On the Role of Information in Physical Interpretation

Steven P. Sax

Abstract

The causal relationship between information and physical reality is discussed. A working definition of information is attempted, as well as physical reality - i.e. what it means to be "something" - thus setting up the analysis of Wheeler's statement regarding "It from Bit." Several experiments are reviewed to demonstrate the conversion of information to physical effects. An expanded bound of the conversion, as well as transcendence of information throughout a physical system, is discussed. This is extended to see useable effects arising from the vacuum of space. Further ideas are discussed and expanded upon to explore information correlation and how it relates to causality in physical reality.

Introduction

Wheeler posited in 1990 the bold idea[1] that

" 'It from bit' symbolizes the idea that every item of the physical world has at bottom—a very deep bottom, in most instances—an immaterial source and explanation; that which we call reality arises in the last analysis from the posing of yes–no questions and the registering of equipment-evoked responses; in short, that all things physical are information-theoretic in origin and that this is a participatory universe"

Chalmers summarized this view as[2]

"Wheeler (1990) has suggested that information is fundamental to the physics of the universe. According to this 'it from bit' doctrine, the laws of physics can be cast in terms of information, postulating different states that give rise to different effects without actually saying what those states are."

Indeed, the merging of Shannon's information entropy and physical entropy already suggests the centrality of information in physical phenomena. To fully consider the idea of It from Bit, as well as the converse Bit from It, the very nature of information and physical reality must first be flushed out.

What is Bit?

