

# Objective Bayesian Reality and its Darwinian Evolution

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## Introduction

Scientific understanding has come to regard objective reality as a 'point of view invariant' realm where information that can be known about any entity by an observer or other entity must be consistent with what can be known by any other observer. Scientific law must provide consistent explanations and predictions for each observer or entity regardless of its circumstances.<sup>i</sup> The standard model of particle physics tells us that one entity within objective reality may influence, interact with, or be detected by another entity only through one of the three fundamental physical forces: electro-weak, strong and gravitational forces. This formulation suggests boundaries for a physical arena of objective reality.

Recent research by W. Zurek and others delineates the boundary between quantum reality and classical objective reality. This boundary is formed by a Darwinian process that selects information that is adapted for survival in the classical reality from the vast number of potential quantum outcomes. Zurek has named this process Quantum Darwinism and it effectively forms a boundary for objective reality.<sup>ii</sup>

Zurek's work reveals that there exists an inherent knowledge mechanism within quantum wave functions that serves to model the environment of quantum entities and the information they may potentially exchange. Surprisingly this knowledge mechanism has many similarities to those utilized by other emergent forms of matter.

From our understanding of the history of the universe it is clear that near its beginning the web of interactions between fundamental particles joined through quantum forces composed the extent of complexity existent in the universe. Later emergent levels of complexity appeared forming the scientific subject matter of atomic physics, chemistry, biology, population genetics, neuroscience and culture. These emergent structures in reality display reduced local entropy suggesting they are highly improbable and require explanation.

The principle of Maximum Entropy tells us that systems will evolve to states of lower entropy only when they are constrained to do so by scientific law.

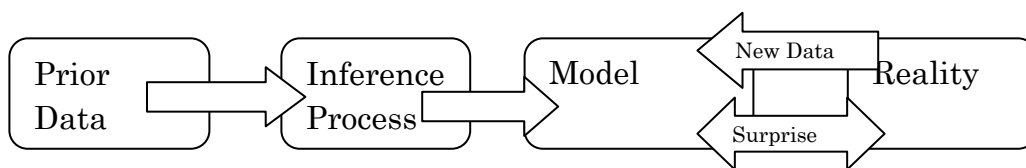
Explanations of these low entropy states must entail a statement of the scientific laws responsible for constraining them from visiting higher entropy states.

Many low entropy states in the realm of atomic physics and chemistry are well explained by the operation of fundamental forces and particles in a cooling universe and other specialized environments without the need for additional scientific laws. Explanation of the evolution of life on earth and its subsequent evolution into more complex forms requires additional scientific law.

These explanations and their attendant scientific laws might be understood using the concept of adaptive systems. Adaptive systems, as defined by Friston and others, involve the dynamics of systems which act to optimize their relationship with their environments in order to retain their low entropy states. Central to Friston's analysis is the conclusion that adaptive systems must contain models of their environments and of causes within those environments. The optimality of an adaptive system results from its ability to minimize its free energy, in an information sense, or to reduce the discrepancy or 'surprise' it experiences in interactions with its environment.

In this light we might consider much of the ontological subject matter of genetics, population genetics, behavioural and neuroscience and culture as adaptive systems driven through Darwinian processes to optimize internal models in a manner leading to minimal free energy or 'surprise' when interacting with their environment.

A general model for this process might take the form:



In these areas of science Darwinian processes are responsible for having developed internal models from prior experience through a process of inference. This interpretation treats the internal model building as an algorithm that is substrate neutral and has been instantiated in many forms including genetics, neurological models and scientific hypothesis in the realms of biology, neuroscience and culture respectively.

Much of scientific law associated with these fields might be understood as the design details inherent in each adaptive system that were discovered and evolved to their present state through the operation of Darwinian processes.

## History of Objective Science

Merriam Webster provides a modern definition of 'objective'<sup>iii</sup>:

*of, relating to, or being an object, phenomenon, or condition in the realm of sensible experience independent of individual thought and perceptible by all observers :having reality independent of the mind*

The idea of an objective reality is a core assumption of science and has provided much guidance for the development of science. A common theme in the development of science is its move to greater objectivity. We are progressively coming to understand, through our scientific knowledge, that we exist in an independent reality that evolved a huge amount of scientific subject matter before humans existed and that humans are only a natural extension of this reality and are in no way fundamental in shaping it.

Prior to the beginnings of science, as it is understood in a modern sense, dominant world views were largely those of the great religions; revealed through sacred texts and interpreted by a rigid bureaucracy. For the less theistically inclined Platonic philosophy with its focus on an ideal reality unseen by the senses was an alternative as were Aristotelian ideas, eventually morphing into those of the church, that were largely based on a priori ideas concerning the 'natural' state of things and came to be relied upon by reason of authority. More 'scientific' ideas, expounded by Archimedes, had little influence through the end of the middle ages as only few copies of his works existed. Much of his work was only discovered in relatively recent times.

These sources of knowledge of the reality in which we exist down-played the ability of the senses to inform our worldview. Justifications in the battle between the Church and Copernican astronomy, culminating in the prosecution of Galileo, hinged on the assertion by the Church that sensory data was not to be relied upon and that the creator could order things as he wished including the reliability of our sensory information. Of course they reserved for themselves, on the pain of death, the sole right to interpret this arbitrary divine mind.

With the advent of Newtonian scientific understanding in the 17th century a beautiful picture became available to the educated of a helio-centric solar system,

accurately predictable from the law of gravitation that applied equally to planets and to objects in our everyday life. This was a giant step involving an understanding that human affairs exist in an objective reality that does not necessarily imbue their situation with special significance. Educated people gained an aesthetically pleasing alternative to believing that they were the central focus of creation and that their home planet was at the centre of the universe.

In his twenties Newton became part of a small group of natural philosophers who practised science in a tradition largely established by Francis Bacon. This approach became known as the British Empirical School and stressed the importance of empirical evidence derived from experimentation in support of theoretical explanations. It was a revolutionary change from the authority centric approach which had dominated since the time of the Greeks and the beginnings of scientific speculations. Now evidence rather than authority was considered the best guide to truth.

This movement also heralded a revolutionary change in thinking about objectivity. Explanations, in the form of theories, gained support if they in turn were supported by the evidence. Further along this chain the quality of evidence was judged by its repeatability. To hold any weight observations must be repeatable. That is any individual, given the appropriate setting, must be able to make the same observation as made by any other observer. This consensus amongst a group of individuals concerning the empirical evidence they witness leads to a stronger notion of objectivity and of evidence as an objective fact free from the dictates of authority or subjective interpretation. Here was the beginnings of the understanding that ontological reality must look the same to all observers.

This small group of British investigators, practising empirical methods of investigation founded the Royal Society in 1660 and it continues today as one of the world's most prestigious scientific organizations.

