Does the Non-Locality of Quantum Phenomena Guarantee the Emergence of Entropy?

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Abstract: Quantum-Mechanical objects and phenomena have a different nature, and follow a different set of rules, from their classical counterparts. Two interesting aspects are the superposition of states and the non-locality of objects and phenomena. A third aspect, that gives quantum-mechanical objects which have common roots a non-local connection, is quantum entanglement. This paper takes up the question of whether these three properties of quantum mechanical systems facilitate the action of entropy's increase, in terms of creating a condition where energy is dispersing, or going from being localized to being more spread out over time. Quantum Mechanics gives each quantum entity the nature of a container or vehicle for both energy and information, some part of which is necessarily non-local. The author feels that quantum-mechanical systems take on aspects of computing engines, in this context. He discusses how the onset of chaos is possible with even the simplest calculational processes, how these processes also result in complexity building, and why both of these dynamics contribute to the character of entropy as observed in ordinary affairs, or with macroscopic systems.

Keywords: locality, microcausality, non-locality, quantum entropy, quantum computing

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1. Introduction

The answer to the question in the title depends largely upon the definition we apply, when we ask "What is entropy?" The common notion that increasing entropy requires the system under observation to become increasingly disordered is not entirely accurate. It is far more accurate to state that entropy is the measure of a process by which energies that are localized become more spread out over time. The spreading and sharing of energy can happen through processes that are orderly *or* chaotic, and nature simply chooses the most efficient means available to make that happen. In physical systems encountered in everyday life, the spreading and sharing process is often accompanied by increasing disorder, or is manifested through apparently random forces acting upon the constituent parts of a system, and this is a familiar example of how entropy's work is carried out. Unfortunately, it is not a very good way to define entropy or to study the subject. Frank Lambert is emphatic "Entropy is not 'disorder.' Entropy change measures the dispersal of energy [1]." He has championed a re-examination of the approach taken to teaching the subject of entropy, resulting in numerous Chemistry textbooks being re-written to change from the confusing view that entropy is a measure of disorder to the far more scientific view that it measures the spreading and sharing of energy.

Harvey Leff has, for a number of years now, been espousing the utility of a similar view to the subject of Physics [2]. As an educator; he also found it difficult to deal with the incongruities of the common view that 'entropy is, more or less, disorder.' Although he acknowledges that this metaphor has a long history, and definitely has value in some settings, Leff shows [3] it is by no means a scientific definition allowing one to get a clear idea of its measure, and argues that we need to change the language we use to describe entropy. He agrees with Lambert that the spreading and/or sharing of energy should be our real concern, when trying to measure entropy, and that gauging the degree of disorder does not give us a reliable or repeatable approximation of entropy's extent. The recent work of researcher J. Miguel Rubi also reflects this shift in view for Physics, away from the idea that entropy can be identified with the disorder in a system. In his article [4] for the November 2008 Scientific American; he stated that while entropy "is popularly described as the degree of disorder in a system ...this can be misleading." He goes on to explain "Nonequilibrium systems behave in some fascinating ways that the classical theory of thermodynamics does not capture and that belie the idea that nature tends to become steadily more disordered." It is clear that we need a better definition of entropy than the one in common usage, therefore, and thankfully there is one.

In some sense, entropy is *only* a measure; however it does not measure disorder, but rather the spreading and sharing of energy. Leff suggests [3] it is convenient that the symbol S is used to denote entropy, as it can be thought of as shorthand for spreading. This could be a spreading out spatially, of the particles that make up a sample of a gas, and a sharing among the various location states available to its atoms and molecules. Or it could be the spreading into and sharing among the various energy states available in a system over time (increasing the number of available microstates). Restated; we have both spatial and temporal spreading and a sharing of energy, which increases the number and utilization of available microstates, until equilibrium is reached. So, in trying to quantify entropy we are actually concerned with the fact that energy in a system tends to disperse, if it is not constrained. We can also say that energy tends to manifest in a way that is not localized, or is by nature non-local. It is evident that energy can exist only in motion or in a dynamic condition where there is a constant exchange between, and a sharing among, the unique microstates of a system. Its nature is motive. And entropy measures how much spreading and sharing of energy a system has evolved, or how dispersed once-concentrated energies have become.

In systems near-equilibrium, where classical thermodynamics is the only concern, entropy is quite well-defined and the spreading and sharing of energy is easy to gauge. The quantum realm, however, imposes its nature on the mechanisms by which energy can propagate and thus influences how entropy may arise. Instead of the continuous range of variations possible in classical systems, there is only the possibility for things to vary in finely-tuned discrete jumps. The regularity and consistency this gives to quantum-mechanical interactions might make one naively wonder how entropy *could* occur, as quantum-mechanical systems all preserve this perfect order. One might think all form would have a crystalline nature, but this is obviously not the case, as real-life forms and systems are considerably more complex. How do they get that way? I will deal with that question later, but a trivial answer to our title's query doesn't require us to address this issue at all. The unique attributes of quantum reality expand the range of possibilities for quantum mechanical entities, beyond those available to classical objects and systems, and non-locality is perhaps the most important reason. It is my view that this basic property of all quantum entities may be a driving force behind entropy, simply by creating an expanded palette of possibilities, in terms of the spaces a given particle can occupy.

It would seem non-locality is a bit hard to pin down, though. It is not a single phenomenon, but a collection of related phenomena driven by the dual nature of quantum-mechanical entities. The most basic expression of non-locality is called kinematical. This is a photon or sub-atomic particle's fundamental tendency to resist localization when we are observing its wave-like properties. Equivalently; our measurement of its location becomes less and less precise, the more precisely we measure energetic properties like momentum. This is simply the action of Heisenberg's uncertainty principle, but it arises from the fact that each unit of form is both matter and energy, both particle-like and wave-like simultaneously. This inherent duality gives photons, particles, and atoms (at least) some measure of indeterminate nature as a quantum, or wave unit, and part of this innate ambiguity manifests as its kinematical non-locality. Kinematical non-locality certainly allows quantum entities to occupy (or influence) more space than an idealized point-particle or classical billiard ball could. Thus; the energy of each quantum-mechanical object is somewhat more spread out than that of its classical counterpart, in terms of what each model suggests. But this answer fails to satisfy.

For one thing, we find that any time a measurement of locality is made, we only locate one particle, or we locate a particle at one unique location, rather than having a cloud of particles spread out over the entity's possible locations in space. So; on some level, the classical logic still works – a particle is either here or there, when we measure its location rather than measuring other (wave-like or energetic) properties. We are therefore faced with a kind of paradox that is quite common when studying quantum mechanics. On the one hand, we must acknowledge that each entity encompasses a range of possible states, including its orientation and location in space. This is called quantum indeterminacy. But once we measure certain attributes, other information we might have obtained becomes obscured, and is thereafter unavailable. When the wavefunction of a quantum collapses through measurement, the indeterminate becomes a definite state. Its quantum statevector effectively reduces to a single possibility or manifestation of form, though while in transit through our experimental apparatus it possessed a larger collection of attributes and conditions, where some subset could be measured at any one time. Therefore, photons, sub-atomic particles, and atoms, appear to be *both* quantum-mechanical and conventional objects, and this makes things interesting. However; this discussion has not shown why non-locality or other innate quantum mechanical properties might lead to an increase of entropy. So I will go back to the basics.

