Probability as a state of knowledge

Physic's defining mission for the several centuries following Galileo was to reveal the laws of ontological reality; the laws describing what is really happening in the real world. This movement may have achieved its high water mark with the logical positivists who argued from the mid eighteen century that scientific discourse should be limited to a very narrow view of ontology; to the results of objective measurements performed by human observers.

Soon however this ontological purity experienced two epistemic challenges from which it has never recovered. Epistemology is the study of knowledge or of what can be known of reality.

The first and most extreme challenge came with the development of quantum theory. The central entity of quantum theory is the wave function which is purely informational and which is the basis from which any prediction of outcomes must be determined. The second was the development of Bayesian inference which in the hands of E.T. Jaynes came to subsume a number of branches of physics including thermodynamics and statistical mechanics.

Bayesian inference is an epistemic theory. It describes how the predictive accuracy or knowledge of theories or models may be optimized using the available data. It involves the concept of information and the mathematics of probability.

Quantum theory may also be subsumed by Bayesian inference due to the simple observation that the theory's predictive accuracy is achieved through an updating of the wave function from data, either the data supplied by a measurement or data of environmental influences which evolve the wave function via the Hamiltonian operator. That is its predictive accuracy is maintained through inference. Thus both of these challenges to the dominance of ontology within physics may be understood as a challenge presented by inference. The threatening aspect of these challenges seems to be the pollution of ontology purity, their suggestion that epistemology may be deeply involved with ontology.

The reaction of physics to this challenge may be considered neurotic. The inescapable epistemic component of quantum theory led to a total rejection of even the value of attempting to understand ontology within the theory by most physicists. The dominant interpretation of quantum theory, the Copenhagen school, claims that the theory is almost entirely epistemic, that it only describes a method of calculating measurement results conducted by humans and that its only ontological aspect is the expected measurement results. The ontological reality of quantum systems retains its purity only through abandoning it as unknown or even as unknowable.

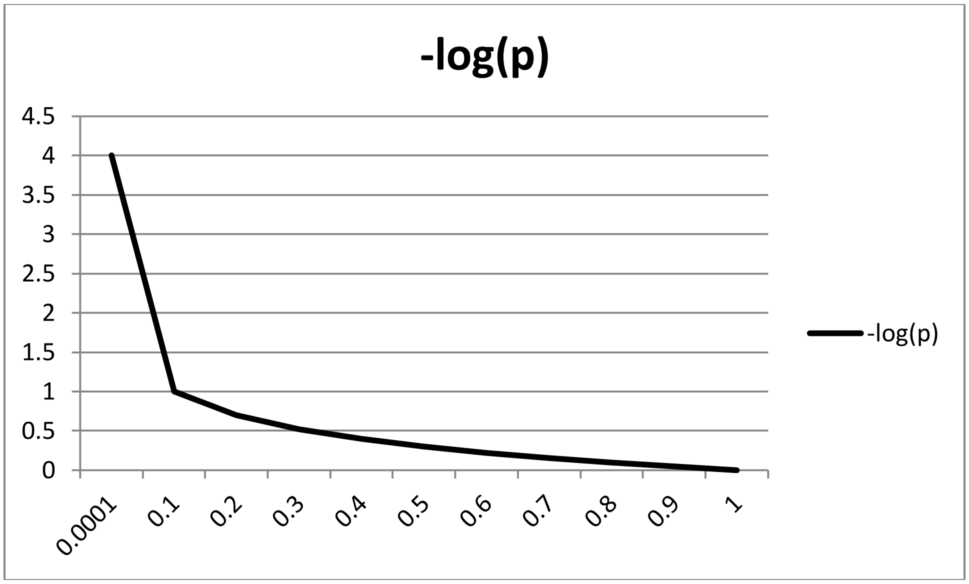
Even though quantum theory was abandoned as a description of ontology its epistemic scope was limited to that of the human observer. The principle of 'point of view invariance' was ignored, the possibility that the theory describes the information concerning a quantum system that is available to any other entity, to other quantum systems as well as to humans remained until recently largely unexamined.

