It from Bit *and* Bit from It

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Abstract

It is tempting to think that, once we have understood scientific theories behind IT and BIT, it will be easy to fix an order of precedence between them. I argue that it will not. Contrary to appearances, a key to softening this problem of precedence is to be found in the meaning of FROM, understood as rigorous reconstruction, and that of OR, which in the framework of epistemic loops is put on a par with AND. But, as anyone would expect, I begin with IT and BIT, suggesting that we adopt an attitude of epistemological modesty and treat the observer as informational agent.

1 IT, or Against ontology

Our brains are wired to do many different things: to look for a cause of every event they register, so that cause-effect relations appear to be fundamental elements of reality; or to construct representations of the external world, implying that we are not apt to question its very existence. In this sense, solipsism is a remarkable achievement of the human mind, because it goes against the nature of the human brain. It is interesting to ask what will remain of reality of the external world if one clears up the prejudice that X or Y are fundamental just because our brains are wired to believe so. Human habits, conventions, natural inclinations, and neuronal connections all have to go.

But can they all go? Take a problem of foundations of physical theory. What will remain of a theory if one clears away its human inventors and users? Probably not much. Quantum mechanics relies on a convention between scientists about the possibility of multiple runs of experiments on strictly identical systems, or different measurements identified over time as being one, or some other such statement [19, p. 290]. General relativity uses Riemannian manifolds, but it is an open question whether this geometric picture is adequate at all scales. Henri Poincaré infamously tried to motivate the inevitability of Euclidian geometry [20], however, as the sorrow history of Kantian science shows [12], *a priori* claims—that something conditions all experience rather than being a theoretical entity supported by it—usually end up being false.

On what foundation, then, can we build physical theories? There aren't many candidates; ontological commitments about the world aren't among them. Any such commitment would keep us shut inside the wired brain: here and now we may simply lack the imagination that would let us dispose of wired X or Y. What remains? The mathematical structure of physical theories, plus the relations between theories based on their mathematics. I call this attitude *epistemological modesty.* It differs from structural realism in consistently denying that physics provides unconditional, larger-than-one-theory knowledge about reality, even in the case when reality is thought to be made of structures. Science does not warrant absolute claims, and it is appropriate to leave the latter to metaphysics or personal beliefs.

Writing about the measurement problem in quantum mechanics as early as 1939, London and Bauer emphasized that physics can make an impact on philosophy insofar as it makes "negative philosophical discoveries", i.e. certain philosophical positions cannot be maintained as a result of accrued physical knowledge [17]. The possibility of negative philosophical discoveries is one reason why physics does not warrant unconditional metaphysical assertions of the sort 'true ontology of the world is so and so'. But physical theories, for sure, rely on certain principles. Aren't these first principles our best candidates for being primeval truths about reality? Epistemological modesty suggests that they are not specimens of ultimate knowledge about nature; independently of one's ontological commitments, they only retain a minimal epistemic status as postulates needed for the derivation of a specific theory.

2 FROM, or Reconstruction of physical theory

We call *reconstruction* the following schema adopted to the needs of quantum theory and different from Carnap's notion of rational reconstruction [5]: Theorems and major results of physical theory are formally derived from simpler mathematical assumptions. These assumptions or axioms, in turn, appear as representations of a set of physical principles in the formal language. Reconstruction consists of three stages: first give a set of physical principles, then formulate their mathematical representation, and finally rigorously derive the formalism of the theory.

As opposed to interpretation, the three-stage structure of reconstruction gives it supplementary persuasive power: established as valid results, theorems and equations of the theory become unquestionable and free of suspicion. 'Why is it so?'—'Because we derived it.' The question of meaning, previously asked with regard to the formalism, now bears, if at all, only on the selection of principles. The meaning of the theory's mathematical apparatus becomes free of mysteries.

As in the 19th-century mathematics, in theoretical physics the axiomatic method must be separated from the Greek attitude that axioms represent truths about reality. Historically, progress was due to understanding that an axiom may no longer be considered an ultimate truth, but merely a fundamental structural element, i.e., an assumption that lies at the basis of a certain theoretical structure. In mathematics, after departing from the Greek concept of axiom, "not only geometry, but many other, even very abstract, theories have been axiomatized, and the axiomatic method has become a powerful tool for mathematical research, as well as a means of organizing the immense field of mathematical knowledge which thereby can be made more surveyable" [14]. A similar attitude is to be adopted in physics. Within the framework of reconstruction, epistemological modesty suggests the following attitude:

Principle 1. If the theory itself does not tell us that the states of a system (or other variables) are ontic, then do not take them to be ontic. [13]

This economical precept requires that we bracket all subjective influence: wirings of one's brain, one's personal beliefs about the nature of reality or personal motives that drive the choice of first principles. Indeed, explanatory power of reconstruction is a power of explaining where the structure of the theory comes from, not necessarily that of explaining the real world. Reconstruction shifts the focal point of traditional interpretations: its added value for better understanding quantum theory originates in the insights into the structure of the theory, made possible thanks to information-theoretic techniques.