Scientists have learned that understanding entropy in a quantum-mechanical context requires a different mindset, and thus a whole new vocabulary, when compared with how entropy is studied in classical thermodynamics. To some extent, it becomes a matter of probability and statistics, but that only carries us so far. When we study entropic processes at the molecular level, or smaller, the graininess of quantum reality becomes a very real concern. Though the increments between the quantized energy levels of an atom or molecule are exceedingly small and often quite numerous, this is the true nature of the reality we are studying. Every quantum entity in a collection can occupy a multitude of energy states, as well, representing the various conditions it can possess within a system, and some of these states correspond with a locality that is separated from where the supposed object we are examining appears to be, at any instant. That is; all photons, particles, and atoms are inherently non-local entities, by nature, and the view that they are material objects in the conventional sense breaks down in some contexts (wherever the wave-like, energetic, or other quantum-mechanical properties of those entities are observable). Remember that while particles may appear localized, waves tend to be spread out, and duality requires that both natures be expressed.

This fact has some interesting consequences. For one thing, the idea that a particle has a definite size and a distinct location, which can be precisely determined, must be replaced by a probabilistic view, where we can only determine the probability of finding quantum objects in a particular location. But there is a more intriguing aspect to this as well, because non-locality introduces the condition where each quantum mechanical object is joined through its interactions with all it touches, and may even be coupled to objects or environments it hasn't encountered yet. This is why we must consider the whole array of available microstates which can occur for a given system, and study how the evolution and utilization of accessible microstates changes over time, when exploring molecular entropy. But we find that studying quantum-mechanical entropy introduces yet another twist, as we must also consider the question of information flow [5, 6] or information loss in quantum-mechanical systems, since researchers have come to believe that the conservation of information [7, 8] is every bit as important to the study of quantum systems as the conservation of mass and energy is for classical systems. This is why it has been so important for some physicists to understand whether the Hawking radiation from Black Holes leads to information loss [9-13], as this would violate quantum-mechanical unitarity (the sum of all probabilities would no longer be 100% or 1) if it were true.

2. The Quantum Trio

So the important question then becomes; how does quantum behavior relate to the study of entropy? And this, of course, leads to other questions. Can we fathom the quantum roots of entropy, given a basic knowledge of quantum mechanical phenomena and an understanding of how systems develop mechanisms to propagate change, and disperse energy? More importantly; if we do learn how entropy arises from quantum interactions; does this improve our knowledge of macroscopic systems or our understanding of reality in general? We can find answers by studying what I call the quantum trio. These are the three innate aspects of quantum mechanical objects and systems most fundamental to our investigation - **non-locality**, **superposition**, and **entanglement**. In combination, they provide the basis for a wide range of phenomena having no counterpart in the world of mundane objects and classical systems. Some of these phenomena border on the bizarre, and appear to be impossible, given only a familiarity with the everyday world. However; this quantum strangeness is something we must deal with, even embrace, in order to thoroughly understand the true origins of entropy.

Superposition is the possibility for a particle or system to occupy two or more states simultaneously. Its states are said to be superimposed, one with the other, so that they coexist rather than being mutually exclusive. This is somewhat different from classical superposition, where waves ride on top of each other and add together, as quantum probability amplitudes for each outcome are combined to determine the most likely of all the possible states an object or system can occupy. If any two quantum states can exist, so can a linear superposition thereof. Nor are we limited to only a few possibilities. In fact; a great number of states can be assumed by any of the entities involved in even the simplest interactions among small numbers of particles. And in quantum mechanics we must consider all the possible states and configurations at once, and figure in their individual and relative contributions to the overall picture. The possibilities multiply quickly, too, and calculations become difficult if we add more and different particles or atoms, irregular boundaries, or more energy, to our system under study. Though complex and chaotic behaviors arise even in relatively simple dynamical systems, and this limits the range of deterministic predictions, quantum superposition makes things more interesting still, and this is why we must include all the microstates a given system may occupy as simultaneously existing possibilities. Every entity in a quantum mechanical system can occupy a variety of states at once, between interactions. But there is another side to this story.

Superposition is also the possibility for a collection of objects to occupy the same state, or to exist in a coherent relationship with one another, so that they merge and become effectively a single entity. A large scale superposition of this sort is called a Bose Einstein Condensate, or BEC. This once near-impossible feat has become relatively easy to achieve, with the apparatus now fitting on a single workbench and being miniaturized further still [14]. Experimental teams have achieved containment and detection on a single chip [15, 16]! In a BEC, hundreds of thousands of similar atoms (or more) appear to be the same object, a superatom, rather than being a collection of unique objects. One might also refer to a BEC as a coherent system of objects, or a collection of entangled objects, but the essence is that their quantum states are in agreement. This is distinctly different from the normal situation dictated by the Pauli Exclusion Principle, which asserts that no two fermionic objects can occupy the same quantum state. But in a BEC, the energy keeping them separate has been carefully removed, and a whole collection of atoms shares a tiny volume of space, whose size is determined by Heisenberg uncertainty. In effect; the atoms become bosonic, so they can merge.

However, the opposite of this condition is also a reality. As I have discussed; a quantum mechanical object like a single particle or atom can appear to occupy a space larger than its size, or inhabit more than one location. Non-locality can thus be seen as an expression of superposition, as it manifests in a single entity's ability to behave as though it exists in two or more places (distinct location states), at once. But in a more general sense, there is an essential indeterminacy, and a basic ambiguity, to every quantum-mechanical object. And part of the indeterminacy is positional, which is its kinematical non-locality. A sub-atomic particle cannot be precisely localized, if our experimental procedure allows us to observe its wavelike properties. Nor can we know its position accurately, while accurately measuring its momentum. So, the locality of particles and atoms will always be a little fuzzy, or ambiguous. And this broadens the area we must allow for any one atom to inhabit, when we study a collection of atoms and examine the ensemble of states in a statistical analysis, to determine the entropy. But there is another side to this story, as well.

The products of any quantum mechanical process or interaction also share a non-local connection, through entanglement. If we perform a measurement on one half of an entangled pair, this determines (or reveals) the outcome of a similar measurement on its counterpart. This is dynamical non-locality. Although we generally think that entangled states arise in carefully set-up experiments, any breakdown resulting in pairs of particles creates entangled states. And there are a host of naturally-occurring processes and interactions which likewise result in pairs or other groups of particles that are entangled, and appear to share information non-locally. Therefore; non-locality is not a single phenomenon, but instead a collection of related functional attributes. Whereas the kinematical non-locality of quantum objects is simply positional indeterminacy; this other type is dynamical in nature, influencing the way things change. It can be confusing, and it makes things more complex, as this leads to effects that are counter-intuitive, or unexpected, given only familiarity with macroscopic objects and systems. The quantum reality often seems strange, in this way, as it forces us to deal with paradox.

