

The Nature and Meaning of *Information* in Biology, Psychology, Culture, and Physics

4. The Nature and Meaning of Information in Quantum Physics

4.1 Wave Function and Probability Waves

In quantum physics, equations have been developed that describe the outcomes of experiments with great accuracy; however, physicists increasingly admit that they do not understand how to interpret or conceptualize the terms in the equations (Greene, 2004; Greenstein & Zajonc, 2006; Schlosshauer, 2007). For several decades, physicists focused on applying the equations, while generally ignoring questions about interpreting the equations. This resulted in the development of invaluable quantum-based technologies, including transistors and modern electronics. However, in recent years there has been increasing interest in attempting to understand the nature of reality indicated by these equations. This understanding may be important for developing new technologies such as quantum computing.

The primary equation of quantum physics is in the form of waves that include terms for every potential or possible outcome of an experiment or observation. However, there is intrinsic variability and uncertainty on the quantum level and the waves indicate only the probability that a given outcome will occur. The equations do not deterministically specify which outcome will actually be found. The actual outcome that manifests appears to be random. The waves are described as *probability waves*, and the equation is called the *wave function*. There is no known medium or substance for the waves.

Taken at face value, the wave function indicates that the most realistic description of the state of a particle prior to observation is a combination of all the potential outcomes for the observation. Numerous experiments support this interpretation (Greenstein & Zajonc, 2006; Schlosshauer, 2007). The most well known is the double slit experiment, which indicates that an unobserved individual particle sent toward two slits in a screen responds to both slits. The particle behaves as if it were a wave that is spread over space and that passes through both slits, rather than as a discrete particle passing through only one of the slits. The experimental results display *interference patterns* that are exactly in accordance with the wave function. The combination of possible or potential outcomes in a wave function is called a *superposition*.

4.2 Entanglement

One of the most perplexing features of quantum physics is that particles can become *entangled* in a way that is *nonlocal* (Greenstein & Zajonc, 2006; Schlosshauer, 2007). Two particles become entangled when the wave functions have interaction terms that make the state of one particle related to the state of the other particle. The two particles must be considered as a unitary system. A particle that is not entangled can be completely described with a wave function that does not include terms referring to another particle. The entanglement is nonlocal because the two particles may become widely separated in space, but somehow remain connected. The outcome of a measurement for one particle cannot be predicted, but a measurement of the other particle will always find the expected relationship. A measurement appears to apply to the entangled particles as a unit. Nonlocal entanglement has been verified empirically. The randomness of the outcome that is found with a measurement means entanglement cannot be used to directly transmit useful information between different locations. Entanglement can also occur between a particle and a larger system or the environment.

4.3 Potential Outcomes and Imagination

The terms in the quantum wave function symbolize potential outcomes similar to the human imagination of potential future events. Both involve symbols of potential conditions rather than symbols of existing tangible reality. In both cases, the manifestation of one of the potential outcomes can be viewed as information creation. However, the concepts of media and interpretational infrastructure are clearly applicable for human imagination, but are of doubtful applicability for quantum processes.

4.4 Quantum Physics and Measurement

The Measurement Problem

In quantum physics, a measurement not only obtains information about the state of a system, but also has an active role in forming the state that is found. The system can be in a superposition of possible outcomes prior to measurement. The act of measurement or observation transforms the state of the system from the superposition to a single outcome state consistent with classical physics.

The basic wave function of quantum physics offers no insight into how and when the superposition of probability waves get transformed into the one outcome that becomes manifest (Greenstein & Zajonc, 2006). This is known as the *measurement problem* and is subsumed by the newer term *quantum-to-classical transition*. The wave function predicts that when a particle interacts with a measurement apparatus the particle and apparatus may become an entangled superposition. The wave function does not predict a transformation into one outcome. At present there is not a scientific consensus for conceptualizing the probability waves or for understanding how observed physical reality emerges from them.

Several ideas have been proposed for addressing this measurement problem, but none have convincing support. The key concepts of the theories that have received the most attention are briefly summarized below. The historical development and numerous refinements and criticisms of these theories are beyond the scope of the present discussion. Similarly, other lesser-known theories are not discussed.

