Bayesian Methods and Universal Darwinism

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Abstract. Bayesian methods since the time of Laplace have been understood by their practitioners as closely aligned to the scientific method. Indeed a recent champion of Bayesian methods, E. T. Jaynes, titled his textbook on the subject Probability Theory: the Logic of Science. Many philosophers of science including Karl Popper and Donald Campbell have interpreted the evolution of Science as a Darwinian process consisting of a 'copy with selective retention' algorithm abstracted from Darwin's theory of Natural Selection. Arguments are presented for an isomorphism between Bayesian Methods and Darwinian processes. Universal Darwinism, as the term has been developed by Richard Dawkins, Daniel Dennett and Susan Blackmore, is the collection of scientific theories which explain the creation and evolution of their subject matter as due to the operation of Darwinian processes. These subject matters span the fields of atomic physics, chemistry, biology and the social sciences.

   The principle of Maximum Entropy states that systems will evolve to states of highest entropy subject to the constraints of scientific law. This principle may be inverted to provide illumination as to the nature of scientific law. Our best cosmological theories suggest the universe contained much less complexity during the period shortly after the Big Bang than it does at present. The scientific subject matter of atomic physics, chemistry, biology and the social sciences has been created since that time. An explanation is proposed for the existence of this subject matter as due to the evolution of constraints in the form of adaptations imposed on Maximum Entropy. It is argued these adaptations were discovered and instantiated through the operations of a succession of Darwinian processes.

INTRODUCTION

   Darwin understood that the algorithmic nature of natural selection indicated that its abstraction might be useful to the study of the evolution of other processes such as language. Darwinian processes, (where evolution of some subject matter is described as embodying three steps: replication, variation and differential selection) are now used as the essential explanatory mechanism in numerous fields of study in biological and social sciences such as population genetics, evolutionary epistemology, evolutionary psychology, evolutionary archaeology, memetics and evolutionary linguistics.

   As developed through the work of Dawkins, Dennett and Blackmore (Dawkins, 1976; Blackmore, 1995; Dennett, 1995) the term Universal Darwinism has come to be applied to this collection of scientific theories utilizing Darwinian processes as their essential explanatory model.

   Explanations of the evolution of Science itself have been framed in terms of a Darwinian processes by prominent philosophers of science including Karl Popper and Donald Campbell (Popper, 1972; Campbell, 1965). The field of Evolutionary Epistemology presents the evolution of systems of knowledge, including Science, in terms of a Darwinian process.

In this light the evolution of Science might be understood in terms of copies of existing theories being made in scientists' minds, often with variations from the original. Those variation that experience preferential survival are those that are best supported by the data.

Of course the precise manner by which the measure 'best supported by the data' should be calculated is given by Bayesian methods. Indeed E.T. Jaynes dubbed Bayesian Probability the logic of science. (Jaynes, 2003)

Karl Friston, of the Bayesian Brain school of neuroscience, has proposed a theory of mind which models aspects of mental processes as near optimal Bayesian mechanisms updating mental models from experience.

Given that the brain has evolved over hundreds of millions of years, through natural selection, to gather knowledge and make sense of the world, we are led to the observation that the Bayesian process of updating knowledge was discovered long before the existence of Science or even of human beings. Indeed this observation suggests that the Darwinian/Bayesian mechanism of evolving knowledge of the world is a truly ancient and time tested strategy and, contrary to the view of post modernists, of a different stature from other cultural accounts such as myths or religion in understanding the world.

In view of the homology between Darwinian and Bayesian mechanisms apparent in the evolution of Science, Section 1 will examine the abstract nature of Darwinian processes postulated to be operating by various theories included within universal Darwinism with a view to exposing their Bayesian nature.

The history of the universe has involved the creation and evolution of systems possessing greater complexity over time. Much of scientific subject matter is composed of levels of complexity created and evolved since the time of the Big Bang including atomic physics, chemistry, biology and culture. It is something of a puzzle that while the history of the universe conforms to the 2nd law many objects of scientific interest in the universe have managed to defy this overall trend and maintain their existence in states of low entropy.

The principal of Maximum Entropy tells us that systems will always evolve to states of higher entropy unless they are constrained by scientific law to do otherwise. It follows that systems will only maintain low entropy states if they are constrained to do so by scientific law. Section 2 makes the argument that this proposition illuminates the nature of scientific law. Much of scientific law may be understood as the design details of those extremely rare designs that locally constrain entropy's increase. It is further argued that many of these rare designs have been discovered by natural processes through the exploration of design space by Darwinian processes.