Part of the confusion arises because of our tendency to regard all objects as solely material things. Even in particle physics, where quantum mechanical phenomena are frequently observed, the common view is that sub-atomic particles are idealized point-particles. Nor is this seen only in examples from the old textbooks, as the Standard Model still treats them as such today. And they certainly can behave as if they were. But we know that they are dual entities! Each type and every individual unit simultaneously possesses material and energetic attributes, as they are both material objects and packets of energy. That is; all of the various quantum mechanical objects and force carriers are both particle-like and wave-like, simultaneously. And this wave-particle duality means that sub-atomic particles, including photons, can do some remarkable things which exceed the boundaries of what we imagine objects can do. They do not always behave like simple objects. Not only does this blur the edges of what we can observe, it requires us to entertain a dual, or multiple, view.

Though we can show that all photons of light are like point particles, via the photoelectric effect, we can also show that light is wave-like, via the double-slit experiment. We can repeat the experiments with electrons, and obtain similar results. But if we can't localize an electron to one slit or the other - when we perform the electron experiment - how can we hope to be more precise still, and locate this thing which we label a particle in two or three dimensions? The answer is we can't, because each electron is inherently non-local, or has properties that cloud its locality, any time its wave-like nature is called into play. And conversely; when we set up a beam of light and detector on the exit side, and determine which slit each electron *did* go through, the interference pattern revealing its wavelike nature collapses. Briefly stated; this indicates that our choice of what information to extract influences the outcome of events, so that by focusing sharply on material attributes, we render the view of an entity's energetic attributes more fuzzy, and vice versa.

While it is decidedly matter, an electron is also energy, so it retains qualities pertaining to energetic phenomena, while it simultaneously manifests material attributes. To completely localize an electron (or other sub-atomic particle), one needs to stop it cold. If one were to halt its spin it would cease being an electron, but one must halt a particle's lateral motion entirely, in order to measure its position with absolute accuracy. Equivalently; one could bounce a photon or photons off it, and discern its position that way. Of course; either act would rob us of any knowledge about its momentum, as it would steal some or all of the motion energy the particle had beforehand. Note that motion is rightly considered an energetic or wavelike phenomenon, in this context, just as de Broglie asserted, and we are denied the possibility of observing a particle's material and wavelike properties at once. Thus the uncertainty principle asserts that we can never know both its position and its energy of motion accurately, at the same time. And yet; it possesses both. Every fundamental entity that manifests in the cosmos is simultaneously *both* particle-like and wave-like, *both* matter *and* energy.

So; we see that there is a bit of non-locality to the constituent parts of every physical object that makes it difficult (or impossible) to form a complete picture of them. Individual quanta are hard to pin down. And things get still more interesting when we weave in the subject of entanglement. Entangled objects share a non-local connection, by virtue of their prior interaction or common origin. A good example is pairs of sub-atomic particles resulting from a single interaction, perhaps from a decaying gamma-ray photon. Bell's theorem argues that though the individual objects may diverge, they remain connected somehow, and experiments have shown that measurements on one member of an entangled pair do influence (or indicate) the state of the other. This is a simple manifestation of quantum entanglement. A refinement of this idea, in an experiment by Greenberger, Horne, and Zeilinger with three particle systems [17], conclusively showed the non-local connection entangled objects share. More recently; an experiment by Zeilinger's team showed that a connection can be demonstrated even for entangled photons separated by 144 km [18].

The implication here is that information is shared between entangled objects, apparently without their having to communicate again. One might also say that entangled particles have an ongoing instantaneous communication, or a connection outside of time and space, as a result of their interaction with each other. Unfortunately; this does not allow us to communicate super-luminally. In some respects, however, it appears that entangled entities are actually the same object, although they also have individual, or unique, identities. So; we can surmise that each macroscopic object in our universe is a collection of quantum mechanical objects, some of which are connected to (or entangled with) other quantum objects elsewhere in the universe. That is; each common object is an assemblage of individual units that may retain a functional connection to other units of form with which they have been united, or in contact, despite their later separation in space and time. And it seems that this ongoing connectedness, a dynamical connection, or some shared aspect of identity among particles which have interacted, is an essential feature of quantum mechanical reality.

However; all entangled or coherent states break down, or decohere over time, and it normally happens rather quickly. This process usually occurs through interactions with outside entities, but it would seem that energetically improbable states can also decay. Any localized energy tends to disperse, if it is unconstrained, but quanta of energy can also tunnel through barriers. Thus, energetic entities like electrons or other particles can assert their fundamental non-locality by appearing on the other side of a barrier. And there is certainly plenty of evidence that energy-filled systems do simply run down, over the course of time, just as the second law of thermodynamics suggests they must. But we should be glad that there are also activation energies and binding forces at work, creating a quantum threshold or barrier which holds the second law in check and keeps objects and systems intact long enough to be observed, as well as doing the same for human observers. We also benefit from the fact that increased order and complexity can develop from thermodynamic processes [4], in addition to a chaotic arrangement or a smooth distribution. Entropy is thus far more interesting than a uniform dispersal of matter in space. And this is because the story is really all about the dynamics of how energy gets to become more spread out.

Energy seems to resist being localized, or is fundamentally non-local, and this manifests in a variety of ways. Waves are seen to exist as spread-out or moving phenomena, and while photons and subatomic particles are discrete packets of energy which can appear to be localized entities, they are not solely particle-like. They all share in this wave-like aspect. The non-locality observed in quantum objects and systems can be seen as a direct consequence of this simple fact. And this same fact is, in my view, also the basis for entropy. Energy is not static. It ‘wants’ to spread out or move, over time, and that happens in interesting ways, especially when we talk about quantum mechanical aspects of objects and systems. My observation is that complexity *as well as* chaos emerges as a direct consequence of this most basic property of energy, which is the ultimate cause of entropy. In the remainder of the paper, I will discuss some ways that both complexity building and chaotic evolution result from the fundamental properties of quantum-mechanical objects, as they are vehicles for both energy and information. Specifically; I will show that non-locality, superposition, and entanglement, are energetic phenomena spurring the orderly development of complexity, that the emergence of sufficient complexity automatically gives rise to chaos, even in relatively simple systems, and that this same process also gives rise to more complex and interesting orderly forms.

3. Roots of Quantum Entropy

On some level, non-locality and entropy are actually the same thing, in my view, as they are born from the same basic principle. Entropy involves the dispersal of energy. Energy disperses because of its tendency to be, or become, non-localized. The non-locality observed in quantum-mechanical objects and systems is also a manifestation of this basic property of energy, which appears whenever the entities involved are not constrained to behave solely as material objects, and are allowed to express their wave-like or energetic nature. Energy is not characteristically a local phenomenon. The nature of energy is to expand, move, or propagate. This is what drives entropy, as well. To quote Lambert again “Energy of any type disperses from being localized to becoming spread out, if it is not constrained. This is the ultimate basis of all statements about the second law of thermodynamics and about all spontaneous physical or chemical processes [1].” So a single attribute of energy can be seen as creating both quantum non-locality and entropy.