That the nature of ontological reality is dependent upon human observers and their conduct in making measurements might be seen as a neurotic and desperate attempt to deny the true epistemic power of quantum theory. Thankfully some progress has been made. For instance Wojciech Zurek has shown that the same information is transferred in quantum interactions given the same circumstances whether those circumstances are created by a human for the purpose of measurement or whether those circumstances are naturally occurring and unobserved by any human.

As quantum theory is foundational to all of physics other than relativity this result unleashes the epistemic component of quantum theory to range freely throughout ontological reality. Quantum interactions transfer information throughout ontological reality, the epistemic component of the theory is not restricted to human observers.

The study of Bayesian inference has perhaps been more open minded. Indeed the Bayesian School was almost extinguished by those who would view probability as an objective property of ontological reality having no epistemic content. Having triumphed over this Frequentists challenge Bayesians faltered in embracing inference as a property entwined within ontological reality and have taken the position, similar to the Copenhagen school, that inference and epistemology is limited to humans.

Bayesians loosely define probability as ‘a measure of a state of knowledge’ (Wikipedia 2011), however they do not define knowledge but rather leave that to our intuition. It would be more technically correct to define probability as ‘a measure of information’ as information is a function of probability, the negative log function. The negative log function is a monotonic decreasing function; that is for each value given to the function it returns a single value and as the value given to the function increases the value returned decreases. We can therefore consider information and probability to be the same thing; only the scale used to measure them varies in a non-linear manner.



One important feature we can see from the figure above (probabilities along the horizontal axis and information along the vertical axis) is that a small value of probability corresponds to a large value of information and a large probability corresponds to little information. This makes sense intuitively if we consider that when we assign a low probability to the occurrence of an event and that event actually happens then we have received a lot of information whereas when we assign a high probability to an event and it occurs then we have received little information. Thus probability is akin to expectation and information to surprise when the actual outcome is known.

If we assign probabilities to all possible outcomes of an event these may be considered to form a model for that event. Given such a model there is an associated value of the information we can expect to receive when we learn the actual outcome of the event. This expectation value is called information entropy and is a measure of the surprise we expect to receive on learning the actual outcome; it is a measure of the inaccuracy of the model.

While entropy has been an extremely useful concept the actual focus and goal of any information processing system is generally not that of achieving an inaccurate model but rather of achieving accuracy. The measure of the accuracy of models in this sense is negative entropy and is what I will call knowledge as that seems fitting.

As it turns out any systematic method by which a model can be made more accurately predictive or achieve greater knowledge must be consistent with the mathematics of Bayes' theorem. Bayes' theorem tells us how the model's probabilities should be adjusted when new data is available. This process is call inference and it is the logic of all knowledge producing processes including science.

Our current conception of probability and its relation to information, entropy and knowledge are powerful tools in our quest to understand the natural world. Many fierce intellectual battles have been fought during the past century over the interpretation of these concepts. A great deal of clarity has been won although there still remain some hurdles.

E.T. Jaynes championed the Bayesians to their great victory over the Frequentists in the main campaign fought over the interpretation of probability. Frequentists came to dominance in the early twentieth century through a concerted attack on the work of early Bayesians, such as Laplace. This attack often focused on a perceived lack of objectivity with the Bayesian approach. Bayesians think of probability as a state of knowledge; the reason they assign a probability of .5 to the flip of a coin is that they don't have any knowledge which would lead them to favour either heads or tails over the over. The Frequentists saw this as a subjective approach as another observer might have knowledge that the coin was not fair and therefore assign a different probability to the outcome. The Frequentists preferred to imagine an infinite series of coin flips for a particular coin which would determine an objective frequency, not dependent on the knowledge of a particular observer.

Bayesians define probabilities as states of knowledge about the world and frequencies as properties of the world (Jaynes 1989).

The Bayesian triumph may have been due to several causes:

1) Richard Cox proved, mathematically, that any consistent formulation of Probability would agree with the Bayesian approach.
2) Bayesian probability is relatively simple and much easier to apply and calculate in complex situations. It is especially well suited to calculation by computers.
3) Bayesians were able to make the point that although probability is a measure of an observer's knowledge any two observers having the same knowledge should assign the same probability.