In the Discussion a recent theory from physics is examined that holds some promise of extending this paradigm to areas of scientific subject matter more fundamental than those of biology and culture.

Section 1 - Darwinian processes and Bayesian Methods

The algorithmic nature of natural selection allows its essential mechanism to be abstracted and hypothesized as a possible mechanism operating in the evolution of

subject matter often other than biological. Numerous theories of this type abound in the social sciences and even in the hard sciences such a physics.

The essential abstraction from natural selection, what we are calling a Darwinian process, has been developed in the work of Richard Dawkins, Daniel Dennett and Susan Blackmore (amongst others) to consist of a three step process:
1) Replication of system.
2) The offspring inherit some characteristics that have variation amongst the offspring.
3) The differential survival of the offspring is influenced by which variable characteristics they possess.

It has been proposed that any system adhering to this three step algorithm, regardless of its substrate, must evolve and will evolve in the direction of an increased ability to survive (Dawkins, 1976; Dennett, 1995; Blackmore, 1995).

Offspring that inherit a slate of characteristics providing them with a substantial survival advantage will have greater reproductive success than their competitors. Characteristics that bestow greater survivability are called adaptations. Adaptations are usually discovered through processes with a random 'trial and error' component, such as genetic mutation, but the greater survivability they bestow allows them to become widespread within the population. Systems with long evolutionary histories come to accumulate many adaptations. Indeed any organism may be considered as largely an accumulati`on of adaptations built up over evolutionary time.

Survival of a complex system is only allowed by the 2nd law of thermodynamics if exchanges with the system's environment are achieved such that the entropy of the system is maintained or decreased to an extent more than made up for by the increase in environmental entropy. For instance the strategy of photosynthesis in green plants to improve their survivability (through an intricate process transferring free energy from photons in the environment to a chemical form of energy usable by the plant) is dependent on an overall increase in entropy in the sun/earth system.

Survivability of complex systems thus depends on finding loopholes where environmental entropy increase can be used to decrease system entropy. In this sense adaptations are highly tuned to their environments and might be said to form a model of their environments. Henry Plotkin (1997 p.116) has argued that adaptations are knowledge. They may be considered the knowledge of specific methods used by low entropy systems to maintain or decrease their entropy at the expense of their environments.

Bayesian probability is often defined as a measure of a state of knowledge. It is the degree of belief we should have in a proposition given the data available to us. It is a subjective measure in the sense that it is dependent on the evidence available to a given observer and may differ between observers or with a given observer over time. However it is objective in the sense that a unique probability should be calculated by all observers having the same evidence. (Jaynes, 2003, pp. 44-45)

This objective nature of Bayesian probability precludes it from applying solely to the conscious minds of human observers in cultural systems of knowledge such as Science. We should expect the principles of Bayesian probability to be followed by any system having internal models of external reality that are updated through

experiences in the external reality if those models are to be maintained in a near optimal manner.

A central theme running through E.T. Jaynes great text book on Bayesian Probability concerns the necessary design of any robot capable of plausible reasoning. His conclusion is that such a robot can only be designed according to the principles of Bayesian Probability (Jaynes, 2003). Any system of knowledge that must be updated to model changes in its environment or to model greater details of its environment is performing inference and Bayesian probability is the unique method of performing such inference (Jaynes, 1986).

Karl Friston has argued that any adaptive system must contain internal models of its environment. He argues that the accuracy of these models in characterizing their environments is maintained by Bayesian processes that update the models through inference from data. Friston has proposed a method of understanding many aspects of cortical organization and response that he has called the free energy principle. It suggests that organisms attempt to minimize discrepancies (surprises) between their internal models and actual events in the environment. (Friston, 2007) The Bayesian Brain school has produced a substantial body of research suggesting that Bayesian processes operate at the core of many unconscious mental functions in a wide variety of organisms to update internal models in a manner that keeps them in sync with their environments (Friston, 2007). As Friston notes, the price of experiencing surprise may often be death.

The mechanics of updating models in a Bayesian manner when new data becomes available might be understood as forming an algorithmic process:
1) Bring forward a copy of the model along with the relevant prior data.
2) New data provides variations in likelihoods amongst the competing models.
3) The differential survival of the competing models is influenced by the value of their variable Bayesian likelihoods.