Bateson's view[3] of information as "a difference that makes a difference" and Checkland and Scholes'[4] as "data that can be endowed a meaning in a context" are very similar, and a good place to start. In order not to get stuck in a semantic circle, I will try to express this actively: Information sticks out – and gives a reason for doing so. It's a change, a catalyst that changes the way in which some property about a system (laboratory, particle under the influence of a force, the universe, etc.) is considered or acted upon. Information is distinction. This last bit (no pun intended) leads to Shannon's equality of information to entropy[5], and it's Wiener's placing of the negative sign on Shannon's entropy that equals information as described here: the more distinction given to constituents of a system (i.e. the more order), the less entropy. Entropy historically is derived from the study of heat engines, and is related to energy. It is the unavailability of energy. The Second Law of Thermodynamics (SLT) promises that the entropy of a system will never decrease. For example, heat will always pass from a hot object to a cold object and not vice versa (absent some other influence acting on the system). This is because at every step i of heat transfer the decrease in order of the cold object as heat is applied (i.e. the more disorder of the molecule vibrations, rotations, etc., and thus a measure for the unavailability of energy for a directed useful purpose in that process) is more ($+Q/T_{c(i)}$) than the increase in order of the hotter object as heat leaves it ($-Q/T_{h(i)}$). Here Q is the amount of heat transferring from the hot to cold object; $T_{h(i)}$ is the temperature of the hotter object, which is always greater than $T_{c(i)}$ of the colder object, until they reach equilibrium. The total energy remains the same, but the net disorder or lack of distinction, increases. A system then may be interpreted as being driven by the desire to go from higher to lower order. A positive change in entropy – and thus a negative change in information – is like a potential driving the universe like a battery. In truth, SLT is really a statistical law – probability is the reason entropy increases. In the example of the hot and cold objects, it's simply less probable for the arrangements of molecules, or states in the system as a whole, to become more orderly than less. Counting all the possibilities in which a system can be arranged, the more disorderly ones outnumber the orderly ones incredibly. And this interpretation of entropy, with states and knowledge of their arrangements, takes us right back to information. The thought widget 'Maxwell's demon,' in all its variations, attempts to take probability out of the process, by purposefully choosing an ordered state over a disordered one. Briefly, a famous rendition involves a tiny entity (the demon) that stands guard over a tiny hole in a partition dividing a box of gas. The gas is just a random group of molecules, some faster than others. The entity detects the molecules around it, and will choose to let through the hole those molecules which are faster. In doing so it makes one side of the box hotter than another and thus reduces entropy. But the choice itself, the added knowledge, is was let it accomplish this; it utilizes (that is to say, it adds to the system) information to reduce entropy. Each bit of added information (each yes or no decision to let a molecule through) converts to k log 2 units of entropy reduced. Converting a statistical system to a mechanical one requires information. Furthermore, the information then can be used and converted to energy because the resulting lower entropy due to added information can be used to drive a machine (e.g. choosing more energetic molecules to be allowed to move to one side of a partition can make a heat engine). One must be careful here: once it's added, this information can then subsequently be used in another process – an engine, whereby the information will then be reduced, and this will yield energy to drive a system. If new information were not added, the system would statistically use up already existent information (that gave the system any distinct order), and just play out to higher entropy. Perhaps SLT can be recast as: absent any external influence, a system will tend to lose distinction, and will thus lose information. In any case, the connection between change of information and energy/potential is extremely evident. SLT seems to hold true even when immediate observation suggests otherwise. Consider life for example. Physical systems use information. But a special example seems to be for physical systems that contain life - which uses coded information in the form of DNA to create order – life in a sense acts out a non-fantastical version of Maxwell's demon. In fact, a telltale sign of all life is entropy reduction. (Indeed free will – the philosophical piece de resistance of life – may be viewed as the ability to bring and maintain order at an emergent scale, even in incredibly unstable environments). Nevertheless, looking at the ultimate system as a whole and utilizing the concept of Gibbs free energy, living organisms (let's say trees) preserve their internal order by taking from their surroundings free energy in the form of nutrients or sunlight, and returning to their surroundings an equal amount of energy as heat and entropy, thus creating a net increase in entropy.[6] This suggests the idea that emergent systems of low entropy might arise in Nature as locally efficient ways of ultimately maximizing entropy. Could emergent systems operate like components in a circuit, like local entities that create information but in doing so ultimately fulfil the closing of a greater entropic potential as guided by SLT? In any case, it appears emergent physical interactions create distinction and thus more identifying information, as well as use information. SLT has been upheld theoretically even under rigorous phenomena such as black holes. Bekenstein showed[7] that the entropy increase resulting from information being sucked up by a black hole is not lost (which would have violated SLT) but rather contributes to the area of the black hole. This area (geometry) to information connection is fundamental. (As a mathematical insight, note that the expected value of a random variable is in fact an area[8]. An expected value is a statistical digestion of information – distinction is lost - and this translates directly to a geometric concept, area. It's interesting to note also that in proving Fermat's Last Theorem, Wiles bridged statistics with geometry as well[9]). A very fascinating extension of the area to information connection explains the accelerated expansion of the universe as resulting from entropic considerations.[10] Could the accelerated expansion of the universe ultimately be interpreted in view of SLT, with change of information converting directly to geometric expansion? In summary, change of information relates to a potential, statistically driven, with geometric representation.

What is It?

Whereas information, or change thereof, sets up the potential or pretext for an effect, physical reality itself (forces, matter, etc. - the IT) directly affects things. It may be the slight amount of gravity an object contributes. Fundamentally, physical reality could be one fermion blocking another from being in a particular state to thus affect structure in an atom, or the force a boson carries to transmit some interaction. That's the hallmark of reality: It's impossible to exist and not make some mark, in some tiniest fashion, on the world. In doing so, any meaningful property identified about a system is said to be measured. It is important to note that measurement need not involve a particular observer; rather it is any interaction that determines the property of a system to a description that it is acceptable to be used in another interaction. Anything that computes makes measurements. On a fundamental level, a quantum property, like the spin of an electron, is measured and this yields information. A wave function describes the quantum state of a particle and how it behaves. But the quantum system itself seems to exist as a superposition of states (in the case of spin a superposition of both up or down) simultaneously, until the actual measurement is made. How quantum systems can exist in many states at the same time, and reduce to one state upon interaction with a much more complex macrosystem such as a measuring device can be interpreted through a process termed quantum decoherence, which attempts to explain the coupling of the quantum system (which has a small number of degrees of freedom) with the macroscopic system (which has a relatively much larger number of degrees of freedom). Although this can be thought of as information loss in terms of the superposed states that are lost to the final measurement, nevertheless can this also be considered a form of losing alternate realities, alternate physical manifestations? Indeed, Hugh Everett's many-worlds interpretation[11] attempts to solve measurement interpretation by suggesting there is only one wave function, the superposition of the entire universe, and that it never collapses—so there is no measurement problem. Instead, the act of measurement is simply an interaction between quantum entities, e.g. measuring device, electron which entangle to form a single larger entity, for instance measuring device/electron. Furthermore, if a physical macrosystem is required to make the measurement and obtain particular information, then does physical reality cause information, or do decoherence and the earlier considerations of information suggest that information is the cause of physical reality? Do they have a symbiotic relationship?