This last point has other parallels in science. For instance the measured value of a system's entropy depends on the observer's state of knowledge, the thermodynamic macro-variables under experimental control; however any two observers having the same values for the same set of macro-variables must calculate the same entropy.

While the Bayesian emerged victorious in this battle over interpretation the exact meaning of 'observer' has been left somewhat ambiguous in the sense of who or what may assign probabilities. This ambiguity will be examined within the scholarship of Edwin Jaynes as he comes at the issue from a number of different angles but was not, in my opinion, able to offer the crucial clarifying concept.

I will present Universal Darwinism as a meta-theory which provides a general description of the evolution of information and matter. Along with probability this theory also makes use of the derivative concepts of information, entropy, inference and knowledge. These in turn inherit the question of 'whom' or 'what' may assign the underlying probabilities and has the information.

The main issue, as presented by Jaynes and others, is to draw a dichotomy between epistemic reality and ontological reality. Ontological reality is the world as it really is. Epistemic reality is what can be known by humans about ontological reality. Jaynes is scathing of those who fail to observe the separation of these two realities. Epistemology is based on reasoning from incomplete knowledge but Jaynes cautions us against confusing our incomplete knowledge with ontological reality. He forbids us from reasoning as follows (1990):

> *(My own ignorance) implies (Nature is indeterminate).*

But surely this is a false dichotomy. My own brain along with my own ignorance is part of ontological reality. At least when characterizing our brains we must consider ignorance as a facet of ontological reality.

Edward Thompson Jaynes
1922 to 1998

Ed Jaynes might well be remembered as the Bayesian Bulldog. He was fierce in his defense of Bayesian concepts and scathing of the Frequentists whom he considered had hijacked probability theory from Laplace and taken it in ill considered directions.

Almost single handedly, at least at the beginning, he revised and championed Bayesian probability. He developed the principle of Maximum Entropy and used it to derive thermodynamics and showed the way in applying Bayesian theory to many practical problems.

He had an entertaining but combative writing style and many of his papers are a joy to read. Over and over he hammered away, driving home the idea that Bayesian probability is the only mathematically consistent method of performing inference and that inference, as he sub-titled his great text-book, is the logic of science.

Jaynes ignored the ambiguity inherent with a distinction between epistemology and ontology when considering the human brain but argues that other aspects of ontological reality should be understood as untainted by an epistemic component.

In Jaynes' view epistemic reality or what can be known about ontological reality revolves around Bayesian inference and he considers inference and the use of probabilities as uniquely human characteristics:

> *it is the job …. of probability theory to describe human inferences at the level of epistemology.*

Indeed he viewed incomplete information as a property unique to humans and seems to consider ontological reality as quite separate from epistemic reality and free from ignorance.

Although Jaynes often maintains this distinction he also considers many examples where inference, based on probabilities, is conducted by non-human epistemic systems. While considering these examples he employs sophisticated mental gymnastics to avoid explicitly acknowledging that inference is conducted by non-human agents.

By contrast I suggest the way forward is to acknowledge that epistemology and ontology are entwined and inseparable, that inference and knowledge are a fundamental part of what we consider ontological reality.

Claude Shannon, whose work had a formative impact on Jaynes, derived the quantity he called entropy to describe the information content of communication systems. Jaynes puzzled over the question of who or what has this information (1986):

> *In a communication process, the message* M_i *is assigned probability* p_i, *and the entropy* $H = \sum p_i \ log p_i$ *is a measure of "information." But whose information?*

Following his assumption that information must belong to a human he considers and rejects the possibility that the information belongs to the sender or receiver of the message and seems to settle on the notion that it is related to the communication system itself:

> *Shannon, however; proceeds to use H to determine the channel capacity C required to transmit the message at a given rate. But whether a channel can or cannot transmit message M in time T obviously depends only on properties of the message and the channel – and not at all on the prior ignorance of the receiver!*

However Jaynes does not conclude that information is a characteristic of the communication system itself. He holds fast to the principal that probability is a state of knowledge and seems driven to conclude that knowledge is a uniquely human characteristic. As he has ruled out both the sender and receiver of the message the only remaining person involved is the designer of the communication system:

> *Agonizing over this, I was driven to conclude that the different messages considered must be the set of all those that will, or might be, sent over the channel during its useful life: and therefore Shannon's H measures the degree of ignorance of the communication engineer when he designs the technical equipment in the channel.*

It is interesting that Jaynes would invoke a 'designer' as a last ditch attempt to exclude the extension of epistemology into nature other than in human form. It is reminiscent of the position taken by creationists in their attempt to deny the epistemic component of biology. Shannon's theorems apply to all communication systems not just to those designed by electrical engineers. What about communication systems involving jungle drums, or those involving networks of neurons, or those involving whale's songs? Whose ignorance does the Shannon entropy measure in these systems?

Later in his career Jaynes became more open to the possibility that non-human entities might assign and process probabilities while performing inference. A central theme of Jaynes' great textbook (Probability Theory: The Logic of Science 2003) concerns possible designs for a robot capable of performing human-like inference. Exploration of this theme led him to discuss a number of facets of biology and neurology. In his examination of the workings of vision he notes:

> *Seeing is Inference from Incomplete Information, no different in nature from the inference that we are studying here.*

It may speak to Jaynes' foresight that today the Bayesian brain school of neuroscience has successfully described the details of many basic neural functions including sensation, perception, memory and learning as examples of Bayesian inference (Friston and Klass 2007).

Clearly Jaynes is claiming that in producing sight the brain is performing 'Inference from incomplete information'. It is processing probabilities in a Bayesian manner. A crucial question we might ask, in connection with inferential robots and even our sight, is who or what has the incomplete information, in other words whose probabilities are being processed? It cannot be those of a human intellectual mind, our scientific brain; the processing of vision is an unconscious process and besides vision is a sense shared with a multitude of other animals.

Indeed Jaynes' understood this distinction very well. Later in the book he talks about the disjoint nature of our 'inner' brain which performs unconscious functions such as vision and our 'outer' conscious brains (2003 p. 561):

> *But our outer brain can become corrupted by false indoctrination from contact with the outer world, while the inner brain, protected from this, retains its natural Bayesian purity.*

However he does not address the question of ‘who’ then has the incomplete information. I suggest that in this example it is the inner brain that has the incomplete information and assigns the necessary probabilities. Indeed when Bayesian brain researchers attempt to model perception the probabilities used are estimates of those that the brain assigns due to its incomplete state of knowledge. It may have been fruitful if Jaynes had agonized over this question in regards to vision. As he was a Darwinian in biological matters he would not have reached the conclusion that the probabilities are those of some god-like designer!

The robot brain he describes is designed by humans to perform inference but the probabilities used are not supplied by the designer, they are assembled from the data gathered by the robot and thus the probabilities are assigned by the robot itself.

I shrink from this assertion that the sub-conscious brain or robots may have incomplete knowledge and assign probabilities. The brain, especially the brain of a robot, is part of ontological reality and perhaps the strongest condemnation that Jaynes reserves for sloppy thinking is the dreaded mind projection fallacy, which occurs when we confuse the state of our knowledge with ontological reality.

Jaynes forbids us from thinking along the lines of (2003 p. 74):

> *I don't know the detailed causes - therefore - Nature does not know them.*

Although the inner brain of both humans and other animals is part of ontological reality it does not know the causes of its sight; it has incomplete information. The brain attempts, by using the incomplete information it does have, to infer through sight the best visual model of ontology that it is able. Jaynes appears to argue this as well but then seems to assume that the probabilities assigned during inference are those of the scientist studying vision. I am contending that we may be well rewarded if we conclude that these probabilities are assigned by the epistemic system itself, in this case by the inner brain.

