not exhaust the informational structures that emerge in quantum theory. In particular, we have shown that von Neumann entropy plays two conceptually distinct roles in quantum mechanics. When applied to a global mixed state, it functions analogously to Shannon entropy, quantifying the observer's probabilistic uncertainty about which pure state the system occupies. In this context, information is epistemic, reducible to uncertainty about a pre-existing state. However, when the same mathematical expression is applied to the reduced state of a subsystem entangled with another, it measures not ignorance, but physical correlation—an objective interdependence that cannot be explained by classical probability or separable states.

This second use realizes a conception of information as correlation, relational information which is neither reducible to probabilistic uncertainty nor to communicative exchange, and therefore calls for the recognition of a new *kind* of information.[30] We have argued that it is legitimate to speak of "information" in this second sense, insofar as entanglement entropy satisfies the same structural and operational criteria we associate with informational quantities: it is quantifiable, experimentally significant, and independent of the observer. More importantly, we have proposed that this new kind of information should be interpreted in ontological terms—as a physically real, relational structure instantiated by entangled systems. The information captured by entanglement entropy is not merely a measure of what an agent can or cannot know, but a formal expression of how parts of a quantum system are objectively constrained by their joint state. It is a kind of information that belongs not to the subsystems individually, but to their relational configuration.

In this way, our analysis sheds light on a latent conceptual tension within the notion of information in quantum theory. Moreover, the case of relational information exemplifies a broader insight: that the general theory of information, as currently understood, may be incomplete. The formal and empirical richness of quantum correlations compels us to expand our informational vocabulary, recognizing "information as correlation" as a distinct and irreducible kind of information . This proposal, while grounded in quantum theory, also points beyond it—toward a more pluralist and structurally sensitive understanding of information in fundamental physics.

The recognition of a different kind of information—grounded in objective correlation rather than epistemic uncertainty—opens the door to a conceptual expansion of information theory beyond the Shannon paradigm. At present, this informational kind has a single well-understood physical manifestation: quantum entanglement. This, however, does not rule out the possibility that future physical theories or scenarios may reveal additional instantiations.

[30] In this paper we highligths a different kind of information within quantum mechanics, in a future work we plan to develop also an analysis of the interplay between the new kind of information introduced here and the type/token distinction proposed by Timpson.

While it is unlikely, from our perspective, that classical systems could instantiate genuinely non-separable structures analogous to entanglement, quantum entanglement remains the characteristic hallmark of this second informational kind. At the same time, there are promising developments in quantum gravity in which analogous forms of relational dependence may emerge. In particular, several approaches to quantum gravity suggest that spacetime itself may exhibit structural features analogous to entanglement, with non-separability becoming a fundamental aspect of its physical description. In this context, violations of separability—especially in the study of black hole evaporation and the information paradox—have been central to recent developments. For istance, Raju [34] and Penington [31] suggests, in different ways, that relational structures analogous to quantum entanglement might play a role in the microstructure of spacetime, pointing to the possibility that our new kind, *relational information*, extends beyond quantum systems to encompass quantum gravitational degrees of freedom.[31] We intend to investigate these possibilities in future work, exploring whether relational information can offer a unifying framework for understanding non-separability across quantum mechanics and quantum gravity.

Moreover, our proposal also stands in contrast to two dominant trends in the literature of interpretations of quantum theory. On one side are epistemic approaches such as QBism [16], which reduce quantum information to subjective belief or agent-relative knowledge. On the other side are metaphysical views, such as [52]'s "It from Bit," which posit information as a fundamental, abstract principle underlying physical reality. Against both, we advance a form of structural informational realism, according to which information—as correlation—is not merely a product of our knowledge, nor a metaphysical primitive, but a real, physically instantiated aspect of the world's structure. From this perspective, it would be fruitful to explore how our account of information as correlation can illuminate the foundations of Relational Quantum Mechanics [35]. When RQM claims that "an electron knows about another electron," [2] our interpretation suggests that this "knowing" should be understood not in epistemic or psychological terms, but in terms of the physically instantiated relational information that constrains their joint behavior. We plan to explore this connection between relational information and the ontology of RQM in future work.

Overall, we view the results presented in this paper as part of a broader effort to rethink the ontological status of information in physics. Not all information, we have argued, admits an epistemic interpretation; some forms—such as the relational information instantiated by quantum entanglement—are constitutive of the physical structure of reality itself. Recognizing this new kind of information invites further inquiry into its conceptual and theoretical ramifications, not only for the interpretation of quantum mechanics but for a more general understanding of information as a foundational category in physical theory. Future work will explore how this notion may illuminate phenomena in quantum gravity, where non-separability and entanglement-like structures appear to underlie the very fabric of spacetime.

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[31] See [5] and [7] for a philosophical discussion of these developments in quantum gravity, and [6] for an in-depth analysis of separability within such scenarios.

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Declarations

Competing interests The authors declare no competing interests.

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