One notable philosophical difference among the proposed interpretations is the role of mathematical equations. Some physicists view the equations of quantum physics, and perhaps physics in general, as abstract models that can be used to make predictions, but that should not be associated with concepts about mechanisms or the nature of reality. On the other hand, others view the concepts about mechanism and the nature of reality as import in working with the equations, and particularly in developing increased scientific understanding.

Orthodox or Standard Interpretation

The *orthodox* or standard interpretation presented in most past textbooks on quantum physics postulates that the act of measurement causes a discontinuous *collapse* or *reduction* of the wave function from a state of superposition to one observed outcome (Schlosshauer, 2007, pp. 330-334). There is no explanation of the nature of the collapse or the act of measurement. This interpretation generally takes the position that the equations are useful only for making predictions and that it is not appropriate to try to conceptualize the properties of quantum phenomena prior to measurement. It is sometimes referred to as a “shut-up-and-calculate” approach (Schlosshauer, 2007, pp. 329).

Copenhagen Interpretation

The closely related *Copenhagen* interpretation adds the postulate that the wave function collapse occurs when a quantum system interacts with a macroscopic measurement apparatus (Schlosshauer, 2007, pp. 335-336). In this dualistic worldview, the realm of classical physics

does not emerge from the quantum level, rather the macroscopic realm is the primary reality and the quantum level is secondary. This interpretation implicitly focuses on measurements or observations by humans and treats other situations as not knowable.

External Observer Interpretation

The *external observer* interpretation proposes that the wave function collapse occurs when a measurement result comes into the consciousness or mind of an observer (Schlosshauer, 2007, pp. 359-365). This interpretation derives from the fact that an observer finds a specific outcome, but the wave function does not describe or predict a collapse to a single state. The transition from a quantum superposition to a discrete classical state is placed at the last step in the process of measurement and observation. This dualistic interpretation distinguishes consciousness from physical matter and has a long and varied history. Some authors argue that it is implied in the orthodox and Copenhagen interpretations.

Many Worlds Interpretation

The *many-worlds* interpretation proposes that with each measurement interaction, the world splits into separate, parallel, non-interacting worlds with each new world having one of the possible measurement outcomes (DeWitt & Graham, 1973; Schlosshauer, 2007, pp. 336-344). Observers happen to find themselves in a particular world, and are not aware that there are other worlds with different outcomes and counterparts of themselves. This interpretation assumes each possible outcome in the wave function fully represents a parallel reality. This interpretation does not require unexplained collapses or observers that are not part of the wave function, but it does require a continuous, infinite splitting of the world. *Many-minds* interpretations apply the splitting to the consciousness of observers rather than to the physical world.

Bohmian Mechanics Model

Bohmian mechanics is a model developed by David Bohm that proposes that quantum effects are produced by a field or wave that guides discrete particles (Bohm & Hiley, 1993; Schlosshauer, 2007, pp. 354-357). The quantum field consists of “information” rather than energy, and manifests through a *quantum potential* that includes nonlocal connections and depends on the entire system and environment in a unitary manner. The model assumes that “a particle has a rich and complex inner structure which can respond to information and direct its

self-motion accordingly” (Bohm & Hiley, 1993, p. 39). The wave function is irreversibly reduced when the location of a particle is registered on a macroscopic or classical level, such as with an experimental apparatus. This model gives results identical to traditional quantum physics in most situations, and the cases with predicted differences cannot yet be empirically tested. Bohmian mechanics has received relatively little attention—perhaps because it cannot be empirically distinguished from other interpretations and the practical value of the additional complexity is questionable.

4.5 Which-Path Information and the Quantum-to-Classical Transition

Developments in physics in the past two decades have provided remarkable clarification of the surprising properties of the quantum domain, and particularly the roles of measurement and information. Concepts of information are increasingly viewed as a central factor in quantum physics.

Recent studies have investigated what constitutes a measurement that causes the quantum-to-classical transition. For a traditional double slit experiment, it has long been known that adding a detector to determine if the particle passed through a certain one of the slits will eliminate the quantum superposition. Experiments have investigated different methods for obtaining this *which-path information* or *which-way information*.