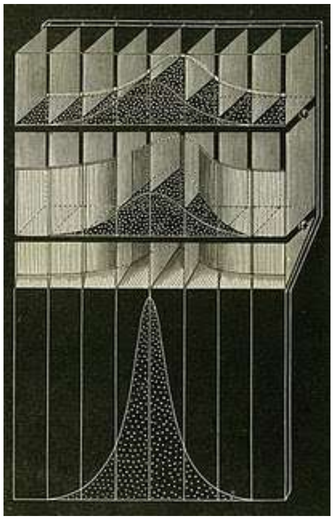
This challenge to the mind projection fallacy may be resolved if we entertain the notion that ontological reality may contain numerous epistemic systems. These epistemic systems may include science and technology, neural functions, genetics and dare I say quantum systems. Epistemic systems may legitimately have incomplete information and the mind projection fallacy should be restricted to those parts of ontological reality which are not epistemic systems.

While this perspective on epistemic systems is unusual it provides some immediate benefits. It allows us to avoid the anthropocentric notion that Bayesian probability is all about humans, that it is exclusively about **our** state of knowledge. In the view offered here ‘knowledge’ includes our state of knowledge but also grants other epistemic systems the status of having states of knowledge.

A further example may be found in Jaynes' explorations of the work of Francis Galton, Charles Darwin's half cousin, and his ground breaking efforts in applying statistics (in particular properties of the normal distribution or bell shaped curve) to biology. Jaynes places particular emphasis on the idea that the normal distribution describing biological diversity also provides insight into the evolution of physical systems towards equilibrium:

> *The remarkable - almost exact - analogy between the processes that bring about equilibrium in physics and in biology surely has other important implications, particularly for theories of equilibrium in economics, not yet exploited.*

One item perhaps overlooked by Jaynes' scholarship that would surely have been of great interest to him is a device designed by Galton and used in a lecture to illustrate his ideas concerning probability (Galton 1877). The device, pictured below, has recently been re-discovered within the statistics community and repurposed as a 'visualization of Bayes' theorem' (Stigler 2011).



The device contains three compartments: a top one representing the prior distribution, a middle one representing the application of the likelihood to the prior and a third representing the normalization of the resulting distribution. Beads are loaded in the top compartment to represent the prior distribution and then are allowed to fall into the second compartment. The trick is in the second compartment where there is a vertical division in the shape of the likelihood distribution. Some of the beads fall behind this division and are 'wasted'; they are removed from sight and the remaining beads represent the product of the prior and likelihood functions, the 'Bayesian update'.

Perhaps the most remarkable thing about this demonstration is that Galton never mentioned Bayes in his lecture; he had probably never heard of him or his theorem. Rather, his purpose in building the device was to demonstrate the principle of natural selection. The top compartment represents the child generation with variations and the middle compartment represents the individuals selected from that generation.

That this device may be used to model both Bayesian updating and natural selection illustrates an isomorphism between the two. Natural selection, as well as other Darwinian processes, may be understood as a physical implementation of Bayesian inference (Campbell 2009).

The pertinent implication for our discussion is that any system driven by a Darwinian process is performing inference. The predictive accuracy of its internal model is increased by processing the data available to it, its experiences in the world. I am suggesting that all such inferential systems should be considered epistemic systems; that is systems which develop knowledge and in the process must assign their own probabilities to outcomes.

From this perspective, given the numerous scientific theories which use a Darwinian process to explain the creation and evolution of a wide range of subject matter, we have a basis for understanding the deep and subtle relationship between ontology and epistemology in nature.

Jaynes came remarkably close to this conclusion. He thought it obvious that natural selection would design our brains so they could perform plausible reasoning or inference. In referring to possible organizing principles for the brain he writes (2003):

> *we wonder whether the principles of Bayesian inference might serve as a start. We would expect Natural Selection to produce such a result; after all, any reasoning format whose results conflict with Bayesian inference will place a creature at a decided survival disadvantage.*

Having progressed this far it may have been only his basic assumption that Bayesian inference could be practiced by humans alone which kept him from reaching the obvious conclusion that natural selection performs a form of inference.

Biologist have developed a sophisticated view of the relationship between epistemology and ontology; in biology these are named genotype and phenotype and their relationship is perhaps the central focus of study within biology. The genotype is a epistemic model of the organism stored within each of its cells while the phenotype is the organism itself which exists in ontological reality.