It can be argued that this algorithm is isomorphic to the algorithm underlying Darwinian processes.

Darwinian process	Bayesian Process
Replication of system	Bring forward copies of the competing models along with the relevant prior data.
The offspring inherit some characteristics that have variation amongst the offspring.	New data provides variations in likelihoods amongst the competing models in accordance with Bayes' Theorem.
The differential survival of the offspring is influenced by which variable characteristics they possess.	The differential survival of the competing models is influence by their variable Bayesian likelihood.

If we consider the range of scientific subject matter that might be included within this Darwinian/Bayesian framework of adaptive systems we should consider Science itself, the branches of Social Science such as Evolutionary Psychology with 'Evolutionary' in their titles, many aspect of behavioural and neuroscience and of course most aspects of biology resulting from natural selection.

The primary model of all organisms is coded in their genetics and expressed in their phenotypes. The adaptations composing an organism form a detailed model of what is expected in their environment and how to respond to this environment in a manner facilitating survival. At the level of population genetics the composition of a population's genetics is determined by generational transformations largely mediated through natural selection (Lewontin, 1974). These transformation serve to maintain a close fit between the model inherent in the population's genome and characteristics exhibited by the population's environment.

The genetic plan retained at any given time is selected on the basis of the adaptations produced in the phenotype. Adaptations encapsulate knowledge of the environment, specifically knowledge of how to survive in the particular environment the organism expects to find itself in (Plotkin, 1997). If we accept a definition of inference as conclusions drawn logically from premises and perhaps limit the usual meanings of 'premises' and 'conclusions' to 'facts revealed by experience' and 'models derived from experience' then we might view natural selection's selective retention of adaptations as analogous to updating of knowledge through inference.

Bayesian theory tells us that there is only one mathematically sound method of updating the plausibility of models (Jaynes, 2003). That method is Bayes' Theorem. Thus we should expect, to the extent that a population's genomic model is maintained in a state fit to its environment, that this updating is accomplished through mechanisms analogous to Bayesian methods.
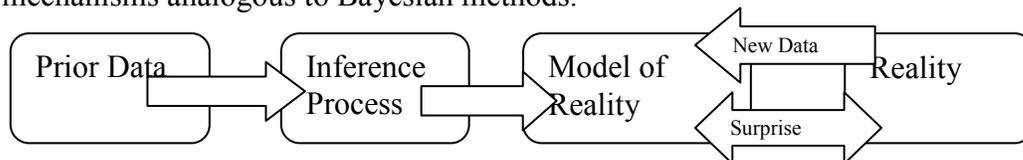

Figure 2 A schematic for adaptive systems containing internal models of their environments that are inferred, through Bayesian methods, from prior data. These models are tested by new data or experience in the environment and updated when surprised.

Since the mid twentieth century many new fields have been introduced to the social sciences which employ Darwinian processes as explanations for the creation and evolution of their subject matter. These include evolutionary psychology, evolutionary linguistics, evolutionary archaeology, evolutionary anthropology, evolutionary sociology and evolutionary economics. These disciplines often borrow theoretical constructs directly from evolutionary biology. For instance evolutionary archaeology has adopted the biological method of cladistics, with only minor alterations, to studies of artifact evolution such as arrowhead design (O'Brien, 2003).

Besides applying the Darwinian process to explain evolution of specific cultural entities, theories have also proposed Darwinian processes to be responsible for the overall emergence and evolution of culture. Two of the most developed are the Dual Inheritance theory (Henrich, 2007) and Memetics (Blackmore, 1995)

Theories, within Universal Darwinism, have in common the supposition that the knowledge structures of their subject matter are created and evolve through the operation of Darwinian processes. This knowledge exists in the form of adaptations that server to increase survivability and that are passed between generations.

Section 2 - Maximum Entropy and Evolution

The principle of Maximum Entropy predicts a system will evolve to a state of highest entropy available, subject to constraints in the form of prior information applicable to the system. The constraint often represents our knowledge in the form of scientific law (Jaynes, 1985). In fact scientific law might be viewed as generalized principles that have been derived from prior information.

