**Reality and Information: Is information a physical entity?**
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**Abstract**: Landauer's principle and Bekenstein's bound establish a link between energy and information. On the other hand, information theory and algorithmic information theory show how reality can emerge irreducibly from an underlying reality, establishing a system of irreducible functional layers. All this allows conjecturing if information is a physical entity and if information processing is the foundation of natural processes. Additionally, the axiomatic definition of mathematical models suggests an axiomatic and therefore relativistic reality, and, according to Gödel's incompleteness theorem nature could be something ultimately inscrutable.

**Keywords**: Landauer's principle, Bekenstein's bound, information theory, algorithmic information theory, emergent functionality, irreducible and relativistic reality, Gödel's incompleteness theorem.

## What do we mean by reality?

Without any doubt, the science that has achieved great success in the understanding of nature has been physics. Thus, we can put as paradigm models of classical mechanics, statistical mechanics, electromagnetism, relativity, and quantum physics. All of them have meant great advances in the knowledge of physics, but also a profound change in human thinking.

Surprisingly, the development of physics has been supported by mathematics, so that by relatively simple laws, generally expressed as a set of equations, we can model complex physical problems.

Other branches of knowledge have tried to follow in the footsteps of physics, but their success has been much more limited. The determinism of the physical models established until the nineteenth century supported the idea that everything in nature could be explained on the basis of physical laws. This idea known as reductionism has been proved as totally unsuccessful. In this line of thought, the analysis that a naturalist could make of a living being from the atoms that compose it would be totally logical under the view of deterministic physics. This is what is known as the Laplace Devil. Thus, if the devil knew at a certain instant the position and momentum of the atoms that compose the universe, its past and its future would be totally pre-established and could be determined by the laws of classical physics. This line of thought held an arduous debate about free will, but the development of statistical mechanics and the establishment of the concepts of irreversibility and entropy of thermodynamic processes ultimately undermined ideas about predestination and reductionism.

All this occurred in the midst of the development of mathematical logic. Initially propped up by Boole, unifying the rules of calculus as part of the logical operations and that a century later has sustained the development of computing. Subsequently, Frege's contribution to propositional logic and predicate calculus and the work of Russell and Whitehead condensed into his "*principia mathematica*" espoused the idea of mathematics as a solid and consistent body of doctrine based on a set of axioms, in whose framework could find all the answers in a logical and structured way. A sample of this current is the fundamental idea posed by Hilbert, embodied in his second problem and defined as metamathematics, which should be able to respond to any proposal in a mechanistic form, from a complete axiomatic system free of contradictions. It is easy to imagine the reason for this approach. The emergence of mathematical contradictions in axiomatic systems, for example in set theory, led to the development of this new idea as an inescapable goal. But Gödel's incompleteness theorem [1] fully invalidates it, something that is intuitively easy to understand, since it triggers a recursive process that inevitably leads to the metamathematics of metamathematics!

Already in the twentieth century, the development of quantum physics, relativity and the theory of complex systems opened new horizons to the thought. New concepts such as the quantization of the states of a system, the quantum observables, the uncertainty in the observation determined by Heisenberg’s uncertainty principle, the collapse of the wave function of a quantum system produced by the measurement, the loss of correlation between successive states of a system produced by its complex dynamics, the absence of absolute points of reference and the relative perception of space-time, are clear examples of the new scenario that overturns the classical concept of reality. Undoubtedly, from an anthropic point of view, this new perspective may cause a feeling of emptiness and insecurity when we ask ourselves about the nature of reality.

If we analyze the nature of the physical models we can say that they are consequence of observation and experimentation, leading to the definition of a theoretical model scrutinized by a recursive process of verification. However, there definition in mathematical terms could be considered merely as instrumental, something that would surely refute mathematicians, ensuring that mathematical models are essential. But on the other hand it can be seen that the mathematical structure is based on a set of inescapable and inexhaustible axioms, as shown by Gödel's incompleteness theorem.