Another huge blow to the remaining anthropocentric components of the scientific worldview was dealt by Darwin with his theory of Natural Selection identifying humans as only one more animal form evolved from common ancestors. This theory was seen by many as threatening human values as it awoke us from our previous shared delusion of being the central purpose of creation. Human beings were revealed to be animals created by the same evolutionary process as all other life forms. Yet his views were interpreted by some as adding grandeur to our situation. We are revealed as amongst the most complex of living things. Our involvement in cultural entities is unprecedented and sets us apart from other living things. We are

joined to the rest of life and to the wider universe in a natural way. Perhaps this theories greatest gift, was to reveal that the drama of life is most clearly seen in an objective context. A universal process has created us along with all other life forms, it was in full operation long before the existence of humans was even a faint possibility and it will probably continue long after the human species has ceased to exist. To gain understanding of our true situation we must give up the infantile delusion that we are 'special' in the sense of existing outside of natural processes and be open this objective world.

Philosophy, up until the late 19th century had largely been at odds with scientific understanding in general and objectivity in particular. Emmanuel Kant, perhaps the most renowned philosopher of all time, believed that the nature of reality was based on relationships between objects and that what could be known of objects could only be based on our relationship with them and that this excluded the possibility of objective knowledge.

Starting with the works of Ernst Mach in the mid 18th century a new branch of philosophy, the philosophy of science, began to take shape formed mostly from the work of scientists such as Mach who saw science as providing a philosophical vantage point. This work was expanded by the school of Logical Positivists who during the early 20th century challenged previous philosophical understanding with the notion that only those thing that could be measured should have cognitive significance.

This branch of philosophy was tremendously influential on the thinking of the great scientific works of the early 20th century including the theories of relativity and quantum mechanics.

Einstein revered Mach. He digested Mach's thinking and reaped a huge intellectual harvest. He came to understand that objectivity required constraints on scientific law in the sense that all laws must provide every observer with the same predictions regardless of their own particular circumstances. Special relativity provides common predictions for all observers regardless of their own velocity and General Relativity provides common predictions to all observers regardless of their own acceleration. Einstein was led to General Relativity largely through steadfastness to this principle.<sup>iv</sup> The guide of objectivity was so compelling to Einstein that he initially called his theory 'Invariance Theory' and only acquiesced when 'Relativity' became more widely adopted by Max Planck and others.<sup>v</sup>

Einstein expressed his objectivity requirements by demanding that valid scientific theories must provide all observers with accurate predictions of what they would

measure. This might seem quite human centric but he also made it clear that in his view objectivity extended beyond human experience and measurement. General relativity in particular predicts the behaviour of all mass and energy in response to gravity whether or not there is a human observer present.

As the baffling world of the quantum was being probed and a scientific formalism regarding it developed the dominant interpretational model came to centre on the work of Niels Bohr. Bohr understood the quantum world underlying the classical world to be a distinct reality. These two realities are spanned by the process of measurement where quantum phenomena emerge in classical reality. He insisted that quantum reality could only be known through measurement and that it did not make sense to talk of quantum reality in terms other than what could be measured. In this sense his theory was epistemological, about what we can know, rather than ontological, about what is really out there.

Einstein, also one of the founders of quantum theory, had a much different point of view and insisted that any fundamental physical theory must describe an objective ontological reality. Philosopher CP Snow described the ensuing debate: *'No more profound intellectual debate has ever been conducted'*.<sup>vi</sup> As described in more detail below perhaps the most persuasive evidence we have today serves to illuminate how they were both correct, Einstein from an ontological viewpoint and Bohr from an epistemological one.

Some variants of quantum theory have supported an anti-objective interpretation of physical reality culminating in that of Wigner's where human consciousness was proposed as a necessary component of quantum measurement and quantum wave collapse. Even the dominant interpretation of quantum theory with its focus on measurement might seem to give special status to humans and their perspective. The paradox resulting in the requirement that a human measurement is necessary for the resolution of quantum reality was brought to the fore by Erwin Schrödinger in his famous thought experiment that has come to be known as the Schrödinger's Cat paradox. This paradox hinges on the assumption, as implied by quantum theory, that a cat can neither be considered alive nor dead until its state is measured by a human observer.

The century long confusion over the meaning of quantum mechanics, sometimes even abetted by our leading interpretations of scientific theories, concerning the nature of objective physical reality may recently have been largely resolved. The set of axioms underlying quantum theory have been revised and simplified. The most contentious ones, those requiring quantum measurements to produce classical

results and that assign probabilities for the competing classical results, have been shown to be implied by the other axioms and therefore unnecessary as separate axioms. Measurement is no longer seen as a fundamental physical process but rather as just one of many types of physical interaction. At the quantum level all physical interactions between the fundamental building blocks of reality may lead to decoherence, the process where quantum effects are recorded in classical reality. Whether these interactions are initiated by a human motivated measurement or by any other natural process is irrelevant. In this sense our new understanding is entirely objective.<sup>vii</sup>

A further recent breakthrough in our understanding of objective reality, a direct descendant of Einstein's thinking on 'invariant theory' has been made.<sup>viii</sup> This work details the fact that much of physical law can be derived purely from assuming an objective reality. If scientific law is to describe an objective reality a 'point of view invariant' reality, one where accurate predictions concerning the behaviour of all interacting matter and energy are attainable regardless of the particular circumstances of any of the participants, then this constraint is sufficient to derive many of the fundamental components of physical law including: special relativity, general relativity, quantum gauge theories and the symmetry laws.

That these components of physical law are amongst the most accurate and powerful is strong evidence that reality is objective in the sense of point of view invariance.

In some sense this theory of reality brings us full circle back to Kant. All of reality is a web of relationships. The crucial added ingredient is that this web is objective. No entity in the web has a privileged position. We can have objective knowledge of other entities contained in the web through insisting that our knowledge of other entities is no different than that experienced by any other entity. Our experience of an electron must be the same as a proton's experience of an electron; a valid scientific theory of the electron must describe both experiences. It must describe the effects of an electron in an objective reality.

If we accept that reality is at bottom this kind of objective network or web then we must also accept that it was become continuously more complex over time since the 'Big Bang'. It has evolved new hierarchies over time including chemistry, biology and culture. Still none of these newcomers is privileged over the others; each experiences the rest of the web in a common manner.

We should remember that the fundamental interactions consist of physical forces. These interactions determine some of fundamental particles' basic properties such as position, momentum and, in some theories, mass. In some sense we might think

of these properties, ingrained in fundamental properties as a kind of rudimentary 'knowledge' of the outside world; that is they contain information concerning other components of the web of reality.

