On the Relational Character of Physical Reality

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> *"Science [...] is a system of relations. [...] it is in the relations alone that objectivity must be sought; it would be vain to seek it in beings considered as isolated from one another."*

With this statement,[1] Henri Poincaré rejected the metaphysical assumption that reality is grounded in *universals*, i.e., properties that can be instantiated by different entities. In metaphysics, the focus on universals traces back to Aristotle and is central to what is now broadly referred to as *realism*. The way Poincaré opposes realism, though, is not by treating properties as mere names without intrinsic connection to reality, as *nominalists* (anti-realists) do, but by claiming that reality resides in the relational, meaning mathematical,[a] structure of properties, a view currently known as *structural realism*.[2] If properties aren't fundamental, then substance-based ontology is undermined too, since elementary substances are by default instantiations of a fixed set of properties, so the primary element of reality lies not in the entities themselves, but in the coherent structure in which they are embedded.

Metaphysical claims serve as axioms upon which science is built. Since they are, by construction, unfalsifiable, their justification must lie in their ability to provide a coherent framework free of paradoxes. In what follows, I argue in favor of structural realism by showing how this metaphysical approach can resolve certain paradoxes. I also illustrate how a structural view of reality already underpins contemporary descriptions of the world, though it is often not explicitly emphasized.

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COMPLEMENTARITY

In its broader sense, complementarity refers to an unavoidable trade-off in the precision with which two properties can be simultaneously measured. This phenomenon finds a clear expression in the practice of photography: adjusting the aperture of a camera, while keeping all other settings constant, creates a trade-off illustrated in Figure 1. A smaller aperture allows less light to reach the sensor, resulting in a darker image but with greater depth of field, meaning that objects at varying distances remain in focus. Conversely, a wider aperture lets in more light, producing a brighter image but reducing the depth of field, so only a narrow range remains sharp while the rest becomes blurred. This very trade-off explains why people instinctively squint their eyes to see distant objects more clearly.

Complementarity in photography admits a clear explanation[b] and does not challenge any metaphysical assumptions, since brightness and depth of field are understood not as intrinsic properties of the image itself, but as properties related to our perception of the image as an arrangement of points (e.g., pixels) that together form a coherent whole. The situation becomes conceptually troubling, however, when complementarity arises in the context of properties attributed to a single, indivisible particle. This is

[a] In the introduction of *The Value of Science*,[1] Poincaré writes "*what we call objective reality is [...] the harmony expressed by mathematical laws.*"

[b] A scene emits light in all directions, and some of it passes through the camera lens and is directed toward the sensor. Ideally, light rays coming from the same point in the scene should converge at the same point on the sensor. When this happens, the point appears sharp rather than blurry. However, this occurs only if the lens is properly focused for the distance to that point. A small aperture allows less light to pass through, making the image dimmer, but it also reduces the variation in incoming angles, resulting in fewer points having large mismatches, so a larger portion of the image appears sharp, a condition known as wide depth of field. In contrast, a wide aperture lets in more light and brightens the image, but the light arrives from a broader range of angles, increasing the number of mismatches, so a smaller portion of the image appears sharp, a condition known as shallow depth of field.

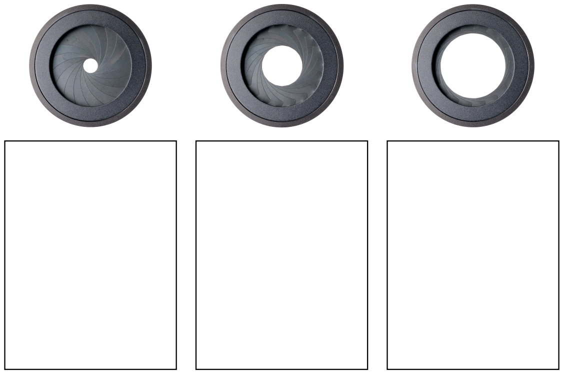

Figure 1: Three photos of the same composition are compared for three different aperture settings, while the rest of parameters are kept constant. Brightness and depth of field vary in a complementary fashion as the aperture, i.e., the opening for light, changes.

precisely the case with photons, the fundamental building blocks of light.

The ability of a photon to pass through a specific type of filter, called a polarizer, is associated with a property called polarization. A polarizer can be oriented in any direction. For instance, if it is oriented vertically (↕) and a photon passes through it, the photon is said to be vertically polarized, and analogously for any other orientation. When a photon is known to be polarized in a certain orientation, such as vertically, and is then sent through a polarizer oriented in the orthogonal orientation, meaning horizontally (↔), the photon is blocked. Interestingly, if a vertically polarized photon is sent through a polarizer tilted at 45 degrees (⤢), it passes through with 50% probability.[c] This behavior suggests that the property that imposes a binary distinction between vertical and horizontal outcomes (↕ or ↔) is complementary to the one distinguishing diagonal outcomes (⤢ or ⤡), i.e., precise knowledge of one entails maximal uncertainty about the other.