Some individuals feel that there is no need to study quantum-mechanical phenomena, in order to fully grasp the mechanisms of entropy, but quantum mechanical entropy is something different entirely, from its classical counterpart. Instead of a simple range of actions and motions, for a collection of objects, quantum mechanics gives us a cloud of discrete possibilities to examine. When studying entropy at the molecular level, we need to consider the vast array of microstates available within a given system, and how changes in the configuration of a system, or its composition, will affect the utilization of accessible microstates. Specifically, an increase in entropy is associated with increasing numbers of microstates that are accessible. On some fundamental level, the *very existence* of an extended array of microstates seems to be associated with the superposition of quantum states, and with the basic attribute of kinematical non-locality possessed by all manifested quanta. Thus; the indication seems to be that quantum principles are at work even in systems we would not generally expect to exhibit quantum-mechanical behavior.

So; we need to take seriously the idea that the entire universe is, by nature, quantum-mechanical. While the common perception is that quantum mechanics is mainly concerned with things happening at a level of scale having nothing to do with our common experience, this perception is changing because the evidence is now more plentiful, and so much easier to obtain. Experiments investigating some quantum phenomena used to fill a laboratory. This has all changed, in the last 10-15 years. Any college or university can now afford the apparatus to create BECs, which fits on a bench top as I mentioned, and things have been reduced further to the scale of IC chips. Today we can study these large-scale superpositions with relative ease and relatively small expense (a few thousand US dollars, perhaps). Detectors based on superconducting quantum interference (SQUID) technology have continued to evolve, as well, such that the carbon fiber nanoSQUID is sensitive enough to measure the magnetic polarization of a single atom [19]. And new materials like graphene provide us with a means to explore quantum relativistic phenomena in tabletop experiments [20]. So the possibility of designing experiments to test quantum-mechanical properties, or creating technologies by exploiting those same properties, is more real than ever before.

Though more than 100 years have passed, since most of its fundamental principles were known, quantum mechanics is still incompletely understood, and its implications are somewhat poorly accepted by scientists in general. Part of the reason for this is the broad range of interpretations of QM by physicists themselves, which makes the subject confusing, but there is a more cogent explanation. Prior to this point in history, we had the means to learn about the quantum-mechanical principles, and ways to exploit that knowledge, but we didn't have ways of making some of the basic quantum properties obvious, or visible to all. Although we have long had electronic devices that depend upon quantum principles to operate, the means of their function remains hidden from view. Transistors and ICs require quantum mechanics to function, but the circuits they are a part of are still largely in the classical realm. However, this will change as technology is pressing to make those circuits still smaller, which forces designers to consider quantum-mechanical effects, as there will be no avoiding it. And applications like quantum cryptography, which *exploit* the properties of entangled systems, will move quantum-mechanical phenomena further into the mainstream. So; the public perception of quantum reality's ubiquity will be expanded, and we can hope this will benefit Science.

But for now let us explore whether the exotic non-local aspect of entangled objects having apparent 'spooky action at a distance' has any bearing on the overall spreading of energy in a system, and therefore on its entropy. Do the limits nature places on the amount and kinds of information we can measure at once prevent this sort of non-local connection from mattering, in ordinary objects? As we add more or stronger positional constraints to any quantum object, it *is* exactly like making a measurement of its location, and we know this removes some non-local information. We also know that special care must be taken, to keep coherent or entangled states intact, so they will not decohere. Are we then right to assume that the strong constraints of being part of a macroscopic object, or part of a massive closed system, make all questions about non-locality and non-local connections between particles or atoms irrelevant? We might be tempted to believe that *any* non-local information would be washed out, or would quickly get damped out, in all these cases.

Proponents of Decoherence theory would have us believe that rather than getting washed out; the non-local information gets spread out, instead, either by being absorbed by the environment, or by being incorporated into a network or system of entangled entities [21, 22]. The superposition a quantum entity is in can exist only until it is measured, and we have seen that making one kind of measurement destroys information of other kinds. Sub-atomic particles, atoms, and small molecules, possess a certain amount of quantum-mechanical freedom to exist in a superposition, but bumping into something constitutes measurement and forces some level of decoherence. However, this can have varying degrees of finality or irreversibility. If it is absorbed, its wavefunction becomes (a non-local) part of the macroscopic system or universe, and if it bounces off another similar particle, the two are thereafter entangled (and share a non-local connection). Given an entangled pair, an electron and a positron diverging in space, chance encounters with another particle might have a very different outcome for each, though this process would spread the non-local information which is coherent with the original entangled entities, regardless. But doesn't decoherence happen very quickly, when quantum entities in a superposition are part of, or do encounter, a macroscopic system?

This is exactly the case in most instances, for common large-scale systems or with ordinary objects, especially in the range of density and temperature with which we are most familiar. Thus; there is a large class of systems for which the classical description gives us a perfectly adequate estimate of the entropy. For examining how entropy arises in quantum spaces, however, we must consider the information-theoretic aspects of this matter, before we dismiss the ongoing importance of non-local interactions and superpositions. Quantum correlations may be far more important than we have imagined, and entanglement more persistent. Nor is it enough to say that because a system or object is macroscopic, we can simply ignore quantum effects on its microscopic structures, and the contribution of superposition, non-locality, and entanglement to its properties. As computing technologies utilize smaller and smaller structures, to incorporate more processing power on a single chip, quantum effects are becoming more and more important to consider. And for some exotic materials being explored for IC manufacture, like carbon nanotubes or graphene, quantum-mechanics is absolutely essential for understanding the basic properties of the substance. So where is the dividing line between quantum spaces and the realm of classical physics, if there is a clear distinction?

The fact is that this line is rather blurry, and we can make a distinction only with respect to certain kinds of interactions. Some of the confusion arises as a direct consequence of our attempting to derive classical information from quantum systems, but there is a natural transition to classical behavior, for quantum entities. H.D. Zeh states that “most molecules (save the smallest ones) are found with their nuclei in definite (usually rotating and/or vibrating) classical ‘configurations’, but hardly ever in superpositions thereof, as it would be required for energy or angular momentum eigenstates. The latter are observed for hydrogen and other *small* molecules [23].” But in response to the question of whether QM breaks down for systems with more than a just few particles he replies “Certainly not in general, since there are well established superpositions of many-particle states: phonons in solids, superfluids, SQUIDs, white dwarf stars and many more! All properties of macroscopic bodies which can be calculated quantitatively are consistent with quantum mechanics, but not with any microscopic classical description.” And he asserts that we first should assume that QM is universally valid (i.e. – it is the root cause of all phenomena) and then study the process of decoherence to explain the emergence of classical behavior in inherently quantum systems. If we take the view that all sub-atomic particles are made of energy, and that energy retains the same basic (non-local and wave-like) nature even while bound into particles, his assertion makes good sense.