Isolated fundamental particles may be in situations where they seldom interact with other entities in the web. In this case they might be said to experience a limited existence. The lack of interactions experienced and the lack of internal mechanisms for information storage would indicate such particle might be said to have only very limited 'knowledge' of the world around them.

## Quantum Darwinism

Our best physical theories, often called the standard model of particle physics, tell us that the objective web of reality is held together by only three types of interactions, the bonds of the three forces of nature: gravity, the electro-weak and the strong force. A main thrust of current physical research is attempting to reduce these three theories to a single 'theory of everything' that operated in undivided splendour near the time of the Big Bang, when things were simpler. Leading candidates in this search are String Theory and Loop Quantum Gravity.

It is clear that the success of these new theories will be dependent on accounting for phenomena occurring at the plank scale, that is about  $10^{-35}$  meters. When we consider that the diameter of a proton is about  $10^{-14}$  meters we see that there is a greater relative difference in scale between the Plank scale and that of 'fundamental' particles than there is between that of fundamental particles and phenomena in our experience. We might expect that as much emergent phenomena occurs below the scale of 'fundamental particles as occurs at scales above it.

Indeed some physical theories of reality at the Plank scale propose that 'fundamental' particles themselves, such as the photon may be emergent phenomena.<sup>ix</sup> We are thus faced with perhaps an infinite regress of 'fundamental' realities. It looks like it might be 'turtles' all the way down. In spite of that daunting consideration, we may still be amply rewarded by appreciating boundaries on those aspects of reality that may have the ability to influence us or to interact directly with us.

The small number of interactions described by our physical theories are the only interactions known to exist at the particle physics level. In this sense the Logical Positivists have been exonerated; anything that does not interact by these forces is in principle unknown and unknowable to the web of reality we inhabit and from

this vantage point may be said to have no existence nor produce any effects that are in principle detectable.

All physical interactions may be viewed as quantum interactions and the theories describing them are the most accurate and powerful in all of science.<sup>1</sup> Thus quantum interactions are at the core of our objective reality, are the gateway through which all of its participants must pass and form a boundary around the extent of reality that can be objectively known. If we are to understand the nature of our objective web we must start with an understanding of quantum mechanics.

Until recently this has not been possible. We have had extremely accurate theories of the quantum for nearly a hundred years but unfortunately although these theories were useful for calculations they shed no light on the nature of the quantum process. As one of the great creators of quantum theory, Richard Feynman said: "*I think I can safely say that nobody understands quantum mechanics.*"<sup>x</sup>

Fortunately this century long impasse has recently been skirted. The work of Wojciech Zurek, of the Los Alamos National Laboratory, and collaborators has revealed in detail the processes of quantum decoherence, the process central to understanding the mysteries of the quantum.<sup>xi</sup>

Quantum theory may be erected from a number of axioms. Usually it is a good sign for ease of understanding if a scientific theory can be constructed from a few simple axioms using only the assistance of logic. In these cases we need only understand the axioms and all the rest is implied.

With Newtonian classical mechanics this is surely the case. If we take Newton's three easily understood laws of motion as axioms, much of the resulting easily understood classical mechanics can be derived using logic alone. Unfortunately this has not been the case with quantum theory. The axioms underlying it do not seem to relate to anything understandable. Worse, they seem contradictory. We will list a set of axioms for quantum theory and comment on the problems of understanding they entail.

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<sup>1</sup> Gravity is not usually considered a quantum theory but it has been shown that a quantum formulation is equivalent to General Relativity in the classical limit. This is the same limit in which General Relativity has been shown to be valid. It is in trying to extend the theory of Gravity to non-classical situations, including extreme energies and time and space resolutions on the plank scale, that both formulations fail. As noted in Wikipedia's article on the graviton: 'In this framework, the gravitational interaction is mediated by gravitons, instead of being described in terms of curved spacetime as in general relativity. In the classical limit, both approaches give identical results, which are required to conform to Newton's law of gravitation.'

*1) For every physical system there is a corresponding mathematical object called a state vector in Hilbert space that has no physical embodiment. This state vector is the most complete source of information that exists concerning the physical system.*

How do we understand this? The most complete information we can have of a physical system is a non-physical mathematical object? Sounds like something outside of our web of reality whose existence is in principle unknowable.

*2) The state vector evolves in time according to a continuous, deterministic mathematical function except when a measurement occurs and then it jumps to the state described in 4) and 5) below.*

This axiom is a little more promising in that the undisturbed state evolves in a mathematically tractable manner. The jump part seems somewhat contradictory; smooth, continuous evolution and then a jump?

*3) Once a measurement is made the state vector assumes a state such that the same measurement immediately reapplied to this state has 100% probability of achieving the previous measured result.*

More promising yet, this axiom tells us that although there is a jump involved when we measure a quantum system this jump is not arbitrary and that the system's evolution picks up after the jump at the state revealed by the measurement and resumes its smooth evolution from there.

*4) The outcome of any measurement on a physical system can be predicted by performing a specific mathematical operation on its state vector.*

Not good for understanding. Predictions can only be made by performing a seemingly arbitrary mathematical operation on the mathematical object that is the source of all knowledge we can have of the quantum system?

*5) The outcome of any measurement process on a physical system can only be predicted as a probability for obtaining that result. The procedure for obtaining this probability is known as Born's rule.*

Not good either. Predictions can only be made in the form of probabilities and these probabilities must be calculated using another seemingly arbitrary mathematical rule?

The first step we can take to achieve clarity is to replace the word 'measurement' with 'interaction' in all the axioms above. As guided by our analysis of objective

reality we must conclude that interactions conducted by humans and labelled by us 'measurements' are indistinguishable from other types of interactions taking place within the web of objective reality.

Still we are left with a huge lack of clarity that might be summarized:

- 1) The source of a quantum system's effects that can be experienced by any entity within the web of reality is a non-physical mathematical object.
- 2) The effects experienced by any entity within the web of reality concerning a quantum system can only be predicted by the application of two seemingly arbitrary mathematical procedures.

Zurek's work rigorously explains both. The first, as might be expected, is the nub of the conundrum. Zurek shows that we should not expect the quantum world to be part of the objective web of existence that we inhabit, only the effects of quantum systems that can pass through the filter of decoherence should be included in this reality. Quantum systems participate in reality only through those interactions. When analysed in detail these interactions or quantum decoherences consist of a transfer of information between the quantum system and the web of objective reality. Not all information concerning the quantum system is transferable. In fact the vast majority is not transferable. The relatively tiny amount of information that can be transferred is selected from the huge range of quantum possibilities and numerous copies of this information are deposited in the environment by a Darwinian process that Zurek coins Quantum Darwinism.

Second Zurek has succeeded in showing that the two seemingly arbitrary mathematical procedures specified by the last two axioms required to predict the nature of quantum systems' interactions are inherent in the first three axioms. In other words once we concede that much of quantum systems exist outside of our web of objective reality, in a manner described by the first three axioms, the nature of their interactions within our reality follows.