THE EPR PARADOX

The existence of complementary properties within a single fundamental particle, such as a photon, challenges the conventional notion of reality, which pressuposes that fundamental entities possess definite and intrinsic attributes. If two properties of an entity cannot be independently measured, because measuring one affects the outcome of the other, how can it be justifiable to treat them as distinct? Do they both correspond to an element of reality? Are they both, to put it in philosophical terms, universals? In 1935, a seminal paper by Albert Einstein, Boris Podolsky, and Nathan Rosen explored this issue in depth, proposing the following sufficient criterion for a property (or quantity as they refer to it) to be considered an element of reality:[4]

> *"If, without in any way disturbing a system, we can predict with certainty the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity."*

Complementary properties may initially seem ineligible to both qualify as elements of reality, however, a phenomenon called *entanglement* introduces a subtle yet profound counterexample. Entanglement refers to a correlation between two (or more) particles whose measurement outcomes remain correlated[d] regardless of the measurement orientation, even when the orientations are complementary. For example, two photons can exhibit perfect correlations when both are measured in the vertical polarization orientation: either both pass through the vertical polarizer or both are blocked. Remarkably, similar correlations persist when the measurements are performed in a complementary orientation, such as at 45 degrees. This behavior would not be observed with two photons that are merely vertically polarized, since such pho-

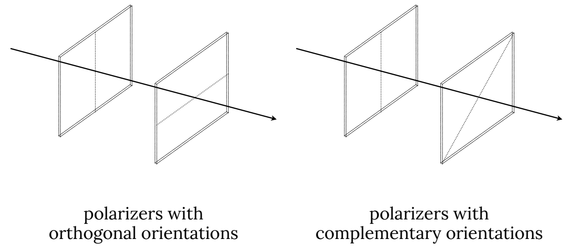

Figure 2: Two polarizers placed in orthogonal (left) and complementary (right) to each other orientations along the propagation of a photon.

[c]For a thorough discussion of the behavior of polarized photons, as well as a clear and comprehensive presentation of quantum mechanics, see Ref. [3].

[d]Correlation is a measure of how strongly one set of values depends on another. For instance, tossing two different coins produces two sets of completely uncorrelated (independent) outcomes. In contrast, when a single coin is tossed, the result on one side is perfectly correlated (more precisely, anti-correlated) with the result on the other side: if one side shows heads, the other must show tails, and vice versa. Such perfect correlation enables us to predict the unobserved value with certainty based on the observed one.

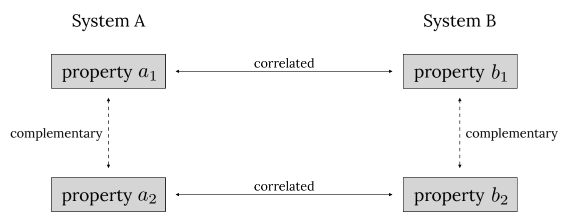

Figure 3: Schematic representation of two systems, A and B, being entangled by having their complementary properties correlated with each other.

tons would show correlations only in the vertical orientation, while measurements in the complementary orientation would yield entirely random outcomes. In essence, entanglement represents a type of correlation that is independent of the choice of complementary orientation,[5] giving it a non-trivial character not found in classical, everyday correlations. A schematic representation of how entanglement is mapped onto correlated complementary properties is given at Figure 3.

Taking this non-trivial type of correlation into account, Einstein, Podolsky, and Rosen argued that when two systems are entangled, measuring one allows for a precise prediction of the other without disturbing its complementary property. Thus, both properties could, in principle, be known with arbitrary accuracy. This, they claimed, contradicts the principle of complementarity and led them to conclude that the physical description of reality must be incomplete. This bold conclusion sparked a heated debate at the time, and the controversy remains alive to this day. Most physicists adopted a more instrumental perspective, focusing less on the ontological question of what is real in nature, and more on the epistemic question of how we can acquire knowledge about it. As Niels Bohr put it:[6]

> *"There can be no [...] unambiguous interpretation of the symbols of quantum mechanics other than that embodied in the well-known rules which allow to predict the results to be obtained by a given experimental arrangement described in a totally classical way."*

From a philosophical point of view, Bohr's perspective aligns closely with nominalism, in which the terms used to describe properties do not necessarily correspond to real universal entities, but rather serve as a sufficient framework for understanding the operational context in which the current practice of physics functions, namely, how theories are used to predict and interpret experimental outcomes. Einstein, Podolsky, and Rosen, by contrast, can be classified as realists, assuming that reality consists of universal properties and seeking to determine whether a physical theory accurately maps onto them.