Portal to the Worlds

A wonderfully exciting phenomena in nature - quantum entanglement - gives valuable insight into quantum superposition and measurement. Quantum entanglement occurs when particles such as photons, electrons, and even macroscopic particles interact physically and then become separated; the type of interaction is such that each resulting member of a pair is properly described by the same quantum mechanical description state. When a measurement is made and it causes one member of such a pair to take on a definite value (e.g. spin up), the other member of this entangled pair will at any subsequent time be found to have taken the appropriately correlated value (e.g. spin down). Thus, there is a correlation between the results of measurements performed on entangled pairs, and this correlation is observed even though the entangled pair may have been separated by arbitrarily large distances.[12] Decoherence actually involves entanglement, but not all entanglement states are decohered from each other. (In Everett's many-worlds, quantum entanglement for the spin system would be like a portal connecting the two worlds so that each possible outcome lives out in the same measurable reality, each being considered part of the same single state all in one universe).

Assume a pair of entangled particles separated in space. For example, a neutral pion at rest in a lab, which decays into a pair of back-to-back photons. The pair of photons is described by a single two-particle wave function. Once separated, the two photons are still described by the same wave function, and a measurement of one observable of the first system will determine the measurement of the corresponding observable of the second system. For example, the neutral pion has zero angular momentum. So the two photons must speed off in opposite directions with opposite spin. If photon A is found to have S_x (spin along an x axis) is up, then photon B must have S_x down, since the total angular momentum of the final-state, two-photon, system must be the same as the angular momentum of the initial state, a single neutral pion. Thus one knows the spin of photon B along the x axis even without measuring it. Two systems can be entangled in many properties. Likewise, the measurement of another observable property of the first system will determine the measurement of the corresponding observable (property) of the second system, even though the systems are no longer physically linked by local influences. Since this would appear to violate the special theory of relativity, Einstein, Podolsky, and Rosen (EPR)[13] postulated the existence of hidden variables, preprogrammed knowledge so to speak in which both systems (here, both photons) knew the properties of each other long before any measurements were even made. In particular, this would otherwise seem to render quantum mechanics incomplete: one person (Alice) could measure S_x of photon A, and another person (Bob) could measure S_y of photon B. According to quantum mechanics, spin measurements in a perpendicular direction are non-commuting, so trying to measure spin along the y axis will destroy the previous measurement of spin along the x axis. If the photons each knew about each other's properties long before anything was actually measured, this renders the concept of non-commuting observables moot. Furthermore, EPR claimed that the hidden variables would be local, so no instantaneous action at a distance would be necessary.

In 1964 John Bell [14] proposed a test for the existence of such hidden variables, and he developed his famous inequality as the basis for such a test. He showed that if the inequality were ever not satisfied, then it would be impossible to have a local hidden variable theory that accounted for the spin experiment. There are many variations for this, and the reader is encouraged to view the references. Briefly, using the example of two photons, consider that in any hidden variable theory, after separation, each photon will have spin values for each of the three axes of space x, y, and z, and each spin will have one of two values "+" or "−". The spin on one axis of one photon and the spin in another axis of the other photon are each measured. If EPR were correct, each photon will simultaneously have properties for spin in each of axes *x*, *y* and *z*. The key to this experiment is in the statistics – it's performed with a number of sets of photons. If N(Sx+, Sy-) means the number of photons with Sx+ and Sy-, and N(Sx+,Sy−, Sz+) means the number of photons with Sx+, Sy− and Sz+, and N(Sx+, Sy-, Sz-) means number of photons with Sx+, Sy-, and Sz-, then for a set of photons