Let us take as an example the models of Newton's mechanics or Maxwell's electromagnetism, which have no physical connection to the underlying reality and in which fields are defined as the product of observation and can be considered real at certain functional level, but which are fictitious at an underlying level. We now know that at the quantum level electromagnetic interactions are produced by means of photons, but the electromagnetic model says nothing of this. Fortunately there is always some hint of the underlying reality. Thus, we can mention the photoelectric effect that led to the discovery of photons, or the fact that Maxwell's equations are not invariant in a Galilean transformation that led to the Lorentz transformation and the discovery of special relativity. In the case of Newton’s mechanics the model emerge from the deeper reality of general relativity and, according to observations, below this there must be other levels of functional complexity.

This indicates that we could consider the physical models as simple axioms, since in a certain layer of functional reality they represent the system without needing to connect with an underlying reality. Consequently, they are emergent and irreducible models and only when they are scrutinized at the edges of the model there are signs of another more complex reality.

**What do we mean by information?**

If we had asked this question only a little more than half a century ago we would have said very generically that it is something linked to the acquisition of knowledge and of course that it is something cannot be quantified. It is as if we had wondered what the mass was before Newton had laid the groundwork for dynamics. Of course, all these concepts would be known in an intuitive way and this is the reason for their existence in the language. But it was not until the mid-twentieth century that Claude Shannon created the information theory (IT), whose foundational publication [2] established the metric of a source of information through the concept of information entropy and determining the capacity of a communication channel. At present, all these concepts have been extended to the quantum world, giving rise to quantum information theory (QIT) [3].

As already noted, this revolution began with Boole creating the algebra that bears his name, being of vital importance for the creation of IT, since it established the nature of logical variables. Also the discovery of the sampling theorem is key in the theoretical development, since it provides a bridge between the continuous and the discrete signals, allowing a sequence of samples to represent the information contained in a continuous signal, whenever certain conditions are verified, resulting that a signal can be represented or coded as a set of 0s and 1s. Indicate here that it was Shannon who defined the term bit as the basic unit of information and can take the value 0 or 1. In the case of quantum information the unit is the qubit.

Although the initial aim of IT was to study the transfer of information through a noisy communication channel, today it has become a basic tool in all fields in which information is an essential element such as mathematics, physics, engineering, biology, etc. This makes its practical application extend to all areas of knowledge, being able to put as examples not only communication, but also to the processing of language and linguistics, pattern recognition, computation, etc. And what to say about the social impact, reaching to terms such as "information society" and "virtual reality."

For this reason, we may ask: Is information only an ethereal representation of reality, a subjective perception, or on the contrary is something inseparable from reality? A remarkable milestone in the interpretation of information as something physical is the argument raised by Leo Szilard [4] to solve the Maxwell's demon paradox, in which he concludes that the decrease of entropy produced in the system by the devil is compensated by the increase of entropy in the memory of the demon.

In this sense, the IT provides a fundamental key as it is the Shannon limit that states that $E_b/N_0 \to \ln 2$ , being $E_b$ the minimum energy needed to encode a bit and $N_0$ the noise power spectral density of the medium, and considering that $N_0 = k \cdot T$ , where $T$ is the absolute temperature of the medium, the bound established by Bekenstein is obtained [5] where $E_b \geq k \cdot T \cdot \ln 2$ , which establishes a link between information and energy. By a different way, Rolf Landauer [6] established the energy necessary to erase a bit of information, whose value is $k \cdot T \cdot \ln 2$ and is known as Landauer's principle, coinciding this amount with the value established by Bekenstein bound.