Which-Path Information In Principle

One of the most important findings is that the quantum-to-classical transition occurs when there is potential which-path information, whether or not someone observes the information and whether or not there is a specific detector for it (Greenstein & Zajonc, 2006; Mandel, 1999; Schlosshauer, 2007). A common expression is that the information is available “in principle.” For example, if individual photons (light particles) are sent one at a time through a screen with two slits, an interference pattern will occur indicating a quantum superposition. If plates that alter light polarization are placed in front of the slits, the photons from the different slits will have different polarizations that could be detected by an appropriate device to indicate which slit a photon passed through. The presence of the polarizing plates eliminates the quantum superposition and associated interference pattern. This occurs even if there is no detector to measure the polarization to identify which slit a photon actually passed through—and thus no observation of the which-path information (Schneider & LaPuma, 2002; Walborn, Terra Cunha, Padua, & Monken, 2002, 2003). Note that the light polarization indicates the path of the particle

and is physical information as defined here, but an actual symbolic representation with interpretational infrastructure as occurs with a formal measurement is apparently not necessary.

Partial Quantum-to-Classical Transition

Another important finding is that the quantum-to-classical transition can be partial and gradual rather than an instantaneous all or none collapse (Greenstein & Zajonc, 2006; Schlosshauer, 2007). When partial information is obtained about the path of a particle, the resulting interference patterns are weaker, but still present. The interference patterns fade out and the results become classical as more information is obtained about the path of the particle.

Time Independence

In other experiments, the decision as to whether to use a which-path device is made after the particle has presumably passed through the slits. The quantum-to-classical results of these *delayed choice* experiments are the same whether the decision is made before or after the particle should have passed through the slit(s) (Greene, 2004, pp. 186-199; Greenstein & Zajonc, 2006, pp. 39-44). Such results are incomprehensible in terms of classical physics and traditional scientific determinism.

4.6 Entanglement as Which-Path Information

If the state of a particle is entangled with another particle, each particle does not have a quantum superposition or interference pattern when observed individually. If photon A has two possible paths and photon B has possible states that are entangled with the path of photon A, then the which-path information for photon A can be obtained by observing photon B. Once photon A becomes entangled with photon B in a way that depends on the path of photon A, photon A will not show superposition or interference patterns if it is examined alone. This is true even if photon B is not observed by a person. However, if the two photons are examined together with a coincidence detector, an interference pattern can be seen in the relationship between the particles that cannot be found with either particle individually. These results have been found in various experiments (e.g., Herzog, Kwiat, Weinfurter, & Zeilinger, 1995; Wang, Zou, & Mandel, 1991; Zou, Wang, & Mandel, 1991) and can be derived from the wave function. If these results were not true, it would be possible to transmit information across unlimited distances from photon B to photon A by the timing of when the superposition and interference pattern for photon A collapsed due to observation of photon B. However, quantum entanglement apparently

cannot be used for this type of transfer of useful information. Some type of classical interaction between A and B is always needed to decode the entangled information.

The fact that which-path entanglement causes quantum superpositions to disappear for the individual entangled particles or systems has important implications and is the foundation of decoherence.

4.7 Quantum Physics and Decoherence

Outside of highly controlled laboratory conditions, quantum systems are in constant interaction with the environment. These countless interactions include air molecules, thermal radiation, and cosmic radiation (Greenstein & Zajonc, 2006; Schlosshauer, 2007; Zurek, 2003a, 2003b). The initial theoretical development of quantum physics focused on isolated systems and did not consider the implications of the interactions with the environment in open systems.

These countless interactions are actually the environment becoming entangled with which-path (or more appropriately which-state) information for a quantum system. Although the amount of which-path information in each individual interaction is tiny, the cumulative effect of all the interactions is decisive. Substantial theoretical and experimental research confirms this conclusion (Schlosshauer, 2007; Zurek, 2003a, 2003b). As noted in the previous section, which-path entanglement results in the loss of quantum superpositions and causes the quantum-to-classical transition.

These environmental interactions cause the absence of quantum effects in our everyday world (Schlosshauer, 2007; Zurek, 2003a, 2003b). The elimination of quantum superpositions by environmental interactions is called *decoherence*. For example, estimates of decoherence times for a dust grain are so fast that superpositions would be extremely difficult to observe (Schlosshauer, 2007, p. 135; Zurek, 2003a). The decoherence times for larger objects are many orders of magnitude faster.