4. Quantum attributes and Information

The existence of large-scale superpositions can now be clearly demonstrated. An experiment in 2000 by Jonathan Friedman and his colleagues put a SQUID into a state where a macroscopic current moved in both directions, around a loop, at once [24]. A year later, an experiment by Eugene Polzik and his team created an entangled state with trillions of atoms, persisting for half a millisecond [25]. So there are experimentally observable examples of coherent states in systems much larger than just a few particles. But the question remains of why coherent states break down. Is it because of a breakdown in the quantum mechanical description of the system, that leads to wavefunction collapse (immediate reduction of the quantum statevector) when a system exhibits some classically measurable behavior, or is it the conflicting interests of too many quantum mechanical effects happening at once, that leads to interference and chaotic development? According to decoherence theory, we can have it both ways, or rather both answers make sense in different instances. There need not be a total collapse of the wavefunction, as some interactions or measurements do not stop a quantum cold, but rather partial decoherence results in a cascading network, or even a chain reaction of entangled entities, which facilitates the local spreading of non-local information.

If we make a position measurement of a sub-atomic particle, or an either-or determination of which slit it went through in a double slit experiment, we are extracting classical information and treating that particle like a material entity. This causes its wavefunction to collapse, and the outcome becomes part of the timeline for the universe it is in. To some extent, each such outcome determines or 'chooses' one of many possible universes to inhabit, and becomes an aspect of the whole of that reality, rather than a single isolated and indeterminate piece. But some interactions, such as elastic collisions between particles, do not cause the wavefunction to collapse altogether. There is a partial decoherence of the wavefunction of each entity, and an entanglement between them, which results from their encounter. Likewise, some measurements allow a quantum unit to retain its indeterminacy, and to possess wave-like properties, rather than forcing it to be explicitly material and strictly localized. However; a combination of measurements or encounters, which progressively limit the remaining degrees of freedom possessed by a quantum entity, will have the same effect, where the wavefunction collapses and a classical outcome is the result. In either case, an element of irreversibility arises from activity at the quantum level. This would seem to provide a basis for the emergence of entropy in the sense of energy spreading out with information, through the action of quantum non-locality, and at the same time shows entropy in the information lost from a system through this process.

To illustrate the last point, I will use as examples two simple experiments cited by Roger Penrose in "The Emperor's New Mind" [26]. In figure 1 below, we have a feeble light source, a half-silvered mirror, and a photon detector. Let us assume our light source emits one photon at a time, and that it has a 50 percent probability of either reaching the detector, or hitting the laboratory wall near the letter A. This setup illustrates time-irreversibility, as any photon arriving at the detector has a 100 percent probability of originating from our light source, but time reversing them would bring them *to* the light source only half the time. If we time reversed the photons landing on the lab wall at A, they would have a 50 percent probability of reaching our light source or point B on the opposite wall, and a photon emanating from A could never reach our detector at all! In similar fashion, a photon coming *from* our detector would arrive at either the light source or point B on the lab wall. But since point B does not receive or emit light in our experiment; we know that whenever a photon is detected, it came from our light source. If the photon strikes the wall, we presume it is absorbed. It will never be detected, so its information is lost to us entirely. We can infer that more photons are being emitted than we detect, if we know the mirrors are half-silvered, but we cannot know how many, or when they are emitted, from measurements made at the detector.