Another conclusion drawn from IT, which usually goes unnoticed, is to show that information has no meaning, what is known as "information without meaning." This conclusion is drawn directly from the very nature of communication in which a transmitter sends information to a receiver that in fact is a sequence of bits without structure. Therefore, the receiver can only interpret that it has received a sequence of bits. This indicates that the interpretation of information requires processing to transform it into a message. In this sense, algorithmic information theory (AIT) [7], also known as Kolmogorov Complexity (KC), gives a broader view, which allows measure the complexity of any mathematical object by means of axiomatic information processing. As a consequence, information processing emerges as an element of reality from which arises the concepts of compression, recognition, learning, knowledge and the emergence of structured systems in functional layers. This model of behavior is something ubiquitous in nature, in which systems formed by particles, cells and individuals exchange information, adjusting their behavior. Thus, if the system is considered as a whole, the level of detail in the lower layers is greater, leaving this complexity hidden to the upper layers.
A paradigm of this behavior is statistical physics in which the Maxwell-Boltzmann and Bose-Einstein distributions have a theoretical development equivalent to that provided by IT [8], [9] and where one can clearly see how certain macroscopic properties of the system, such as pressure and temperature, emerge, leaving behind the enormous underlying complexity. Moreover, concepts developed independently in both bodies of doctrine such as that of

entropy have an identical mathematical structure, although the interpretation of thermodynamic entropy continues to raise controversy.

But examples are abundant and in fact it seems that the significance of information in natural processes is the rule. Thus, the theory of relativity establishes the principle of causality. However, if the transfer of information were not causal this principle would be inconsistent, so that information as well as energy in any of its manifestations must comply with this principle. This is manifested in the entanglement of quantum particles, so that when a measurement is made on one of the entangled particles the quantum state of the other particles is changed instantaneously, regardless of their location. At the time, this gave rise to the EPR (Einstein Podolsky Rosen) paradox, which maintained the impossibility of this behavior by violating the principle of causality, so quantum theory should be an incomplete theory in which there should be missing variables that restrict the consequences of entangle particles. However, Bell's theorem rebuts this idea, since it states that no physical theory of hidden local variables can reproduce all predictions of quantum mechanics. Consequently, the formulation of quantum mechanics is a complete theory, which is not an impediment to the existence of hidden non-local variables that are not observable at the level of the quantum model, as is the case with other physical models in which the underlying reality remains hidden.

As may be posed from an IT standpoint, the formulation of a model does not prevent the described system from having an extraordinarily complex underlying reality that does not emerge into higher layers of functionality and which, of course, hides its nature. However, it does not necessarily have to be an obstacle for this complexity can be scrutinized and used technologically, as is the case of quantum computing. Nonetheless, the possibility that the remote modification of the quantum state of entangled particles can be used for the transfer of instantaneous information at a distance seems to be unfeasible, since it requires the use of an additional classical communication channel, subject to the theory of relativity [10], and therefore to the principle of causality.

To justify the possible existence of an underlying reality on which emerges another totally irreducible, we can establish an abstract model, but we can also save much of the complexity through an intuitive model that is often used in advertising. Imagine a photograph in which each pixel is actually another photo, so that its luminance and chrominance at the global level coincide with the luminance and chrominance of the emerging photo pixel. In this way, we can observe two different and irreducible realities, since from the emerging photo we can never deduce the characteristics of the underlying information. Only in the case that we can establish observables at the underlying level can we deduce their complexity. In the present example by means of a zoom, whose functionality does not correspond to the overlying level! Similarly, in order to have a temporal dynamics, video sequences can be considered whose pixels are in turn other video sequences. So that, a parallelism with statistical physics can be established, in which, for example, internal energy, volume and energy transfer are observables from the overlying level, while velocity, momentum and excitation of the particles, as well as the complexity enclosed in its mass and in its quantum nature are observables at different underlying functional levels.

Space-time also provides clues that suggest that the reality we observe as space-time is based on an underlying reality that for the moment hides its secrets. A simple way to verify this is to analyze the response of a communication channel in which beams from different propagation paths establish the channel transfer function, as a consequence of the interference between beams. But the electromagnetic signal is based on the propagation of photons that are not interfering with each other, which would invalidate the model of interference proposed by the electromagnetic model. The answer to this apparent contradiction is that each photon propagates in different directions and, so to speak, interferes with itself, as can be demonstrated with an interferometer [11]. In addition, if one considers the relativistic phenomenon of time dilation and contraction of the space produced by the photon velocity, it is as if the photon has a timely knowledge of the whole universe, which evidences space-time as an observable and suggests that what we call vacuum is something enormously complex.