In this manner Zurek's work leads us to a new tighter definition of objective ontological reality. It is the sum of the interactions between the fundamental entities composing the universe. Information or influence from anything outside this web that might, in some weak sense, be said 'to exist' cannot in principle be detected within this reality.

Over time this web of interactions, in spite of the 2nd law of thermodynamics, has found emergent paths to forms of greater complexity including atomic physics,

chemistry, biology and culture. These forms are fundamentally composed of the objective web and are participants within objective reality.

## Bayesian component of the web of reality

Given that Zurek's work may offer a new plateau in our understanding of objective reality we might take a closer look at his accomplishments. In particular his derivation of Born's Rule, the rule providing probabilities concerning the outcome of interactions, gives us a new understanding of the place of probability within reality.

Bayesian probability, one of the two main schools of probability and the one we will focus on, considers probability as a measure of a state of knowledge.<sup>xii</sup> It extends Aristotelian logic, where variables are either true or false, to a logic of probability where variables may have continuous real values between 0 and 1 (false and true). It has been proven, given a desiderata of rationality and consistency, that Bayesian probability is the only mathematical system able to extend logic into probability.

As E.T. Jaynes remarked :

*So, thanks to Cox, it was now a theorem that any set of rules for conducting inference, in which we represent degrees of plausibility by real numbers, is necessarily either equivalent to the Laplace-Jeffreys rules, or inconsistent.<sup>xiii</sup>*

Keeping in mind that probability, in this sense, is the science of rational inference, that is making valid inferences from evidence, we can examine Zurek's accomplishment in deriving quantum probabilities from the rest of quantum theory.

It is hard to overstate Zurek's accomplishment in deriving the quantum axioms concerning prediction from those concerning the wave function. Physically his finding implies that the measurable outcomes are modelled by the wave function of the entangled system composed of quantum entity and environment prior to decoherence. The predictive model has two components:

- 1) The property of the quantum system that will be revealed during the information transfer to the environment will correspond to a 'pointer basis'. These properties are roughly classical in nature and do not include weird superposed quantum properties. The nature of the environmental entities with which the quantum system is entangled will influence the composite wave function so that it models a specific property that will be the subject of the information transferred during decoherence. That property might be position or it might be momentum or something else dependent on the environment.

2) The model predicts the possible values of the information concerning the specified property that will be transferred along with the specific probabilities for each value.

Combined these two components provide an exquisitely accurate predictive model. Zurek's work demonstrates that this model is not a creation of science rather it is a model inherent in nature which science has discovered.<sup>xiv</sup>

The predicted probabilities, in a very Bayesian sense, describes the information concerning the quantum entity that will be received or 'known' in the environment of our objective reality. Once an information transfer takes place through the process of decoherence the predictive model inherent in the wave function is updated as required in axiom 3).

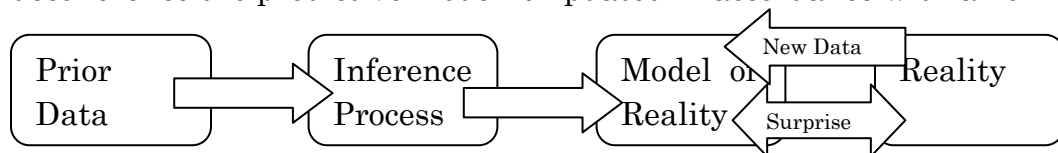
As by definition our objective reality consists precisely of this web of interactions this is the only information or knowledge available to any of the participating entities. At bottom all information is this type of quantum information and it is dispensed to its environment in accord with quantum theory entailing probability.

Quantum theory considered in this context provides a model for what we or any other entity in the quantum web can expect to 'know' about any other fundamental entity in the web. This knowledge is described as a probability distribution over a number of outcomes. It is heavily influenced by prior information; the quantum state at some previous known 'initial condition' and pertinent features of the environment (contained in the Hamiltonian).

A predictive model is inherent in the wave function of the entangled quantum entity plus environment system which provides probabilities for outcomes.

Quantum theory claims to supply the most accurate predictions of expected outcomes that are in principle possible. To date this claim is supported by the evidence. In other words when a measurement, an interaction or a computation is made the 'surprise' or discrepancy between the outcome and the theory's prediction is the minimum possible.

Once information is transferred to the environment through the process of decoherence the predictive model is updated in accordance with axiom 3.



A simple model of a generic knowledge mechanism is illustrated above and is important to our discussion as it will be used repeatedly below to illustrate emergent levels of complexity that have evolved over the course of time.

Although our web of interactions is fundamentally a web of quantum interactions it has, over the history of the universe, evolved emergent structures of great complexity, which will be discussed in detail below. These structures may also be understood in terms of information or knowledge but the information involved with these structures is still quantum information that may be processed and from which inferences may be drawn.

As an example, one might certainly balk at the idea that sensory information gathered by biological organisms has much to do with quantum interactions. However when we consider that the eye functions by receiving a sample of light from its environment and that the interaction between these photons from the environment and molecules such as rhodopsin in the retina is a quantum interaction involving only the transfer of quantum information we can see that it is precisely these interactions that are the source of any information subsequently available to the organism. The eye, the organism's brain and its behavioural reactions function to process this information, draw inferences from it and behave appropriately in response to it. None of these functions however are the source of new information. Likewise hearing depends on the detection of pressure waves. Pressure is transmitted through a quantum interaction where information regarding momentum is transferred to the environment in a quantum manner.

Perhaps an even more dramatic example involves photosynthesis, the biological process through which the sun's light is converted to a biologically useable form of chemical energy. Photosynthesis is a fundamental process in the web of life but complete details of its operation have long eluded researchers; specifically how this biological process can be 95% efficient while the best solar panel technology can produce only about 20% efficiency. Recent research indicates the answer may be that nature employs a quantum computation to decide on the most efficient chemical pathways to employ for each photon of light received.<sup>xv</sup> In this process, crucially important to life, a great portion of the underlying quantum information is harnessed to improve efficiency.

We might now see the web of reality as a web of information flow. The information that one entity can have of another and that composes the web is bound by the laws of physics and is probabilistic in nature.

## Computing the Future

A portentous event occurring in our time is the development of theory and technology concerning quantum computation. As implied by its name quantum computation is thoroughly quantum in nature. A number of quantum particles are entangled in an interactive web and their properties are manipulated to make their relationship logically analogous to a computational problem to be solved such as a prime number factorization. To extract the problem's answer a decoherence of the quantum web is forced and the system deposits its answer into the environment via Quantum Darwinism. In this way quantum computation is entirely equivalent to quantum mechanics. As noted by Seth Lloyd of MIT, the universe can be seen as a quantum computer and each interaction between fundamental particles as a quantum computation. What is computed is the outcome of the interaction.<sup>xvi</sup> In other words what is computed is the future of the constituents composing the universe.