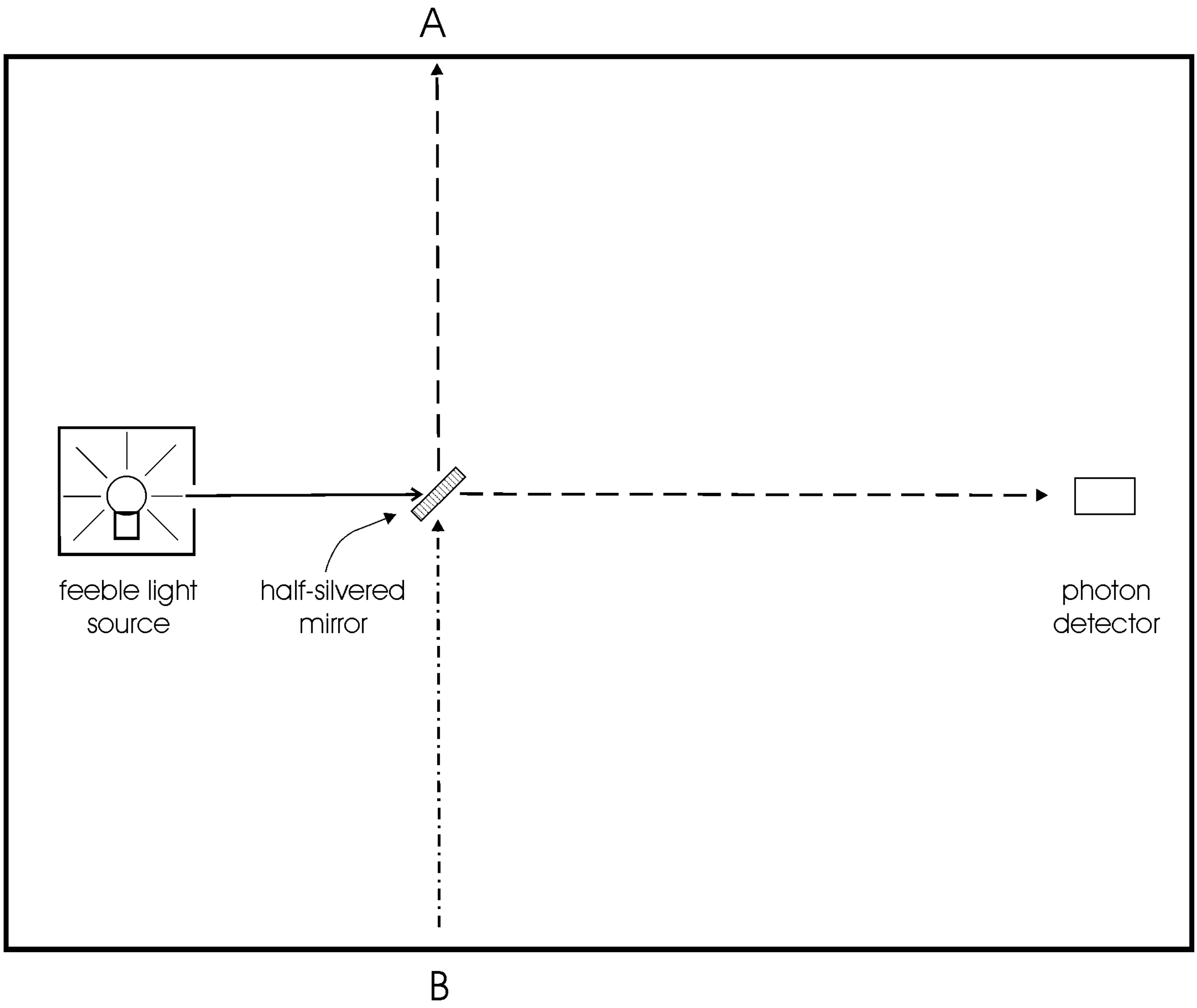

Figure 1 – A simple quantum experiment

In the above example, we can assume that the wavefunction has collapsed for a photon that hits the wall and never gets detected. Any information we might have had about it ended up somewhere else, and is lost to us thereafter. It has become part of the macroscopic system, or part of the universe that system belongs to, but it is no longer available to us for possible detection. Its detection has become impossible, as the energy and information it carried has ended up elsewhere. This is similar to what happens with other forms of quantum decoherence, and explains why this process leads to entropy. Simply put; it is the fact that some of the energy and information goes away, which makes many processes at the macroscopic level irreversible, because the energy and information needed to re-assemble the original forms is somewhere else already. But if we take care to preserve the wave-like aspect, and allow for the fundamental non locality of quantum entities, the information is preserved. By placing a fully-silvered mirror where our photons would hit the wall and another where our detector was, we have created two orthogonal paths to the same spot, where we can place another half-silvered mirror. Of course, we will want to be able to see where our photons appear, but now we will need two detectors. This experimental apparatus is known as the Mach-Zehnder interferometer, and its results have been verified by researchers to work at scales of at least several meters [27]. In figure 2 below, we see the experiment illustrated.

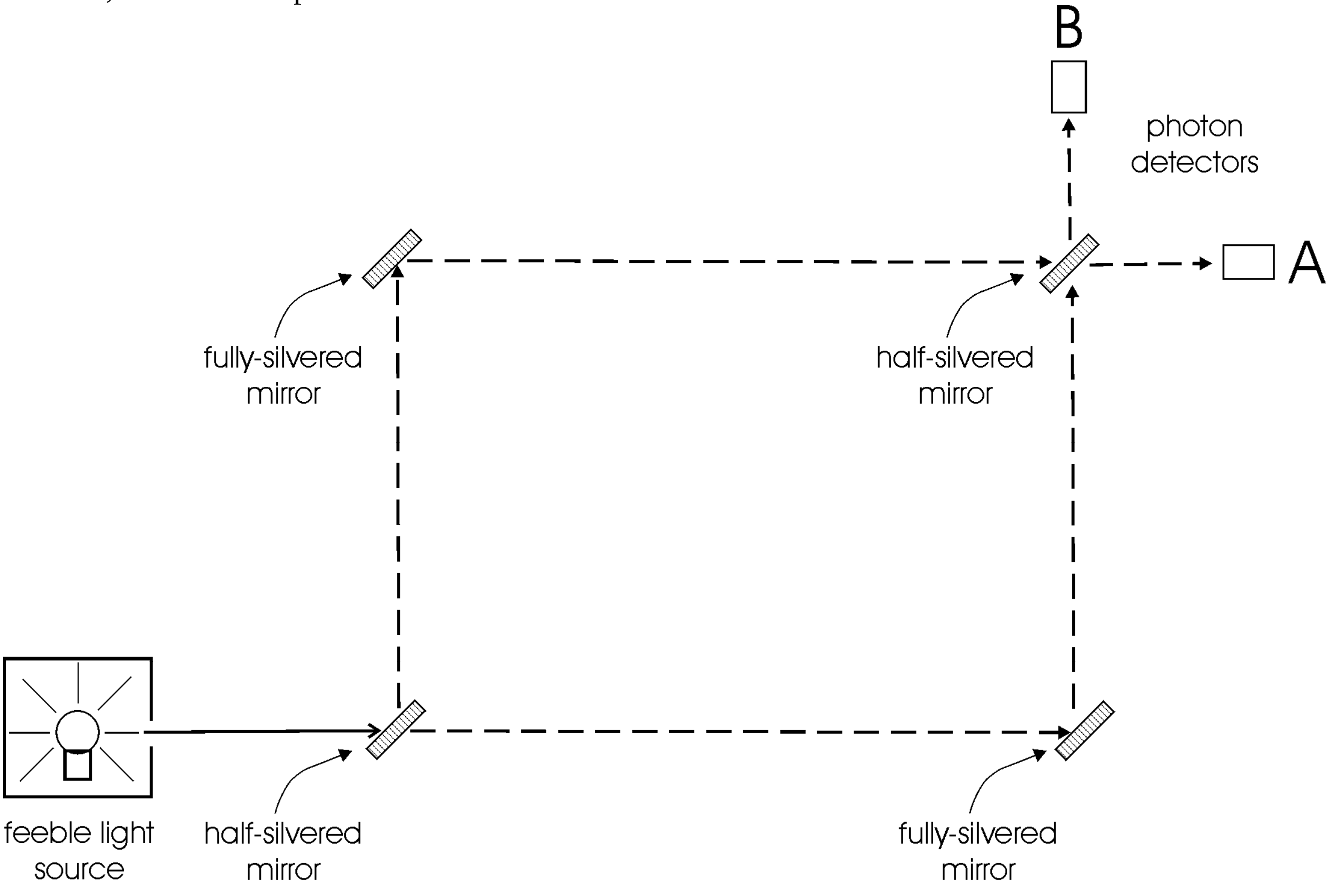

Figure 2- another simple experiment
(the Mach-Zehnder interferometer)

When a photon is emitted, it has a 50 percent chance of being deflected by the first mirror, exactly as before. And a photon coming to the mirror in the opposite corner also has an equal chance of reaching detector A or B, regardless of which path it took. However, we know that photons have a non-local and wave-like character, and this apparatus illustrates this nicely. If we take care to make the paths of exactly equal length we find that only detector A is triggered! But if we place an obstruction in one path or the other, then there is an equal probability that a photon will arrive at either detector A or B. So long as we allow the photons to be non-local and wave-like they are perfectly happy to travel equally down both paths and this is the only way to explain the experimental result. If, however, we constrain them to act like particles by forcing them to take one path or the other, then a different result ensues, where it is equally probable that they will be detected at A or B. It is interesting to note here that the distances involved can be fairly large, and the apparatus we have used is definitely in the realm of macroscopic objects, but even for individual photons; we can clearly observe their non-local character, and demonstrate that the information content possessed by quanta of light and energy can be quite spread out indeed, yet remain intact. This statement should also apply when we are talking about sub-atomic particles, individual atoms, and perhaps even C60 molecules. The exact extent to which this holds true is still being explored, however, and experiments with a Mach-Zehnder interferometer using electrons have yielded some curious results [28, 29, 30, 31].

So; while the latest experiments allow us to probe coherence and entanglement in electrons to an extent that was previously impossible, they also raise questions about just how far current quantum theory can take us, as the quantum-mechanical realm is full of surprises. But one thing is certain; the connection between energy and information is an important part of the story, or is essential to understanding how quantum effects shape reality, or contribute to the emergence of entropy. Energy tends to move or spread out, as that is its nature, and it takes information with it. Energy carries information about the universe (or about any system) to our senses and sensors, and it can also carry away information from a system, preventing some interactions from being reversible. As I have pointed out, waves tend to move or spread, and the wave-particle duality requires all of the quanta in our universe to possess properties that arise from the wave-like aspect of energy, as well as having attributes that are particle-like and material, or substantial. Perhaps the most important of these properties is non-locality. Does non-locality guarantee that entropy will emerge? Just as in the opening paragraph I stated that the answer depends upon how we define entropy, I will say here that it also depends upon how we define non-locality. With a sufficiently narrow description the answer would have to be "probably not," but if we broaden our terms just a little bit, we must say the answer to our query is "almost certainly so."