At higher functional levels, such as biochemistry, biology, and life sciences, information emerges in a very perceptible way. Thus, nucleotides bases constitute a coding system and information processing that gives rise to mechanisms of self-replication, which make possible the synthesis of amino acids and which in turn constitute a system of coding and processing that materializes in the protein synthesis [12]. Taken together, all this forms an extraordinary system that is the basis of life and that makes the treatment of information a basic tool for understanding these processes, beyond their physicochemical nature.

Perhaps where information appears more explicitly is in virtual reality scenarios, as is the case of natural language, which undoubtedly is due to human perception that materializes in psychological and social behaviors, totally disconnected and irreducible from the underlying reality, as is our biological nature. As a consequence, we can use natural language to show that reality is somewhat circular or relativistic. If we look at the lexicon in a dictionary we will see that the definitions support each other without an absolute reference point. We could justify this fact in that natural language does not respond to a formal definition, but is based on sensory experiences external to the language itself, forming an inconsistent structure that gives rise to paradoxes. But the definition of a formal language, like any other mathematical structure, requires the definition of a set of axioms. Therefore, we could construct a consistent natural language by defining a part of the lexicon as axioms. However, the set of axioms is arbitrary, so the relativistic effect remains. This behavior is not something particular of the languages, but is something generic determined by IT and AIT.

**Conclusions**

It seems obvious that everywhere we look in nature information appears as something ubiquitous. In fact it is the information and its processing that allows to model and to simulate on other physical supports the behavior of the systems. Classically this has been done using mathematical models using analytical expressions, but from a KC point of view they are nothing more than models of information processing. This has always been an intriguing issue that has raised the question about the nature of mathematics and its relationship and parallelism with what we call reality.

IT, often referred to in the literature, and AIT, which seems to be the great unknown, give an expanded view compared to conventional mathematics. Thus, we can consider the mathematical process as something situated in a layer of virtual reality, in which information can be treated in an abstract way, which would answer the question about the nature of mathematics. But this raises fundamental questions for this to be possible. What is the nature of the information? Is information a real entity? And here we have to deal with the axiomatic inconsistency of natural language. What does real mean?

Fortunately, physics gives us some clues originated by the study of communication and computation, which have led to Bekenstein bound and Landauer's principle, and which establish a link between energy and information, although these are only criteria of minimal energy to materialize a bit in a classical scenario. On the other hand, statistical physics shows a striking parallelism with IT that has sometimes led to the claim that information is physical. However, there are difficulties for a conclusive statement, including the interpretation of physical entropy as a measure of information, equivalence of energy and information flows, minimum energy criteria already mentioned, as well as the need to establish this type of criteria at quantum level. At the classical level, these difficulties can be motivated by the fact that the information is an observable that depends on the absolute temperature, reason why its perception is relative to the means. There is also a very ingrained interpretation problem such as the consideration that entropy is a measure of the disorder of a system, when in reality it is a measure of its complexity, that is, of the amount of information necessary for its description.

On the other hand, IT and above all AIT show that the information processing gives rise to structures of irreducible functional layers that emerge from an underlying informational reality, indicating that the complexity must increase as you go deeper into the underlying layers. All this seems to be in agreement with observable reality, so its equivalence can be conjectured, proposing a strategy of analysis aimed at solving the raised questions.

This conception seems to provide a vision of reality that could be defined as vertiginous. Thus, the evaluation of the complexity of a continuous variable system is incomputable, solving this situation through a process of renormalization that allows showing the emergent information. Likewise, Kolmogorov's complexity is a non-computable measure, equivalent to Gödel's incompleteness theorem, and ironically is embodied in the "*full employment theorem*", which is a corollary of Kolmogorov's complexity theorem, which in the community of programmers establishes that the whole sector would remain occupied indefinitely to obtain an optimum compiler. A statement which is directly extendable to all areas of knowledge, which raises the question: How deep can reality to be scrutinized?

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