3 BIT, or Observers as informational agents

Historically, quantum physics has been conceived as a theory of non-classic waves and particles, while special relativity has been thought of as a theory of moving rods and clocks. Vladimir Fock argued that such views were only acceptable at early stages of theoretic development, when too few experimental results were available and dominant philosophy still couched in the earlier physical theories. In the same vein, Fock formulated what he saw as the main problem of quantum mechanics: "[The] difference is fundamental: from the epistemological point of view, atomic objects and measuring devices are to be considered as belonging to different categories" [11]. Thus, measurement devices and observers are essential for quantum mechanics; but precisely to what thing do these words refer? There is no consensus. As John Wheeler emphasized, it is extraordinarily difficult to state sharply and clearly where "the community of observer-participators" begins and where it ends [23]. Quantum theory itself says nothing about physical composition of the observer: this term has no quantum description. One cannot infer from a set of measurements, be they projective or POVM, if the observer's IT is a human being, a machine, a stone, a Martian, or the whole Universe.

Remarkably, in spite of what has just been said, quantum mechanics provides information about the content of observation registered by the observer. Differently constituted observers, even if one is a butterfly on Earth and the other a drop of methane on Titan, will obtain the same probabilistic results provided they manage to measure the same quantum system. How is this possible? Only because quantum mechanics uses abstract mathematics: it deals with 'observers' who possess information about 'systems', not with methane or butterflies.

Thus the standard quantum formalism relies on a cut between the observer and the system [7, 22]. No ruse can remove this "shifty split" [1]: the formalism only applies if the observer and the system have been demarcated as two separate entities. Physical properties of the system, on one side of the split, do not exist independently of the observer, on the other side of the split, and can only be instantiated during measurement of the system by the observer.

In a little-known branch of his relative-state interpretation, Hugh Everett argued that observers are physical systems with memory, i.e., “parts... whose states are in correspondence with past experience of the observers” [10]. This is the *universal observer* hypothesis: any system with certain information-theoretic properties can serve as quantum mechanical observer, independently of its physical constituency, size, presence or absence of conscious awareness and so forth. Carlo Rovelli claimed that observers are merely systems whose degrees of freedom are correlated with some degree of freedom of the observed system: “Any system can play the role of observed system and the role of observing system. . . . The fact that observer O has information about system S (has measured S) is expressed by the existence of a correlation. . . ” [21]. However, the universal observer hypothesis can be challenged. For example, Asher Peres maintained that “the two electrons in the ground state of the helium atom are correlated, but no one would say that each electron ‘measures’ its partner” [18]. What is this ongoing controversy telling us about the observer? Nothing about its precise physical constitution; only that to draw a limit of the observer’s IT remains an unresolved problem.

Thus a defining characteristic of observer does not belong with IT but with BIT: it must have information about some physical system. In quantum mechanics, this information fully or partially describes the state of the system. Quantum observer then measures the system, obtains further information and updates the description accordingly. Physical processes listed here: measurement, updating of the information, ascribing a state, happen in many different ways depending on the physical constitution of the observer. Memory of a computer acting as an observer, for instance, is not materially equivalent to human memory, and measurement devices vary in their design and functioning. Still one feature unites all observers: whatever they do, they do it to a *system.* An observer without a system is a meaningless nametag, a system without an observer is a mathematical abstraction. Quantum-mechanical state description only makes sense if the degrees of freedom of the system do not pop up or disappear during unitary evolution. Therefore, the observer is first and foremost a system identification machine, which identifies and keeps track of degrees of freedom relevant to the observed system. Different observers equipped with clock hands, biological eyes, optical memory devices, internal cavities, etc., all share this central characteristic.

Definition 1. An observer is a system identification algorithm.

Particular instances of quantum observer can be made of human flesh or silicon. ‘Hardware’ and ‘low-level programming’ can be different, yet all concrete observers perform an abstract task of system identification. This task can be viewed as an algorithm for a universal computer analogous to the Turing machine: take a tape containing a complete list of degrees of freedom and send a machine along this tape so that it puts a mark against the degrees of freedom that belong to the system. Every concrete instantiation of observer will execute this task in its own way, yet they are all described by the same abstract model. Thus the common-lore view of many individual observers, one hastily printing, another yawning, a third one moving around his DNA strands, is replaced by an abstract information-theoretic notion of observer.