$$N(Sx+, Sy-) = N(Sx+, Sy-, Sz+) + N(Sx+, Sy-, Sz-)$$

because the z+ and z− account for all the possibilities. If n(Sx+, Sy+) means the number of measurements of pairs of photons in which the first photon measured Sx+, and the second photon measured Sy+, and n(Sx+, Sz+) likewise the number for which Sx+ and Sz+ were measured for each photon respectively, and n(Sy-, Sz-) for Sy- and Sz-, Bell showed that in an actual experiment, if the first statement is true, then the following must be true:

$$n(Sx+, Sy+) <= n(Sx+, Sz+) + n(Sy-, Sz-).$$

This is Bell's Inequality, which must be true if there are hidden (or otherwise predetermined) variables to account for the measurements. Experimental evidence[15] shows that this does not happen, and the nonlocality of interactions – the instantaneous determining of information even at vast distances – was validated.

New Bounds on the Conversion

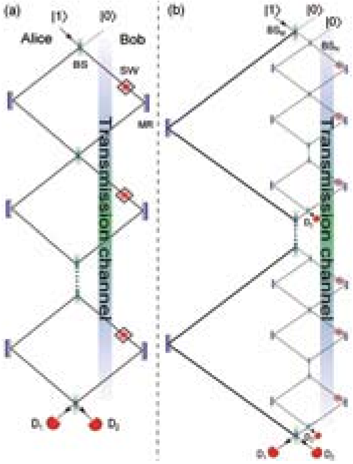
Does this correlation provided by entanglement suggest that information transcends the otherwise working laws of physical reality? Would this suggest that information is more fundamental? Part of the answer lies in determining if information alone, and to what extent, can be converted to having a physical effect.

Funo et al [16] in 2010 showed the correlation of entangled particles could be used to limit the amount of information needed to construct a real version of Maxwell's demon. They showed that it was possible to move a tiny plastic bead up a staircase using the random motion of air molecules, using a door technique similar to what Maxwell had thought up. You put the tiny bead on a tiny staircase and watch it getting pushed around by air molecules randomly bumping into it. Eventually, it'll randomly get pushed up a stair, and you shut an electrical door behind it, holding it there. Over time, you can get this bead to climb the entire stairway without adding energy to the system. In Maxwell's experiment, you need to be measuring the velocity of the molecules all the time, and in stair-climbing bead experiment, you need to be measuring the position of the bead. Per the discussion above, all of this measuring of course takes energy, which balances out the apparent energy that comes out of the system from the entropic potential that's formed. So with the plastic bead, you're taking information on the location of the bead and converting that into the energy required to push the bead up the steps, which maintains the second law of thermodynamics. But now, in this version of the experiment, it starts off with all of the molecules on one side entangled with all of the molecules on the other side. The result is one only has to spend the energy to measure *half* of them to get information about *all* of them, meaning that one can do the door-sorting mechanism and create a hot side and a cold side of the container twice as efficiently! Using quantum entanglement, you *can* get more energy out of a system. An important factor not to forget is that is does take energy to make the doors work, but because they're isolated from the system, the doors don't transmit energy to the bead (or in Maxwell's original thought experiment, to the water molecules). So this still can be used to create a heat engine, for example, twice as efficiently as what would originally be considered necessary. This sets a new upper bound on information - physical reality conversion.

Information In Its Own Write

But would information still normally require some sort of physical carrier? Elitzur et al[17] in 1993 developed an idea for interaction-free measurements. This involves using light to detect the presence of an object without actually bouncing any photons off it. The wave–particle duality of light would allow that an object obstructing one of two paths inside an interferometer can destroy the interference pattern in that device, even though no photons actually come into contact with it, and this was confirmed experimentally. This was used in 2012 to create a quantum-mechanically encoded key for the encryption and decryption of secret messages[18].