A formal equivalency (isomorphism) has been shown between the formulations of information transfer as presented by Quantum Darwinism and that presented by quantum computation.<sup>xvii</sup> Given that quantum computation is analogous to quantum theory we must conclude that quantum measurements, quantum interactions and quantum computations all refer to the process of quantum decoherence occurring in differing circumstances.

This observation justifies a merging of the interpretational explanation offered by Quantum Darwinism with that offered by Quantum Computation. Insight may be gained from hybrid interpretations such as: The future of the universe is selected by a Darwinian process. In other words this interpretation suggests that the future history of the universe is selected from its potentialities through a Darwinian process. The future is selected from possibilities generated in the past on the basis of their adaptability for survival or existence in their environment.

Given that the fundamental web of interactions at the quantum level may be interpreted as composed of a Darwinian process, it is little wonder that many of the best scientific theories describing scientific subject matter of greater emergent complexity: life, population genetics, neurology and culture also rely on Darwinian processes.

## Maximum Entropy

Given that a web of quantum interactions forms the basis of objective reality we are left with a puzzle as to the existence of complex structures, ourselves included.

Complexity is an extremely special state and is therefore rare. This notion is a basic law of physics known as the second law of thermodynamic. It says that the quantity of entropy or disorder, in a closed system, will tend to increase. That in the random walk entailed by the evolution of systems they are much more likely to enter states of lesser complexity than states of greater complexity due to the fact that less complex configurations are much more numerous.

How to explain not only the existence of the many complex systems we see around us but also their increase in numbers and degree of complexity over time? The usual explanation is that entropy need only increase in a closed system and that the complex systems we are considering are not closed but rather part of a larger system whose overall entropy is increasing. For example the complex biological system on earth is not a closed system but must be considered together with the sun. In this sun/earth system entropy is increasing as the decrease on the earth is more than compensated for by the increase of the sun.

Still this is only a partially satisfying explanation as it leads us only to more questions: How are designs for extremely unlikely complex systems such as earth's biology found, how are those designs instantiated and how can they survive and evolve ever greater complexity?

A first step to answering these questions might involve a scientific principle that is a refinement of the second law of thermodynamics known as Maximum Entropy. This principle, although it appears to only tweak the second law, offers enormous insight. It says that the evolution of a system will result in all aspects of the system increasing their entropy except where they are constrained by scientific law.

As an illustration we might consider a historical scientific mystery concerning the atom. The atom was first envisioned as a classical entity with an electron orbiting a nucleus. According to classical scientific law the atom should achieve lesser complexity by radiating away the electron's energy and the electron spiralling inward and collapsing into the nucleus within a fraction of a second. This is a disastrous model as it predicts all matter is unstable. Only when it was accepted as a scientific law that an electron's orbital energy came in quanta or packets and could not go to zero was it understood that an atom remained stable because its electron orbital energy was constrained from falling below its ground state. This quantum scientific law constrains the system's tendency to go to states of higher entropy and the situation conforms to the predictions of maximum entropy; that the system will go to the states of highest entropy available to it subject to the constraints of scientific law.

Although some of the underlying principles of Maximum Entropy have been used by practicing scientist at least since the time of Laplace, it only became formalized during the last century largely in the work of E.T. Jaynes.<sup>xviii</sup> Since then it has become an indispensable implement in the scientific toolbox as it guides modelling of a system on the basis of the second law of thermodynamics and any other applicable scientific laws.

Maximum Entropy is usually considered as a principle providing a tractable method for making predictions on a system's evolution subject to scientific law but it may also be turned around and used to inform us as to the nature of scientific law.

Consider that in the very early universe scientific subject matter was quite limited. I am using the term 'scientific subject matter' in an objective sense; in the sense that scientific law greatly preceded humanity and has only recently been partially discovered by us. In the early universe the only scientific law in operation was probably that of quantum gravity. Atomic physics, cosmology, chemistry, biology and culture, in fact the bulk of scientific subject matter, had not yet emerged in the web of reality.

From this view it is clear that the bulk of scientific law came into existence along with the complex entities that could endure and that now after a long period of evolution compose much of scientific subject matter. Scientific law can be considered as the specific designs found by nature that are capable of retaining and evolving their complexity. Let us remember that complex systems are not forbidden, they are only extremely rare. A complex design able to maintain and evolve its complexity is not impossible, in fact we have overwhelming evidence that such systems exist. When we examine their nature we see that there are scientific laws operating that constrain these systems from evolving to more simple states. These scientific laws however did not pre-date the scientific subject matter composing the complex system rather they evolved with it. The applicable scientific laws might be considered as their design specifications.

Thus we can consider scientific law concerning such things as chemistry or genetics as the design specifications of those systems nature has found and instantiated capable of retaining and evolving their complexity. They specify the constraints imposed by nature that deny the evolution of these designed complex systems access to states of lesser complexity.

## Atomic physics and chemistry

As a result of Zurek's research we can locate precisely the emergence of atomic physics from the web of interacting fundamental processes. As soon after the big bang as allowed by cooling temperature the light elements formed according to the predictions of quantum mechanics given the fundamental forces and environmental conditions in which they found themselves. In fact the success of quantum theory in predicting the observed ratios of the light elements is considered some of the strongest evidence for modern theories of cosmology. The further development of more complex elements within stars and supernovas is also fully explained by the operation of quantum theory within these environments. Further evolution of more complex chemistry has been possible in more specialized environments throughout the universe.<sup>xix</sup> In particular the earth with its moderate temperatures, sources of solar and tectonic energy, and liquid water has proved an ideal environment for the production of complex chemistry.

All of these advances in the evolution of more complex chemistry are fully explained by the laws of quantum physics operating in their particular environments. The interpretation emerging from Zurek's theory is that the states of matter found in atomic physics and chemistry are the results of quantum decoherence that occurs when the underlying quantum states interact with their environments.

Decoherence produces the non-superposed character of these particles in our web of reality. Through the process of Quantum Darwinism multiple copies of information regarding the classical nature of these interactions are deposited in the environment further enforcing its objective nature in the sense that the same information from the environment is available to all systems and that the underlying system need not be disturbed by other systems learning about it or being influence by it from this secondary source of information.

Given the perspective provided by quantum computation we might interpret the creation and evolution of atomic physics and chemistry as the results of quantum computations programmed from fundamental particles by the particular environments in which they find themselves. The evidence for and the only detectable information regarding these more complex entities emerge into the web of reality through the process of Quantum Darwinism.