4 OR in epistemic loops

Some physicists have been slow to appreciate the epistemological lessons of the cut between the observer and the observed. For instance, Einstein believed that a postulate about the existence of a particle or of another elementary object would remain a necessary ingredient of physics. As late as 1948, he wrote in a letter to Born:

> We all of us have some idea of what the basic axioms in physics will turn out to be. The quantum or the particle will surely be one amongst them; the field, in Faraday's or Maxwell's sense, could possibly be, but it is not certain. [2, p. 164]

In Einstein view, physical theory had to be based on elementary objects, i.e. primitive constituents of reality, and facts about such objects should build up to form an account of all physical phenomena. In another illuminating piece of his late writing, Einstein acknowledges the presence of the cut in physical theory between objects and measurement devices, but refuses to recognize its fundamental character. This echoes his distinction between 'principle' and 'constructive' theories [8] and his dislike of the former [3]:

> One is struck [by the fact] that the theory [of special relativity] . . . introduces two kinds of physical things, i.e., (1) measuring rods and clocks, (2) all other things, e.g., the electromagnetic field, the material point, etc. This, in a certain sense, is inconsistent; strictly speaking measuring rods and clocks would have to be represented as solutions of the basic equations (objects consisting of moving atomic configurations), not, as it were, as theoretically self-sufficient entities. However, the procedure justifies itself because it was clear from the very beginning that the postulates of the theory are not strong enough to deduce from them sufficiently complete equations . . . in order to base upon such a foundation a theory of measuring rods and clocks [9, pp. 59, 61].

Against Einstein's hopes, development of physical theories after 1905 proved right those who thought it unreasonable to expect a theory of measuring rods and clocks based on a set of "stronger postulates", while requiring that this theory provide an account of all physical phenomena measured by such rods and clocks. Not only did this development dash Einstein preference for constructive theories, but it calls for a different schema of how physical theories relate to each other. With respect to choice between IT FROM BIT or BIT FROM IT, this schema will demonstrate how OR can be supplemented with AND.

Consider the following representation of physical theories in the form of epistemic loops (Figure 1), whose philosophical ancestry goes from Wheeler [24] back to Descartes [6]. On this view, the usual reductionist pyramid of theories is replaced by an ensemble of circles representing descriptions of phenomena by interconnected theories. An individual theory is obtained by cutting the loop in order to separate target objects of the theory from its presuppositions. Therefore, the cut is a *logical* necessity: it is logically impossible to describe the loop as a whole within one theory.

Each way of cutting the loop fixes one part of the loop in the position of derived concepts, or results, of a theory, while the other part becomes a given, i.e. it belongs to the domain of this theory's meta-theory. If the loop is cut differently, these two parts can exchange roles: *explanans* becomes *explanandum*, and what has been *explanandum* becomes *explanans.* Cutting the only allowed operation, while the form of the loop is preserved; its geometry cannot accommodate the reduction pyramid that descends from less fundamental to more fundamental theories with "stronger postulates". This new schema is circular, which may raise suspicion; however, this circle does not contain a contradiction. On the contrary, the relation between theories becomes that of mutual illumination rather than reduction. Parts of the loop taken as a given for the purposes of constructing one theory become results and derivative concepts within the framework of another. Under the change of the cut, what had previously been a fixed or metatheoretic part becomes itself a theory that explains the functioning of measuring devices of the other theory it had served to reconstruct. As if they were realizing Fock's idea, measuring devices of a theory can remain meta-theoretic and abstract in one loop cut, while in a different cut their constitution can be explained and their functioning predicted.

Constructive physical theories based on objects (IT) and information-theoretic approaches (BIT) belong to different parts of the loop. Two cuts are possible, but they cannot be made simultaneously. As a result, any one theory can give an account of only one half of the circle, leaving the other half for meta-theoretic assumptions. In the cut shown on Figure 1, information belongs to meta-theory of constructive physical theory, and physics is therefore based on information. In a different loop cut (Figure 2), informational agents are physical beings, and one can describe their storage and manipulation of information by means of effective theories that are reduced, or reducible in principle, to a constructive physical theory.

It is mandatory to cut the loop, which makes it impossible to close within one theory the gap between the observer and the observed. Thus the loop view allows a non-reductionist reading of the statements that mark a no small change in the conception of physics, e.g., Jeffrey Bub's dictum that information must be recognized as "a new sort of physical entity, not reducible to the motion of particles and fields" [4]. Though information is an entity in the loop epistemology, the term 'entity' does not mean that it is real: it is not a basic ingredient of constructive physical theory nor an object in Einstein's sense, like particles or fields. If it were otherwise, i.e. if information were a basic *physical* entity, then the information-theoretic viewpoint would not be able to provide a foundation