An instrumental approach to science is certainly a safe position, as it adopts an agnostic stance toward deeper questions about reality. However, the ontological question of what reality is actually made of cannot be so easily dismissed, as the pursuit of understanding the nature of reality has always been a central driving force of science. From a realist point of view, it is reasonable to hypothesize that the properties currently attributed to particles, such as photons, emerge from a more fundamental physical theory. The properties of that deeper theory would then be regarded as the truly "real" ones. However, this line of thought ultimately leads to an infinite regress. A more coherent metaphysical stance is to shift attention away from the properties themselves and focus instead on the relationships among them. In other words, physical properties are defining features of representations of reality, though such representations need not be unique. Therefore, any search for a consistent ontology should focus not on representation-specific terms, but on the relations that reveal a shared underlying reality.

OTHER PARADOXES

While the above discussion might seem far removed from everyday experience, analogous metaphysical issues appear in classical philosophical paradoxes. For instance, at the beginning of the early second century AD, Plutarch described the following philosophical conundrum:[7]

> *"The [...] ship in which Theseus sailed [...] was kept by the Athenians up to the time of Demetrius Phalereus.*[e] *They constantly removed the decayed part of her timbers, and renewed them with sound wood, so that the ship became an illustration to philosophers of the*

[e]The alleged time span between the mythical hero Theseus and the Athenian orator Demetrius Phalereus corresponds to nearly a millennium.

> *doctrine of growth and change, as some argued that it remained the same, and others, that it did not remain the same."*

The *Ship of Theseus* paradox appears meaningful only under the assumption that the essence of an entity entirely resides in some underlying material substance. If that is the case, analogous paradoxes arise for entities such as human beings, companies, and nations. These terms, however, apply to configurations that preserve relational continuity over time. Language itself reflects a tacit commitment to structure over substance in defining what entities are and how they persist through change.

A contemporary philosophical issue that is not exactly paradoxical but appears at first sight oddly coincidental is the *anthropic principle*, introduced by Brandon Carter in 1974, stated as follows:[8]

> *"The Universe (and hence the fundamental parameters on which it depends) must be such as to admit the creation of observers within it at some stage."*

This view, which is closely tied to theological notions like the fine-tuning argument, implicitly relies on the metaphysical assumption that the fundamental parameters of the universe exist as independent entities. From that perspective, it appears surprising that the values of these parameters should align so precisely. However, if the relationships among the parameters are instead regarded as fundamental, then the specific values they take can be seen as quantitative manifestations of those underlying relational constraints.

SAME REALITY DIFFERENT DESCRIPTION

Apart from resolution to paradoxes, it is worth also providing some constructive examples that support the relational character of reality found already in our understanding of the world.

An object falling free to the ground is commonly explained by referring to the gravitational force. *Force* is a concept that when used within the context of a set of equations, e.g., Newton's laws of motion, can explain the object's trajectory. Interestingly, though, the same observation can be described without using the concept of force at all. Instead, one can invoke the concept of *energy*. The corresponding law in this case, known as the principle of least action, finds the most energy-efficient path from start to finish. In other words, the exact same phenomenon can be mapped to two distinct mathematical representations.[f] That is why individual concepts are not by themselves the ends, but only the means for describing reality.

A less technical example can be given by considering how the same physical domain, for instance a cave, might be described by two different types of observers, such as humans and bats. Humans perceive its structure through vision, while bats rely on their auditory system, emitting sounds and extracting spatial information from the returning echoes. Despite accessing the same physical environment, each species constructs a distinct internal representation of the cave, shaped by its sensory apparatus. This suggests that what is common across these differing experiences is not the specific descriptions, but the underlying relational structure that gives rise to consistent patterns.

CONCLUDING REMARKS

Nature becomes accessible through sensory experience, an experience that is expressed through concepts defined within frameworks of communication, such as natural language and physical theories. These notions correspond to reference points among which connections can be discovered. When those connections are sufficiently profound, they are referred to as the laws of nature, and they constitute what is ultimately the essence of reality.

Acknowledgements

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[f] For a rigorous treatment of the two formulations of classical physics, known as Newtonian and Lagrangian mechanics, see Ref. [9].

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