The genetic model of the organism is copied between generations with some variations. The next generation is constructed, in a mechanistic manner, largely by assembling proteins as specified by the genetic model. As this generation matures the experience it gains in the world, in the form of reproductive success, results in a selection of those that will place copies of their models into the next generation. The genome of the next generation differs from that of the previous one in terms of the proportion of individual genes or alleles making up the cohort's genome. The model is thus updated in a process of inference. It has achieved greater predictive accuracy of strategies and adaptations for reproductive success.

This can be clearly seen in the study of population genetics. Here the change in allele frequency between generations is given by (Ricklefs 1979):

$$p' = \frac{NpR_A}{NpR_A + NqR_B} = p\frac{R_A}{\overline{R}}$$

Where p' is the frequency in generation n+1, p the frequency in generation n, R_a the fitness of the particular allele and $\overline{R}$ the average fitness of the various alleles sharing the same locus with the particular allele. Clearly this is Bayesian updating.

The likelihood and marginal are in terms of fitness. Fitness may be understood as the shift in the frequency of alleles between generations which in turn is determined by the contribution made by the allele to the reproductive success of the organism given the environment in which it finds itself. In other words fitness is a measure of the genome's ability to model those strategies and opportunities in a given environment which will bestow reproductive success; it is the ability of an epistemic system to accurately model aspects of ontological reality.

Thus all of biology is an example of epistemic systems operating independently of the human mind. A general theory of epistemic systems is provided by Karl Friston and others in their work on adaptive systems. Friston (2007) describes adaptive systems as containing internal models of their environmentally related survival strategies which they strive to make accurate, that is to accurately predict ontological reality, specifically instances of ontological reality in which they enjoy reproductive success.

It has been argued that science, neural functions and genetics are examples of adaptive systems defined in this manner and that the inference mechanism used in each is a Bayesian processes implemented in the form of a Darwinian processes (Campbell 2009). In this view we are forced to concede that our human epistemic system is not alone. Nature has constructed numerous epistemic systems each with the ability to 'know' the world around it and which use probability as a measure of their own incomplete state of knowledge.

Given the propensity of nature to spawn adaptive systems of this type it may be fruitful to try applying this view to lesser understood systems which appear to have epistemic components as for example quantum systems. That is, we might try to understand quantum systems as independent epistemic systems.

A great deal of progress has been made in our understanding of quantum systems during the past twenty years. Prior to that time, although many researchers were dissatisfied with the dominant formulation, there were few ideas for a way forward.

Quantum mechanics was often presented as an axiomatic system based on the following five axioms or their equivalent:

1) Any information concerning the state of a quantum system is represented by a vector in its Hilbert space.
2) Evolutions are unitary (i.e. generated by the Schrodinger equation).
3) Immediate repetition of a measurement yields the same outcome.
4) The measurement outcome is one of the orthonormal states, the eigenstates of the measured observable.
5) The probability p_k of finding an outcome $|s_k\rangle$ in a measurement of a quantum system that was previously prepared in the state$|\psi\rangle$ is given by$|\langle s_k|\psi\rangle|^2$.

The problem axioms, composing the 'measurement problem', are the last two. To many researchers it was problematic that arbitrary mathematical rules were required as axioms in order for the theory to make measurement predictions. The research program of Wojciech Zurek of Los Alamos National Laboratory was one such fruitful assault on these problems.

Axiom #4 was attacked first. Why, out of the infinite set of orthonormal basis was the particular basis of the measured observable actually measured? Zurek's answer; the 'pointer basis' observed is selected from the quantum possibilities due to the process of einselection emanating from symmetries of entanglement between the quantum system and the measuring device (1983).

In subsequent work, using only the first three axioms, Zurek derived the nature of this selection process. It turns out that upon measurement or interaction an attempt is made to copy all the information contained within a quantum system to its environment but only a very small subset of this information is able to survive the transfer and the type of information which can survive is analogous to the pointer basis. Zurek understands this 'copy with selective retention' process as a Darwinian process (2004) and has named his general theory Quantum Darwinism.