Decoherence is a dominant factor in the quantum-to-classical transition, but whether it fully resolves the measurement problem remains an open question (Greene, 2004; Greenstein & Zajonc, 2006; Schlosshauer, 2007). As yet it is not possible to empirically distinguish among different hypotheses. Given that key aspects of quantum physics remain beyond current scientific understanding, it is appropriate to remain cautious in drawing conclusions on this topic.

4.8 Conclusions about Information and Quantum Physics

Because the human experience most analogous to quantum probability waves is the imagination of hypothetical futures, the attribution of information and mental properties to the

quantum domain may be irresistible. Stapp (2009, p. 195) described the quantum domain as “idealike” rather than “matterlike.” He pointed out that the basic properties of the quantum domain are represented by potentialities and probabilities, and the actual outcomes that are manifest appear to be selected in a way not controlled by any known mechanical law. The interconnectedness in the quantum domain that supports entanglement and delayed-choice apparently has a means to incorporate all the relevant factors, conditions, and possibilities in a given situation, even though the factors and conditions may be spread over space and time, and the possibilities may be potential or hypothetical events.

Because this interconnectedness does not involve any known energy, the closest analogy appears to be information. As might be expected, the term information is increasingly used in discussions of quantum physics (e.g., Bohm & Hiley, 1993; Greenstein & Zajonc, 2006; Schlosshauer, 2007; Zurek, 2003b).

However, as yet there has been virtually no consideration of media, symbols, or interpretational infrastructure for the quantum domain. Theoreticians such as Bohm (Bohm & Hiley, 1993), who attribute to the quantum domain a prominent role for information, appear to be using the term information as a label for unknown and basically incomprehensible processes. Bohm assumes that a particle has a “rich and complex inner structure which can respond to information” (Bohm & Hiley, 1993, p. 39) and that “a rudimentary mind-like quality is present even at the level of particle physics” (p. 386). These assumptions attribute to particles the information processing capabilities of life. The analogies he offers to help clarify his ideas about information on the quantum level all involve living systems (seeds, people, ships guided by people). However, the theory does not attempt to identify or describe the medium or interpretational infrastructure in the quantum domain that functions as if there was transfer of nonlocal information.

Discussions of decoherence often include descriptions that imply that the environment serves as media for symbolic representation of the state of a quantum system. These descriptions include, “encoding information in the environment,” “transfer of information to the environment,” “environmental monitoring,” and “environment as witness” (Schlosshauer, 2007; Zurek, 2003b). However, there has been no description of an interpretational infrastructure that decodes the symbolic representations and takes corresponding actions for the quantum-to-classical transition.

Entanglement and Physical Information

On the other hand, there appears to be an emerging understanding that entanglement is the key factor for the quantum-to-classical transition, not whether the which-path state is actually

measured or is symbolically represented in media (e.g., Ferrari & Braunecker, 2010). The expression “which-path information in principle” implies that formal measurement with symbolic representation in media is not necessary. The concept of information “in principle” has other ambiguities. For example, under certain conditions, which-path information can be erased and quantum interference patterns reappear (Kwiat, Steinber, & Chiao, 1992). This occurs even though “in principle” a path detection measurement could be made between the device that initiates and the device that erases the potential which-path information. In principle, the path information could be obtained whether or not it is subsequently erased. As another example, which-path information has been based on the time of arrival of a particle even though the actual time differences were “millions of times shorter than the resolution of the detectors and electronics” (Mandel, 1999, p. S280).

Entanglement and decoherence appear to relate to physical information and entropy (Schlosshauer, 2007) rather than to symbolic information. Current evidence indicates that entanglement and decoherence are inanimate processes that do not involve the creation of symbols by living beings. Terms such as “witness” and “encoding information” imply perception and symbol creation as occurs with living systems. Such terms have dubious connotations when used in context of explaining inanimate physical processes.

The term *which-path entanglement* may be more appropriate than which-path information. Describing the effects in terms of entropy may be more accurate than using concepts of symbolic information processing.

On a more general level, Bell argued that the term information should be excluded from fundamental theories in physics because the term requires the specification of “whose information” and “information about what” (Bell, 2004, p. 215). Bell’s point recognizes that established symbolic information processing is associated with life and requires the context of interpretation by a living being. Bell’s position can be debated, but there is no question that a failure to distinguish between symbolic information and physical information is confusing and can result in attributing properties of life to nonliving systems.