The second law is widely recognized as providing perhaps the most fundamental framework for the evolution of the universe. Yet when we view the actual evolution of the universe as revealed by our best scientific theories there is an apparent paradox. The scope of scientific subject matter near the time of the Big Bang was limited but since that time there have occurred successive introductions of new low-entropy subject matter including atomic physics, chemistry, biology and culture. All of these complex systems operate in accordance with the second law but they appear to exploit loopholes in order to maintain their low entropy local states.

The principal of Maximum Entropy tells us that the failure of complex systems making up the bulk of scientific subject matter to evolve to states of higher entropy is due to scientific law. It is apparent that scientific law has accumulated over the course of time along with the creation of scientific subject matter. Within biology it is a near consensus that this accumulation is due to natural selection. Numerous theories within the social sciences also explain the creation and evolution of the low entropy states composing their subject matter as due to the operation of Darwinian processes.

Prior knowledge, as used by the principle of maximum entropy, is not only a subjective attribute of the researcher's mind. To provide useful results it must capture all the constraining attributes pertinent to its predictions. Indeed experimental results that do not agree with the predictions of maximum entropy indicate that the researcher is missing some pertinent prior knowledge (Jaynes, 2003, p. 371).   In this sense a researcher's prior knowledge may be deficient if it does not encompass all of the design constraints pertinent to his or her predictions.

Thus prior knowledge or scientific law, forming constraints on maximum entropy, is an attribute of objective reality and one that has evolved during the history of the universe. An understanding of how such constraints were created and transformed may have been most thoroughly developed within biology where it forms the subject matter of evolutionary biology.

It is proposed that much of scientific law or prior knowledge may be understood as generalizations of those rare design details, discovered by Darwinian processes, that are capable of maintaining states of low entropy and that are central to their continued existence. It is suggested that much of scientific subject matter is the accumulated adaptations discovered over evolutionary history by Darwinian processes. Scientific laws regarding these systems may be largely understood as generalizations of operational design characteristics discovered and retained by Darwinian processes that confer survivability to the system's low entropy state.

Theories within universal Darwinism describing the evolution of their subject matter in terms of information accumulated through the operation of Darwinian processes are closely aligned to the Principle of Maximum Entropy as they may explain the creation and evolution of the constraints employed by maximum entropy.

Discussion

The unreasonable effectiveness of mathematics in the natural sciences has seemed something of a wonder to many researchers including Eugene Wigner (1960). Why is mathematics so powerful in describing natural processes? Max Tegmark (2009) has offered a solution, that may appear somewhat obvious, suggesting that physical reality is isomorphic to a mathematical structure which we are gradually discovering.

Bayesian probability may well lay claim to be the 'logic of science', given that it is the unique mathematical structure providing a valid extension of logic to areas of incomplete knowledge where degrees of plausibility must be dealt with (Jaynes, 2003, p. xx). Science is one such structure. However we might consider extending this claim to all areas of the natural world where structures containing knowledge have evolved. Gaining knowledge requires logical inference which operates according to Bayesian principles.

Outside of the realm of biology and the social science lies much of reality that also persists in states of low entropy, notably atomic physics and chemistry. These states seem to owe their persistence as low-entropy entities directly to scientific law.

Discovery of scientific laws might be most complete in the fields of physics and chemistry where constraints on entropy production are perhaps of a simpler design. Here the operation of constraints are quantum in nature. It must seem highly unlikely that these constraints may also have been discovered through the action of Darwinian processes. Currently there is a shortage of interpretations of quantum processes that are explanatory in the usual sense. Indeed Richard Feynman (1967) famously remarked that no one understands quantum mechanics.

This barrier to understanding, existing for nearly a century, may have recently been breached. Wojciech Zurek, of the Los Alamos National Laboratory, and collaborators have proposed a resolution to the primary point of misunderstanding known as 'the measurement problem'. Central to this resolution is a theory they have named Quantum Darwinism. Quantum Darwinism portrays quantum interactions in terms of a Darwinian process where information is copied from the quantum system to its environment. According to this theory only a limited subset of available information can survive the transfer and forms the 'classical' reality we witness and are composed of, a reality that is selected, in a Darwinian manner, from the vast array of quantum potentialities (Zurek, 2009).

It remains to be seen if Quantum Darwinism can be interpreted as portraying the complexities of atomic physics and chemistry as adaptations discovered through the operation of Quantum Darwinism and following Bayesian principles.

ACKNOWLEDGMENTS

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