Most of atomic physics and chemistry are derivable, at least in principle from quantum theory with the assistance of other basic physical law such as thermodynamics. Few emergent laws are required to explain the scientific subject

matter of atomic physics and chemistry although there appears to be some exceptions in the realm of complex chemistry.<sup>xx</sup>

## Biology

There is a near consensus amongst scientists working in this field that life evolved from chemistry on our planet through natural processes. Fundamental to any definition of life are (a) reproduction, and (b) controlled local entropy reduction. These characteristics might be taken as a rough demarcation between chemistry and life. There has been much research aimed at identifying plausible chemical systems as candidates for the precursor of life. One such area of research is 'RNA World' which has marshalled extensive evidence in support of various theories of how RNA chemistry may have evolved the ability to catalyze its own reproduction.<sup>xxi</sup>

It is perhaps the central organizing principle of Biology that once life did emerge from chemistry it evolved to its present state through the operation of Natural Selection. As Dobzhansky, a leading researcher of the twentieth century, stated "*Nothing in Biology makes sense except in the light of evolution*".<sup>xxii</sup>

The emergence of life and its subsequent evolution created the scientific subject matter of biology. The laws of biology, from genetics to population dynamics, may be said to be emergent in the sense that they are not directly derivable from the laws of physics. Natural Selection might be understood as a Darwinian process that, once instantiated in the realm of chemistry/biology, was able to discover survivable biological designs. The design specifications of this emergent biological world form the scientific laws of biology.

Since Darwin published his theory almost one hundred and fifty years ago the evidence in support of it has poured in from numerous disciplines, most notably perhaps genetics. DNA was identified during the 1950s as the molecular unit of storage for much of life's heritable designs. Strong arguments have been made for the biological unit of selection operating at the genetic, organism and population levels.<sup>xxiii,xxiv</sup> Most likely biological entities are selected at each of these levels. We will examine this process at the organism and population level below and also its operation in the emergent biological field of behavioural science and neuroscience.

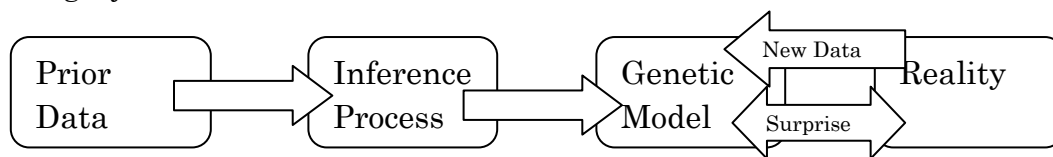
### Organism genetics

The design specifications of most organisms are coded in their DNA. A subset of the DNA codes for the assembly of specific proteins which, in concert, compose and

orchestrate much of life's chemistry. The successful functioning of this DNA is entirely dependent on the environment in which it finds itself. The organism 'expects' to find itself in an environment similar to that experienced by its ancestors. Crucial components of the genome's expectations include:

- 1) A specific internal chemistry of the cell including cytoplasm, enzymes and other proteins.
- 2) Specific sub cellular bodies and organelles including ribosomes and mitochondria.
- 3) Structural cellular integrity including cell walls and centrioles.
- 4) Specific features in the external environment including presence or absence of oxygen, pH range, and available sources of energy which the organism is adapted to consume.

At the time of its conception an individual organism contains inherited DNA that has been under continuous design since the beginnings of biological time. This DNA contains knowledge of the environments experienced by the organism's ancestors.<sup>xxv</sup> It may be said to represent a model of the environment in which the organism expects to find itself and that this model is constructed from prior information accumulated by its ancestors. The organism's subsequent interactions with its environment test this model. Large surprises or 'unanticipated' features of an organism's environment for which it is ill suited may result in the organism's death, leaving the field open for those models with variations more closely in tune with the actual environment. In this manner the genetics of individual organisms come to roughly track and model their environments.

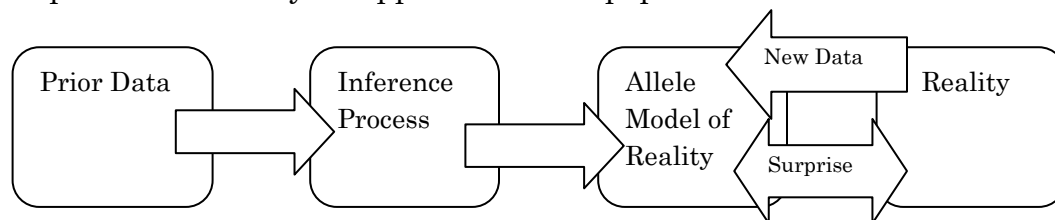


## Population genetics

Population genetics is the study of the change and frequency distribution of alleles under the influence of evolutionary forces.<sup>xxvi</sup> Alleles are gene sequences that may code for a specific protein and that vary between organisms within populations of the same species. For instance a population may contain variable alleles coding for differing colorations of the organisms. Typically each member of a population will contain a full complement of that species' genetics, but the population as a whole

will contain a frequency distribution of the specific alleles at each gene location on the chromosome.

In a manner analogous to the genetics of organisms the frequency distribution of alleles may be said to represent a model of the environment in which the population 'expects' to find itself. This model has been designed from prior data due to selection pressures operating on the population's ancestors. This prior data, or experiences of ancestors, has been subjected to an inference process (evolution by natural selection), the result being a model which provides expectations concerning the current environment. As the population interacts with its environment this model is tested. Some changed features of the environment may be expected by some alleles but not by others, in which case the alleles that more accurately model the environment may be more heavily represented in subsequent generations. Those alleles that are 'surprised' by a feature of the environment may become less represented or may disappear from the population.



## Neuroscience

Obviously much of the neurology evolved by an organism serves the purpose of providing it with information concerning the world around it. This information is taken in by the organism in the form of sensory data which is further processed by the organism's neurology to form models of the external world and to influence its behaviour in that world.

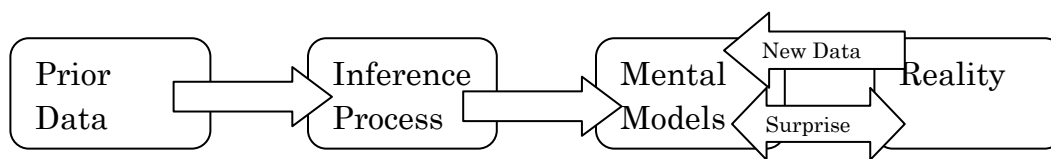
Prior data in the form of experiences of ancestral organisms has shaped the neurological mechanisms producing these models but the brain also possesses a powerful emergent ability to update its models from sensory data in near real time. In this respect the brain gathers prior data over the course of its lifetime and continuously uses new data to update its models. These models are tested against the actual experience of the organism in the real world and large discrepancies between the model and reality may motivate either learning or negative selection pressure.