If the term information is used as an active explanatory factor in physics, the distinction between physical and symbolic information should be clearly noted. Any implications that nonliving natural processes encode, perceive, or interpret information must be carefully described. Hypotheses that the mysteries of the quantum domain involve symbolic information processing would appear to require significant alteration of the current scientific understanding of the nature of life.

Moving Front of Increasingly Complex Entanglement

The fact that which-path entanglement results in decoherence of each particle, but superposition of the relationship between particles, demonstrates that an interaction can cause both superposition of a higher order and decoherence of a lower order. This point is implied in various writings and was clearly described by Garret (2008). This shifting of superposition may be typical of interactions and is consistent with the quantum wave function that predicts endlessly increasing entanglement, but does not specifically describe a collapse of the wave function.

One important question is whether some interactions cause superpositions to collapse as historically assumed for measurement, or whether a more appropriate model is that superpositions endlessly shift to higher order interactions—with the classical world emerging behind this moving front of increasingly complex entanglement. The latter is more consistent with the wave function. Analysis of multiple and sequential interactions may provide insights about limitations on higher order entanglement and lower order decoherence, and about the measurement problem.

The quantum-to-classical transition may be similar to a change of state of matter, like liquid water freezing or evaporating. The new state has very different properties than the previous state. The changes in state for water would probably be considered counterintuitive and mysterious if we did not have reliable everyday experience with them. The changes of state for water depend on environmental conditions, notably temperature. Similarly, the quantum-to-classical change of state appears to involve environmental factors, but the key parameter appears to be entanglement rather than temperature.

Quantum Fluctuations and Randomness

Quantum fluctuations and the *virtual particles* that briefly flash in and out of existence as a result of quantum fluctuations are well established. The fluctuations are a manifestation of the innate uncertainty on the quantum level. One model (that I have not seen described anywhere) is that the state or outcome that becomes manifest is determined by the state of the fluctuations when an outcome inducing interaction occurs. The selection of the quantum outcome that becomes manifest would be analogous to the operation of certain electronic random number generators. These devices internally oscillate rapidly between possible outcome states. When an outcome decision is initiated, a random time delay is implemented using radioactive decay or a noise diode. The state of the oscillator at the end of the delay is the selected outcome. Similarly, the quantum level could rapidly fluctuate among virtual potential outcomes, and the manifest

outcome be determined by the state when an outcome inducing interaction occurs. This model would explain the random outcomes for quantum events.

Entanglement implies that the different components of each possible virtual state fluctuate in a correlated or connected manner that is not constrained by the space and time of classical physics. When two particles interact and become entangled, the fluctuations of one particle would be synchronized with the corresponding fluctuations of the other particle. Thus, the fluctuations would be among the virtual possible outcomes as units, including nonlocal correlations for an outcome.

With this model, a particle steps through space and time from one interaction to another. At any point, the particle fluctuates among possible virtual quantum states given the constraints from previous interactions. Interactions that produce which-path entanglement and decoherence make the particle manifest with the properties of classical physics. This model may be an alternative to information processing on the quantum level.

Normalizing Quantum Effects

Several writers have argued that human perceptions and thinking have been optimized by evolution to deal with the everyday world of classical physics, rather than with the counterintuitive phenomena of quantum physics (e.g., Schlosshauer, 2007, p. 376; Zurek, 2003a). The slow progress in understanding quantum physics is consistent with that hypothesis. As quantum physics shifts from viewing quantum superposition and entanglement as profound mysteries to considering them as resources to be developed for quantum computing (Nielsen & Chuang, 2000), it is likely that human imagination and culture will more quickly adapt to the properties of the quantum domain.

It may be useful to clarify here that the term quantum information in context of quantum computing refers to using quantum systems as media for processing symbols that are specified by humans and have humans as the interpretational infrastructure. That is very different from using the term information as a label and vague analogy for the unknown processes underlying entanglement and nonlocal quantum effects.

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Next Section: [5. Integrating the Nature and Meaning of Information](#)

Previous Section: [3. The Nature and Meaning of Information in Biology, Psychology, and Culture](#)

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