Axiom #5 was also derived from the first three axioms as a consequence of the symmetries of entanglement (envariance) (2003). Thus quantum theory may be developed from only three axioms which all pertain to aspects of the wave function; the troublesome measurement axioms have proved unnecessary.

If we accept that the three remaining axioms are our best guides to quantum ontology, then the power of Zurek's accomplishment is not only in resolving the measurement problem but also in showing that quantum systems have an inherent means of predicting the outcomes of their own interactions. An internal model within quantum systems is consistent with Seth Lloyd's description of quantum interactions as quantum computations where what is computed is the outcome of the interaction (2007). In this view we should consider the wave function as a model, internal to the quantum system, providing predictions of outcomes.

These developments suggest our interpretation of quantum theory should include the notion that quantum systems are epistemic systems along the lines of biological, neural and cultural systems. They contain models which assign probabilities and perform inference.

A means of achieving improved understanding of physical phenomena envisioned by Jaynes involved the discovery of progressively deeper hypothesis spaces (1986):

> *It would be nice if we could go down to a space H_x deep enough so that on it some kind of "symmetry" points to what seem "equally possible" cases, with predictive value. Then probabilities on the space M of the observable macroscopic things would be just multiplicities on the deeper space H_x, and inference would reduce to maximizing entropy on H_x, subject to constraints specifying regions of M.*

A recent paper by Zurek (2011) identifies such a hypothesis space for quantum systems. He shows that, given the symmetries of envariance, it is possible to enlarge the Hilbert space describing the quantum state so that the 'measurement eigenvectors' are represented by a subspace spanned by basis vectors having uniform magnitude. Thus the Born rule, used for calculating the probabilities of quantum outcomes, follows through a mere counting of the multiplicity of these basis vectors. Hopefully this formulation will allow a deeper understanding of 'macroscopic things' as envisioned by Jaynes.

A common source of confusion in our understanding of the epistemic vs. ontological is that epistemic systems must have an ontological representation; there can be no information without representation (W. Zurek 1994). Thus science has its literature, the brain its neurons and the genome its DNA. The proposed dichotomy between epistemology and ontology, which has hounded intellectual progress since it was presented by Descartes as the mind/matter duality, should be laid to rest; epistemic systems are common features of ontological reality.

With this understanding and considering the wave function as an internal model within quantum systems we should expect that an ontological representation of the wave function will eventually be found to exist. Although there is currently no experimental evidence in support of this view it has not been ruled out and there is plenty of scope for such a mechanism to exist in the roughly twenty orders of magnitude between the plank scale and what we are yet able to probe experimentally. Some prominent physicists are developing theories which treat quantum systems as ontological entities (t' Hooft 2006) (Smolin 2011) (Deutsch 1997).

The dual nature of epistemic systems requiring them to also have an ontological existence leaves open the possibility that they can be analyzed from three different perspectives, that of an observer or any other systems which interact with them, that of the epistemic system itself and that of ontological reality. For example, the probabilities used in the formula of population genetics considered earlier can refer to the scientist's incomplete knowledge, to the population's incomplete knowledge of characteristics or alleles that will lead to reproductive success or to frequencies of the ontology. The first two are epistemic systems and we should expect that as these gain accuracy all three should converge.

Quantum physics may be in a historical period similar to the one that biology was in between the discoveries of Mendel and those of Watson and Crick, when we knew the laws of inheritance but did not know the physical mechanism which gives rise to them. With quantum systems we currently know the algorithm which nature uses to compute probabilities for outcomes but we do not know the ontological mechanisms used to perform the calculations and cause those outcomes. We know the epistemic method used but we do not know how it is ontologically instantiated.

Jaynes succeeded in clarifying, to an extent, the relationship between epistemology and ontology (1989):

> *We believe that to achieve a rational picture of the world it is necessary to set up another clear division of labour within theoretical physics; it is the job of the laws of physics to describe physical causation at the level of ontology, and the job of probability theory to describe human inferences at the level of epistemology.*

A further clarification may be achieved by recognizing that inference is not performed by humans alone and that the above statement might be improved by replacing the last phrase with '*and the job of probability theory to describe inferences at the appropriate level of epistemology within ontology*'.

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