A new theory that details this process (called the “Bayesian Brain”) has recently been developed and is hailed by many researchers in the field as the most promising integrated theory of neurology yet developed.<sup>xxvii,xxviii</sup> An emergent feature of this

theory is that the selection pressure on mental models to conform with external reality may take the form of a biological instantiated drive to reduce the system's free energy rather than through direct reproductive success.<sup>xxix</sup> This feature allows the organism the ability to adapt its behaviour to changes in the environment in near real time as opposed to generational change.

Free energy in this context refers not to thermodynamics but rather to information exchange. It is a general property of adaptive systems that they contain internal models of external reality which guide their interactions with their environment.<sup>xxx</sup> Free energy is a measure of the discrepancy between the model and the actual environment or of the degree of 'surprise' that the system experiences when it interacts with the environment.

Again this theory can be fitted nicely to the general conceptual model we have been developing for the operation of knowledge mechanisms.



## Culture

Clearly culture is an entity emergent from the biological realm whose evolution is subject, at least in part, to its own emergent laws.

The prior knowledge from which culture emerged is huge, and encompasses both chemistry and biology. Numerous subconscious mental processes, illuminated by the Bayesian Brain theory, provide components used in cultural processes; of these, consciousness seems the most essential.

Consciousness, specifically that denoted by *qualia* (the subjective experience of consciousness, for example the experience of “redness” by a visual system) is deemed 'the hard problem' by philosophers.<sup>xxxi</sup> From a functional point of view, consciousness may have arisen from a need to bring a kind of “meta-order” to mental mechanisms that are rapidly evolving in complexity. At least the degree of consciousness in animals seems to parallel their mental complexity as exemplified by humans. Some recent research suggests the purpose of consciousness and qualia may be to flag and thereby differentiate between both current sensory information

from the environment, and mental models such as memories, plans and day-dreams.<sup>xxxii</sup>

*Try looking intensely at some distinctively coloured object, such as a red tie. Then close the eyes and imagine the tie. Surely the vivid qualia are suddenly far dimmer in imagination. To reverse the experiment, imagine the object, then open the eyes and look at it. The qualia of the visual now are startlingly vivid by comparison with the memory. So perhaps what qualia do is flag the present so that we do not get confused with remembered past or anticipated future.*

Another widely accepted precursor of culture is the related abilities to imitate and learn. Cultural processes evolve overtime as they are passed from generation to generation through a process of learning or imitation. Again humans excel at the ability to imitate:

*Brain imaging techniques allow the mapping of cognitive functions onto neural systems, but also the understanding of mechanisms of human behavior. In a series of imaging studies we have described a minimal neural architecture for imitation. This architecture comprises a brain region that codes an early visual description of the action to be imitated, a second region that codes the detailed motor specification of the action to be copied, and a third region that codes the goal of the imitated action. Neural signals predicting the sensory consequences of the planned imitative action are sent back to the brain region coding the early visual description of the imitated action, for monitoring purposes ("my planned action is like the one I have just seen"). The three brain regions forming this minimal neural architecture belong to a part of the cerebral cortex called perisylvian, a critical cortical region for language. This suggests that the neural mechanisms implementing imitation are also used for other forms of human communication, such as language. Indeed, imaging data on warping of chimpanzee brains onto human brains indicate that the largest expansion between the two species is perisylvian.<sup>xxxiii</sup>*

The centrality of imitation to culture is conveyed in its Wikipedia article:

*Culture can be defined as all the ways of life including arts, beliefs and institutions of a population that are passed down from generation to generation.<sup>xxxiv</sup>*

Given that imitation is central to culture we can easily see that cultural processes might often involve Darwinian processes:

- 1) Copy - imitate
- 2) Variations in the copies - learning and imitation does not involve perfect duplication but produces some variable perspectives.
- 3) Variations in the characteristics of copies influence their survival - sometimes the new perspective is superior or better adapted and becomes more widespread; sometimes the new perspective has inferior survivability and is not long retained.

This model has been widely adopted in the social sciences and fields of study with 'Evolutionary' in their title abound: Evolutionary Psychology, Evolutionary Archaeology, Evolutionary Linguistics, Evolutionary Epistemology, Evolutionary Economics etc. The school of Memetics views cultural evolution in general as based on a Darwinian process involving memes as the unit of replication.

The concept of an adaptive system is similar to that of systems that evolve through the operation of a Darwinian process. A Darwinian process is after all a means of evolving adaptations and thus many cultural processes may be included in this description.

As pointed out by Plotkin, adaptation and knowledge are equivalent.

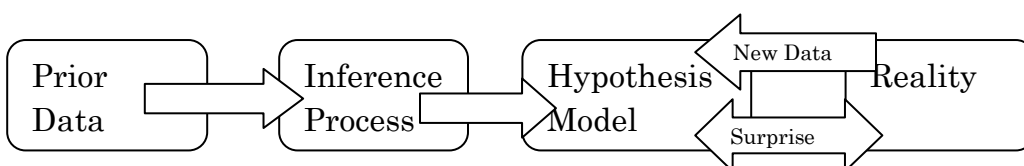
*This direction can only result if adaptations are 'in-formed' by features of the world; they are highly directed kinds of organization and not random, transient structures that may or may not work. Adaptations do work, and they work precisely because of this in-forming relationship between organismic organization and some aspect of the order of the world. This in-forming relationship is knowledge.*<sup>xxxv</sup>

Thus if we consider cultural processes as adaptive systems we might expect to find our model of 'knowledge mechanisms' applicable.

## Science

Science may be culture's most powerful 'knowledge mechanism'. Its evolution by means of a Darwinian process has been well documented within the field of Evolutionary Epistemology.<sup>xxxvi</sup>

The historical achievements of science provide prior data that through the Bayesian process of inference confer varying degrees of plausibility to a range of scientific hypotheses. New experimental data is generated and compared to the scientific model composed of these various hypotheses. The models are updated or revised in



the light of any discrepancy or 'surprise' between the model and reality, as revealed by the new data.

The principle of Maximum Entropy, that entities will evolve to states of higher entropy subject to scientific law, tells us much about scientific law. Specifically it provides us with a measure of the completeness or 'truth' of scientific law. If a theory or scientific law is probed by a range of experiments and none of the new data represents a 'surprise' to the theory then that theory may be said to be objectively true and we may be confident that no additional unknown scientific laws exists that might influence the outcomes under the conditions probed.

This does not mean it is absolutely true in all circumstances, only in the circumstances that have been explored and verified by experiment. Given the nature of objective reality experiments are repeatable; they will provide the same results over all time given the same set of circumstances. It is in this sense that the predictions of the theories can be considered true.

## Adaptive Systems

We should expect, by definition, that any system evolving through the operation of a Darwinian process produces *adaptations*: characteristics that will increase the system's fitness to survive.