Building on this, Salih et al[19] propose direct counterfactual communication, in which it's possible to use interaction-free measurements to communicate an actual message. To do this they used the "quantum Zeno effect", a phenomenon in which repeated measurements on a quantum system prevent it from evolving because of a very high probability that when measured it would revert back into its initial state. The idea is that Person A (Alice) directs a photon at the first beam splitter and Person B (Bob) has a detector placed behind that device that he can switch on if he wishes to try and detect the photon. With the detector switched off the photon exists in a superposition of both reflecting off and travelling through the beam splitter, which allows it to interfere with itself after bouncing off two suitably positioned mirrors. But with the detector switched on, the photon's wave function is forced to collapse (i.e. pick a state instead of remaining in the superposition of possible states) and it follows just one of the two paths.



a)Loop series b)Iterative mechanism with secondary series of loops

The second beam splitter is placed at the point where the two paths meet and Bob has a second detector behind that device. With a further two mirrors placed in exactly the same positions relative to the beam splitter and detector and the configuration then repeated, the result is a series of diamond-shaped loops. Using this set-up Bob is able to relay the actual information to Alice that he has all of his detectors switched on, meanwhile without any photons passing between himself and Alice. With all of the detectors on, the Zeno effect comes into play and the photon's wave function repeatedly reverts to the same high-probability state, which is the reflected one. This causes the photon to register a click in one of two output detectors on Alice's side. Instead, when all of the detectors are off, the repeated self-interference of the wave function causes it to evolve and the final state instead triggers the second of Alice's two detectors. A secondary series of loops with the same set up was placed inside every one of the larger loops, leading to what is known as the "chained quantum Zeno effect," in order to take into account the case where Bob does not block, and the photon's final state would imply the photon passing through the transmission channel after a large amount of cycles. The idea is that these secondary loops reset the wave function at the end of each large loop, such that there is never a significant probability of finding the photon in any of Bob's detectors. The infinite number of both primary and secondary loops would guarantee that the photon always triggers the correct detector on Alice's side and never finishes up in one of Bob's detectors – so ensuring particle-free communication. Although it is impossible to have an infinite amount of loops, nevertheless a finite amount could still approach high success rates to trigger the correct detectors. Nevertheless, in the theoretical limit information is communicated without a physical carrier.

Causality of Information

Do the above experiments suggest information is more fundamental than physical reality, and if so, would this lead to a causality between information and physical reality? This is an especially difficult question when spacetime itself is a part of physical reality, and causality would need to be considered on a deeper level. The example of the two photons decaying from the neutral pion is one of spacelike entanglement (two detectors measuring at a given time and different locations), in that when Alice measures the S_x(A) and then Bob measures S_x(B), not enough time passes between their occurrences for there to exist a causal relationship crossing the spatial distance between the two events at the speed of light or slower. As a result, there is no real causality than can be discerned between Alice measuring A and Bob measuring B.

Olson et al[20] show that timelike entanglement can be extracted and converted into ordinary entanglement between two inertial, two-detectors at the same spatial location, one coupled to the field in the past and the other coupled to the field in the future. A detector in the past is able to capture some information on the state of the quantum field in the past, that would normally escape off into another region of spacetime at the speed of light, and carry it forward in time to the future. Then another detector captures information on the state of the field in the future at the same spatial location at which point the two detectors can then be compared to see if their state has become entangled in the regular spacelike way. This conversion of timelike entanglement into standard spacelike entanglement thus uses a "teleportation in time." One detector coupled to the past operates on a qubit (i.e. the property characterized by the superposition of states) and generates information about how this can be detected. Then the first detector is removed and the future-coupled detector is placed in the first detector's original location, so that the detectors are separated in time but not in space. After a certain amount of time, the second detector receives the information from the first detector - the qubit is essentially teleported into the future, jumping over a period of time - which it uses to reconstruct the qubit. The time correlation must be symmetric – i.e. the first detector must have operated the same amount of time t_o before t=0 as the second detector operated after t=0. At any time between $0 < t < t_o$ the qubit could not be reconstructed. An amazing result of this idea is that a new thermal effect from the vacuum of space can be detected. If timelike entanglement can be extracted and converted like this, it could allow manipulation of these effects all from just the vacuum of space itself.