If we assume that Quantum-Mechanics takes place on a more fundamental level, from which the familiar Classical realm emerges, we must accept a view that is far more inclusive than the one in general use - and this may be appropriate. In "Roots and Fruits of Decoherence" [22] H. D. Zeh attempts to guide us away from a narrow interpretation by offering a set of more general definitions, and to disabuse us of common misconceptions about decoherence and the quantum realm in general. Zeh defines decoherence as "the dynamical dislocalization of quantum mechanical superpositions," and he explains that non-local superpositions don't go away even when total decoherence takes place, but merely become part of a larger system, the universe at large. In this manner, entanglement and superpositions are seen to persist throughout a sequence of interactions, and non-locality is seen as an essential feature of reality. Zeh suggests that the measure of entanglement favored by Nielsen and others focuses too strongly on the 'usable' portion of non-locality and ignores the entanglement of objects with the universe. A recent paper by Laura Mersini-Houghton [32] suggests that the dynamics of entanglement may reach further still, allowing our entire universe to be entangled with others, and shows that (using Wheeler-DeWitt as a Master equation) we can employ decoherence theory to explain why universes like the one we inhabit tend to result from natural selection. This idea solves the "Landscape problem" in String Theory, where too many variations or possibilities have prevented making clear predictions, but it forces us to assume that superpositions can persist for a very long time, while stretching our definitions of non-locality and entanglement to the limit.

When we ask how the measurement process relates to the questions involving non-locality, the answers are quite revealing. Again, the quantum realm does not disappoint, as it offers plenty of surprises. From 1995 to ’98, Paul Kwiat worked with a number of collaborators [33, 34] exploring the possibility of Interaction-Free Measurements of quantum-mechanical systems. Strictly speaking, this is not a reality, as even the possibility for measurement can influence the outcome of quantum events, but there are ways of skirting the issues, by engaging in some quantum-mechanical sleight of hand. One early experiment, suggested by Elitzur and Vaidman, used an apparatus similar to Figure 2 above, which was modified with collimating lenses and polarizers. The experimenters passed hairs and other small objects through one path of the interferometer, and noted the extent to which their passage affected the output. Instead of simply measuring the presence or absence of photons, however, this experiment detected the polarization angle of the transmitted light, and it allowed interaction-free measurement 25% of the time. In other words; information was extracted, but the wave-like nature of the light in the interferometer was preserved. Unfortunately, there was still a chance the photon would be absorbed by the object, as well. Later experiments greatly improved upon the percentage of object detection, however, and reduced the chance of wave-collapse. This result has opened up a panorama of possibilities for interesting explorations and innovative technologies, but left many important questions open. Most notably; it makes us wonder what actually constitutes measurement, how much information we can extract without collapsing the wavefunction, and whether non-local information can be retained or discerned in a given locality non-destructively.

5. Concluding Remarks

I have raised many questions, in this paper, and I do not claim to offer a final answer. Instead, I hope the discussion preceding has served to shed light on some of the important issues surrounding how entropy may arise from the quantum mechanical behavior of the functional units which make up the structure of larger systems. Some might argue that what has been said applies only to certain interpretations of QM, but I have attempted to maintain a focus on the universal aspects of all quantum-mechanical systems, and I hope it is apparent that some facets of the story, such as the wave-particle duality and the decoherence of the wavefunction, are important to our understanding, regardless of which interpretation we favor. If all matter is comprised of energy, then we must treat all physical systems as collections of quantum mechanical entities. Seen from the viewpoint of energy, all spaces are quantum spaces and all systems are quantum systems. Thus superposition, non-locality, and entanglement, are properties that must be reckoned with, when we examine questions of micro-causality, or the quantum roots of entropy. Information exists in a way that is fundamentally non-local, in the quantum world, and this manifests in the form of the hierarchy of the sub-atomic particles. Rather than having an internally fixed nature and content, it would seem that all of the quantum units making up our universe are defined, at least in part, by the relationship or interactions they have with other entities. This appears to be connected with the non-local quality of energy itself, and with its wave-like aspect, but I will leave that aside.

In my opinion, one of the most important considerations here is the preservation of information and both the propagation and the relative proliferation of that information when physical systems behave quantum mechanically. All quanta are containers, or vehicles, for information as well as energy. One might aptly describe all photons and sub-atomic particles as probes which have the capacity to receive, process, and transmit various kinds of information about their surroundings. In contrast, however, some part of the information present is stored in a way that is not localized, as it is spread among the elements, and defined by the relationship between the various species or flavors that are present in a given system. We must therefore be concerned with how information manifests within systems, or flows between elements of a system, and how this relates to the energy flow, when we examine entropy quantum-mechanically. These factors place demands on the study of quantum entropy which have no counterpart in classical formulations. Specifically; it means that all quantum systems take on attributes of computing engines, especially when we examine their behavior at the microscale. But it would seem that the computational limitations of these microscale systems play a distinct part in what we see as classical behavior, and explains the randomness present in macroscopic systems. That is; when a point is reached where the elements of a system can no longer faithfully represent the dynamics of the system that system's behavior tends to become complex or chaotic.

Entropy is conventionally viewed as a dissipative process, resulting not only in lost energy, but also in disorder. This can be seen to result from a situation where more information is being evolved than can be processed, or assimilated by either the individual quanta or their collective arrangement, in any given moment. Some of that information would appear to be lost, or would fail to be preserved and/or transmitted, when this happens. That is; after a certain amount of complexity develops through a process of orderly evolution, a point is reached where the evolving information content of a system exceeds the representational capacity of that system. Once this occurs, its continued development takes on aspects that are complex, often to the point of being chaotic. The class of forms called Fractals is a manifestation, or a product, of this type of process, as it relates to geometric forms having a specific dimension. When an object or dimensional space has more detail than can be incorporated into forms of a whole-numbered dimension, in a given space, convolution or folding takes place, whereby more information can be squeezed into that space. This results in forms with fractional dimension, which span the gap to the next numerical leap. To some extent; this is like the process of folding surfaces into the next whole-numbered dimension, which results from geometric frustration when the attempt is made to join together the extant pieces, and close the gaps.