Friston models much of the subject matter of behavioural biology and neuroscience as an adaptive system with three components: the state of the system, the effect of the system on the environment, and the effect of the environment on the system.

<sup>xxxvii</sup> Using this model he is able to arrive at a number of conclusions:

- 1) The system will possess internal models portraying external causes in the environment.
- 2) The system will evolve, through natural selection, to reduce the discrepancy between the internal models and the external environmental causes.
- 3) A generic scientific law can be proposed that predicts brain functions in numerous contexts; the 'surprise', bounded by free energy, between internal models and external reality is minimized.

As Friston noted:

*In summary, the free-energy principle can be motivated, quite simply, by noting that systems that minimise their free-energy respond to*

*environmental changes adaptively. It follows that minimisation of free-energy may be a necessary, if not sufficient, characteristic of evolutionary successful systems. The attributes that ensure biological systems minimise their free-energy can be ascribed to selective pressure, operating at somatic (i.e. the life time of the organism) or evolutionary timescales (Edelman 1993). These attributes include the functional form of the densities entailed by the system's architecture. Systems which fail to minimise free-energy will have sub-optimal representations or ineffective mechanisms for action and perception. These systems will not restrict themselves to specific domains of their milieu and may ultimately experience a phase-transition (e.g., death).*

This finding illuminates not only the nature of adaptive systems but also the nature of the evolution of emergent levels of matter within objective reality.

The brains of humans and other intelligent mammals are low entropy structures which require explanation. The principle of Maximum Entropy tells us to expect that their existence is dependent on constraints in the form of scientific law.

Evolutionary origins of brain functions can be traced to the abilities of early single celled life to perform phototaxis and chemotaxis. Such abilities clearly provide a selective advantage as they promote adaptive exchanges with the environment.<sup>xxxviii</sup> Natural Selection, the Darwinian process involved, has selected progressive improvements in these abilities, ever more optimal mechanisms for adaptive exchanges with the environment. This progression is evident in examining such things as the evolution of neural chemistry in a chain of life forms from yeast cells to more developed organisms, including vertebrates.<sup>xxxix</sup>

Natural selection operates through the evolution of adaptations such as sensing, perception and learning. Each of these adaptations has its own design details embodied in its functioning. The organisms possessing these adaptations are dependent on them for their survival. Superior adaptive designs are rare and, when found through the operation of a Darwinian process, tend to be adopted and copied in numerous guises. These powerful, widely-copied mechanisms must be rational; they must adhere logically to the objective nature of their environment. Generic essential details of a widely-replicated design, such as genetics within biology or optimal Free Energy structures in the brain, can sometimes be isolated and proposed as scientific law.

In this manner we are able to view adaptive systems, in accordance with the principle of Maximum Entropy, as moving to states of the highest entropy available, subject to the constraints of their design details, those applicable scientific laws.

These laws evolve through the operation of Darwinian processes along with the design of their subject matter.

Successful designs arising in adaptive systems are those that can improve survivability through more optimal exchanges with the environment. Such designs specify lowered entropy states. The specific mechanisms discovered and selected by Darwinian processes to enhance survivability and lower entropy form the constraints (i.e. the applicable scientific laws) that are responsible for preventing the system from moving to states of higher entropy.

Friston's theory provides details of the operation of this process within behaviour and neuroscience, but the model it provides appears to be applicable to adaptive systems in general, as I have attempted to describe above.

## Conclusion

The notion of an objective reality demands point-of-view invariance in the sense that the experience of all observers must be predicted by valid scientific law when those observers are interacting with a given entity regardless of the circumstances or type of observer. The term 'observer' should not be understood here in an anthropomorphic sense but rather in the same sense that Einstein used 'test particle' or Zurek uses 'environment as witness'. All of the interactants in the web of reality are in this sense observers.

At its most basic level and in its totality soon after its beginnings this web of reality consisted of fundamental particles interacting through quantum processes. Although many complex structures have since evolved, all actual information transfers still occur through quantum processes.

Underlying the web of interactions that compose reality is a quantum reality. This quantum reality emerges into our reality through the process of quantum decoherence. The vast range of quantum potentials is narrowed, in our reality, to those that can survive the rigors of quantum information transfer into the environment of our reality. This process, described by Wojciech Zurek, selects those pieces of quantum information that can successfully replicate themselves in our web of reality through a process he has named Quantum Darwinism.

Zurek's work reveals that the predictive model provided by quantum mechanics is inherent in the wave function of entangled quantum systems. This implies that the predictive laws of quantum mechanics are not a scientific creation but rather a scientific discovery of a modeling performed by nature. Sophisticated models within

the web of reality predicting what one entity will know of another exist even at the level of the quantum.

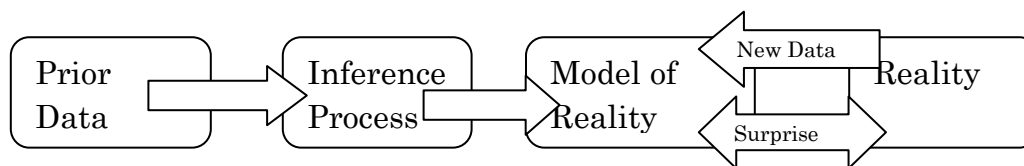
Bayesian probability describes the plausibility of knowledge concerning entities in the web of reality. In all events it describes how this plausibility should be formed from prior data and updated with new data. Knowledge from this perspective is an evolutionary process.

This method of knowing is not constrained to humans. The laws of quantum mechanics, as refined by Zurek, provide the degree of plausibility that fundamental particles should assign to the outcome of their interactions with other fundamental particles.

Quantum Computation also provides a startling vantage point on the nature of quantum interactions: all quantum interactions are computations and what is computed is the result of the interaction. If we hybridize this interpretation with that of the formally equivalent Quantum Darwinism we arrive at an understanding that the future of the universe is constantly being computed or selected through a Darwinian process.

Many complex structures have emerged from our web of reality including most of scientific subject matter. These emergent features represent a local decrease in entropy which according to the principle of Maximum Entropy must be explained by the existence of scientific laws constraining the system from reaching states of higher entropy. The pertinent scientific laws can be considered the design details of the state, causing it to remain in states of lower entropy. Such designs are exceedingly rare and are not easy to find. Darwinian processes operating in the subject matter of atomic physics, chemistry, biology, populations genetics, behavioural and neuroscience and culture have been shown to be responsible for locating and instantiating those rare designs composing their subject matter.

The direction in which these complex entities evolve, at least those of biology and subsequent forms, might be understood in terms of adaptive systems to conform to the model:



The common direction in which these models or systems evolve is towards a reduction in the 'surprise' provided by new data or experience.

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