Causality, Again

An interesting direction to verify ideas of entanglement and information would be to measure entanglement between different reference frames, such that in a spacelike separation, the order of measurement may appear to different observers in different reference frames to be reversed between Alice and Bob. A statistical experiment can be set up with many sets of entangled pairs, to determine what correlations and consistencies exist. This can be performed with Alice and Bob each measuring complementary observables too, to verify if the order change, and thus the breakdown of the prior measurement for each observer, still allows the same entangled correlations and results to agree for all observers.

Conclusion

The analysis and experiments show the fundamental role of information in physical reality. The phenomena of entanglement especially provides many scenarios in which the fundamental quality of information is explored. Expanded bounds by which information is converted to a perceived physical effect, as well as the possible transcendence of information beyond physical requirements, suggest information is causal to physical reality, if not at least symbiotic with it. Further direction for investigation is suggested, with this and other continuing research eagerly awaited.

References

1) Wheeler, 1990, "Information, physics, quantum: The search for links" in W. Zurek (ed.) Complexity, Entropy, and the Physics of Information. Redwood City, CA: Addison-Wesley
2) Chalmers, David. J., 1995, "Facing up to the Hard Problem of Consciousness," Journal of Consciousness Studies 2(3): 200-19
3) Bateson, Gregory (1972). Steps to an Ecology of Mind: Collected Essays in Anthropology, Psychiatry, Evolution, and Epistemology. University Of Chicago Press. ISBN 0-226-03905-6
4) Checkland, P. & Scholes, J. (1990). Soft systems methodology in action. New York, NY: Wiley & Sons, Inc.
5) Shannon, C.E. (1948), "A Mathematical Theory of Communication", Bell System Technical Journal, 27, pp. 379–423 & 623–656, July & October, 1948
6) **^** Lehninger, Albert (1993). Principles of Biochemistry, 2nd Ed. Worth Publishers. ISBN 0-87901-711-2
7) Jacob D. Bekenstein, "Universal upper bound on the entropy-to-energy ratio for bounded systems", Physical Review D, Vol. 23, No. 2, (January 15, 1981), pp. 287-298
8) Emanuel, Parzen (1962). Stochastic Processes. SIAM..
9) Wiles, A. "Modular Elliptic-Curves and Fermat's Last Theorem." Ann. Math. **141**, 443-551, 1995
10) Easson et al, Phys.Lett.B696:273-277, 2011
11) Hugh Everett Theory of the Universal Wavefunction, Thesis, Princeton University, (1956, 1973)
12) Matson, John. Quantum teleportation achieved over record distances, Nature, 13 August 2012
13) Einstein, A; B Podolsky, N Rosen (1935-05-15). "Can Quantum-Mechanical Description of Physical Reality be Considered Complete?". Physical Review **47** (10): 777–780
14) Bell, John (1964). "On the Einstein Podolsky Rosen Paradox". Physics **1** (3): 195–200
15) Alain Aspect, Philippe Grangier, Gérard Roger (1982), "Experimental Realization of Einstein-Podolsky-Rosen-Bohm Gedankenexperiment: A New Violation of Bell's Inequalities", Phys. Rev. Lett. **49** (2): 91–4
16) Funo et al, arxiv.org/abs/1207.6872v2
17) Elitzur A. C. and Vaidman L. (1993). Quantum mechanical interaction-free measurements. Found. Phys. **23**, 987-97
18) Sheng Zhang *et al* 2012 *EPL* **98** 30012
19) Salih et al, Phys.Rev.Lett.110,170502 (2013)
20) Olson et al, 10.1103/PhysRevA.85.012306