A similar information folding effect seems to be happening in the quantum realm that helps to define the transition from quantum to classical behavior. The non-local information that is passed from entity to entity quickly becomes too much to convey (which fragments the information involved), and this results in either an averaging effect, or an amplification of quantum variations, giving the appearance of stochastic processes though the evolution of the wavefunction is purely deterministic. While quantum entities act as vehicles for information, not all of the information which constitutes a sub-atomic particle or force carrier is local in nature, or self contained, but instead is non-local, and is spread out among interacting entities. Bell's inequality experiments show us that the view there may be hidden variables, which can be contained locally within an entity, breaks down. Thus we know that some of the information which defines those entities is inherently non-localized. This information seems to be associated with the wave-like or energetic aspect of an entity, and hence with its quantum wavefunction. So the manner in which coherent states persist and decohere is of the utmost importance to study, for our understanding of the quantum-classical transition. And this study will most definitely add to our understanding of the quantum mechanical roots of entropy.

In their purely energetic form, as wave-like entities, all quantum units are indefinite or ambiguous in some measure. When as individual quanta they decohere; they pass on the information, as well as the energy, that exists in their quantum wavefunction. Since the process of decoherence involves mutual ‘measurements’ by the entities involved, whenever quantum units and systems interact, and it seems there is both processing and propagation of information among interacting entities, it is wise to consider them computing engines, on some level. This idea, first stated by Konrad Suze in 1967 [35], was well articulated on the last page of “Mind Tools” [36] by mathematician Rudy Rucker, where he sums up the consequences of believing that everything is information. He concludes that reality is “An incompressible computation by a fractal cellular automaton of inconceivable dimensions.” In Physics; this idea has a history which most certainly includes John Archibald Wheeler’s “It from Bit [37]” and Edward Fredkin’s “Digital Physics [38].” They indicate it is information and the processing thereof, which defines the characteristics of physical systems, with time, space, and energy weaving the shape of form thus defined. However, this concept has evolved somewhat since then. The idea that each sub-atomic particle or atom is a mini quantum computing engine has merit, and there is some truth to the notion they can function much like a computer, when linked together. Many have thus imagined that the universe is like a gargantuan digital computing network.

However; we must remember that we are talking about quantum information, and accordingly quantum information processors and quantum computing networks and systems, where much of the information involved is non-local. This makes the idea of a connected network of localized processors a crude approximation to the actual state of things. In more recent years, this idea has been adopted and revised, where David Deutsch and Paola Zizzi have evolved the term “It from Qubit” to reflect the fact that we are talking about Quantum Computing [39, 40], which allows communication to take place in a diverse range of interesting ways not possible for conventional computers. Indeed; much of the promise of quantum computers evolves from the fact that they do access and process information differently from conventional machines. This should allow the quantum computers of the future to quickly solve problems which are nearly intractable (or quite impractical) for the linear, sequential computing machines of today. But exploring this territory leads to some interesting Physics, as well. The view of the universe as a quantum computer has been adopted and expanded upon by others, including Seth Lloyd [41] and Jack Ng [42], but the link between quantum-mechanics and quantum information science has inspired many. It seems any working theory of quantum gravity will have to address the information creation and loss questions in a definitive way. But the question mentioned earlier, about information loss at the event horizon of a Black Hole (when what falls in is compared with the Hawking radiation), has been the catalyst for a lot of relevant theoretical physics.

In his article for the July 2003 Scientific American “Information in the Holographic Universe,” [43] Jacob Bekenstein echoes this last statement, calling the Black Hole “a central player” in recent theoretical developments. His article also weaves together a number of the themes I have covered in this paper, starting with Wheeler’s idea above, “to regard the physical world as made of information, with energy and matter as incidentals.” Interestingly, one section of the article is entitled “A Tale of Two Entropies” which focuses on the similar conceptual and mathematical basis of the two common formulations. “Thermodynamic entropy and Shannon entropy are conceptually equivalent:” he states, “The number of arrangements that are counted by Boltzmann entropy reflects the amount of Shannon information one would need to implement any particular arrangement.” He goes on to explain why the two measures are different in practice, but then declares “When the two entropies are calculated for the same degrees of freedom, they are equal.” So; how does this relate to Black Holes? Gerard ’t Hooft’s landmark 1993 paper on “Dimensional Reduction in Quantum Gravity” [44], showed us that because the degrees of freedom are reduced for a Black Hole at its event horizon, the entropy varies with its surface area not its volume. This has opened the door for a whole new chapter for theoretical physics, based upon the idea of a holographic correspondence, where one can envision interactions as occurring on the boundary of a surface with the next higher or lower dimension, allowing otherwise intractable problems to be solved. But the inspiration for ’t Hooft’s insight was an awareness of the essential connection of information theory with quantum mechanics, and this remains important.

So how does computation enter the picture? It seems that once we have information moving around, and being processed by quantum systems, we have a computing engine of sorts. And once we have computing capability, only a small amount of orderly development is necessary to get complex processes started. The capacity for even very simple computing systems to evolve great complexity has been amply demonstrated by Stephen Wolfram, in his book “A New Kind of Science [45].” One of the most complex mathematical objects known, the Mandelbrot Set, is seen to arise from iterating a very simple formula. The iterated function systems explored by Michael Barnsley in “Fractals Everywhere” [46] require only a handful of numbers as seeds, to generate a vast array of infinitely detailed complex forms. So we find that complexity is very easy to generate, once a certain amount of computing power is assembled, and that both complexity and chaos are inevitable, once a fairly modest level of information processing is exceeded by a system. And it appears that both complexity and chaos can spur the production of entropy. That is; nature does not appear to prefer chaos, and the tendency implied by the second law does not require things to become steadily more disordered. Instead, nature uses both chaos and order to spread energy, and if anything appears to be working to build more complex and interesting arrangements. I suspect that this complexity building may be a direct result of the fact that the elements of form in our universe *do* receive, process, and transmit information as well as energy, because this makes it all compute.

But once any aspect of computing is assumed by a system, it automatically takes on the discrete nature of all evolving processes. Part of what we have seen is that all quantum processes proceed by individual or discrete steps. The very meaning of the word quantum reflects this idea, that there are discrete units which are the vehicles of energy and information in our universe. The most fundamental quantum unit is Planck's constant, which is dimensionally a unit of action (or angular momentum). If actions are quantized, occurring in discrete steps in our universe, this makes all systems quantum systems, and all quantum systems processors of information (or quantum computers) executing the individual steps of an evolving process, much like the sequential steps of a computer program. This idea is crucial to our study of the quantum origins of entropy. It forces us to consider the possibility that computationally efficient processes are more likely, or become probable within the context of the evolution of any system, be it an experiment in a laboratory, or the entire universe. I am reminded here of Philip Gibbs' "Theory of Theories" concept [47], which asserts that out of the entire landscape of theoretical possibilities we can derive a sort of path integral, defined by the most sensible Mathematics and Logic, and that this determines the most likely possibilities to manifest in the physical world. This idea has great appeal for me, and prompted me to coin the term "It computes; therefore it is!" [48], in imitation of René Descartes. So when, in his Scientific American article, J. Miguel Rubi stated that (mesoscopic non-equilibrium) "thermodynamics offers a computational shortcut" [4] over other methods of analysis, I imagined it is because this more accurately models how nature follows the path of least (computational) resistance, to spread energy and information.

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