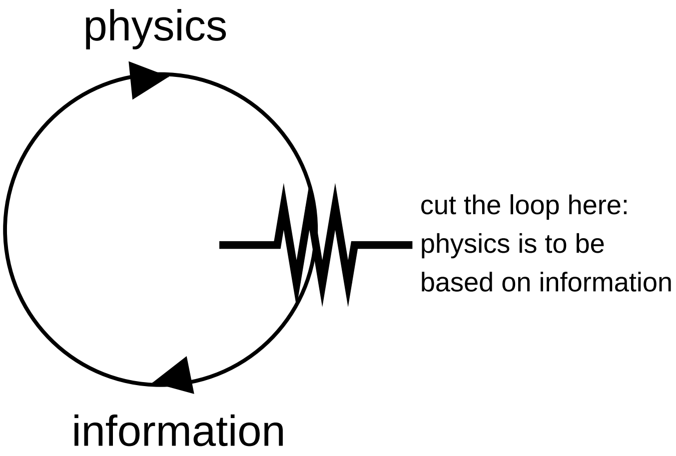

Figure 1: Loop cut: physics is informational

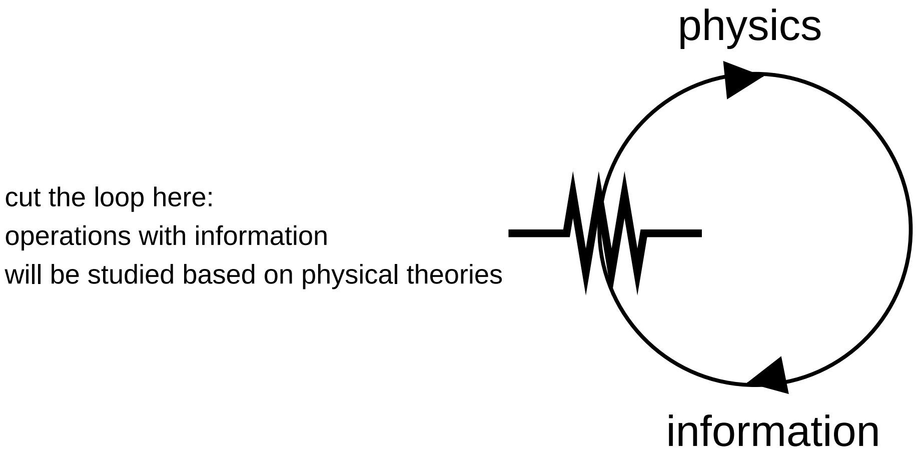

Figure 2: Loop cut: information is physical

for quantum *physics*, for the whole argument would have been irreparably circular. The loop view avoids this problem by cutting the circle in two different ways. In one cut, conventional physical concepts, including particles and fields, are reduced to information; but in a different loop cut, information itself becomes a derivative notion within a constructive theory based on particles and fields. In the cut shown on Figure 2, reconstruction of IT from BIT is a meaningless task because physical theory (IT) is taken for granted. In the cut shown on Figure 1, it is the other way round. Once a cut has been fixed, it becomes a *logical* error to ask questions that only make sense in a different loop cut. For instance, a critique of quantum information based on Landauer's dictum "information is physical" [16] merely mixes two cuts. Similarly, Einstein's plea for "stronger postulates" is an epistemological illusion, for any consistent defense of this view would lead to logical inconsistency of operating in two cuts at once. Epistemologically speaking, we are better off gazing at the epistemic loop from a distance, from a vantage point that allows us to learn from different ways of constructing theories, i.e. where both IT FROM BIT **and** BIT FROM IT are acceptable—but not simultaneously.

5 Conclusion

I argued in this essay that the meaning of FROM should imply, not some vague linguistic notion of "it follows", but a rigorous mathematical reconstruction. Hence, by epistemological modesty, only belongs to physical theory that which is necessary for its reconstruction. Ontological beliefs can be replaced by a set of foundational terms and axioms not pretending to describe reality: they are accepted only for the purposes of deriving a particular theory. The problem of IT is therefore not as scientifically sound as it may seem.

On the contrary, the question of BIT is fundamental. The observer is capable of identifying a system, and this definition is purely abstract and informational, even if all particular instances of observers are material objects. The reason why BIT is currently more interesting than IT is purely circumstantial: we learn more today about the structure of quantum theory by pursuing information-theoretic studies of the observer. New insights will yet appear in the future.

The key to understanding the opposition between IT and BIT is in choosing a vantage point from which OR looks as good as AND. Then this opposition becomes unnecessary: the loop view simply dissolves it. For a scientist, it may seem uncomfortable to live within an epistemologically circular structure—but this circularity is not a logical disaster, rather it is a well-documented property of all foundational studies. As Husserl said:

> Thus we find ourselves in a sort of circle. The understanding of the beginnings is to be gained fully only by starting with science as given in its present-day form, looking back at its development. But in the absence of an understanding of the beginnings the development is mute as a development of meaning. Thus we have no other choice than to proceed forward and backward in a zigzag pattern; the one

> must help the other in an interplay. Relative clarification on one side brings some elucidation on the other, which in turn casts light back on the former. [15, p. 58]

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