Historical Development of the Distinction between Bio- and Abiogenesis.

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ABSTRACT

Early greek philosophers laid the philosophical foundations of the distinction between bio and abiogenesis, when they debated organic and non-organic explanations for natural phenomena. Plato and Aristotle gave organic, or purpose-driven explanations for physical phenomena, whereas the materialist school of Democritus and Epicurus gave non-organic, or materialist explanations. These competing schools have alternated in popularity through history, with the present era dominated by epicurean schools of thought. Present controversies concerning evidence for exobiology and biogenesis have many aspects which reflect this millennial debate. Therefore this paper traces a selected history of this debate with some modern, 20th century developments due to quantum mechanics. It finishes with an application of quantum information theory to several exobiology debates.

Keywords: Biogenesis, Abiogenesis, Aristotle, Epicurus, Materialism, Information Theory

1. INTRODUCTION & ANCIENT HISTORY

1.1. Plato and Aristotle

Both Plato and Aristotle believed that purpose was an essential ingredient in any scientific explanation, or teleology in philosophical nomenclature. Therefore all explanations, said Aristotle, answer four basic questions: what is it made of, what does it represent, who made it, and why was it made, which have the nomenclature material, formal, efficient and final causes.[1] This aristotelean framework shaped the terms of the scientific enquiry, invisibly directing greek science for over 500 years. For example, "organic" or "final" causes were often deemed sufficient to explain natural phenomena, so that a rock fell when released from rest because it "desired" its own kind, the earth, over unlike elements such as air, water or fire. This "desire" of inanimate objects was no different in principle than a sunflower "desiring" sunlight, or a chipmunk "desiring" food. All of these "organic" explanations involve a purposeful motion, such that Aristotle believed all motion indicated a purpose. Only stationary, dead, immovable things lacked purpose. If the planets moved through the heavens, it indicated a purpose, a cosmic intellect. We may ridicule this aristotelean physics, as many science textbooks do today, but we must recognize that it provided a coherent framework encompassing both biology and astronomy in a unity never surpassed since.

Despite is marvellous coherence, aristotelean science had some drawbacks. Often final causes, "whys", were given precedence over the others, suppressing, perhaps, any curiosity into the "whats" and "hows" of phenomena. Furthermore, the framework of probing causes led naturally to the idea of a causal chain, an endless succession of "whys" or "whos" that apparently could only be terminated on a "first cause", "prime mover", or "uncaused cause", which both Plato and Aristotle associated with divinity. Nine hundred years later, Augustine of Hippo was to christianize these concepts and incorporate them into the theology of the Church, but even five centuries before Christ, they played an important role in defending greek pantheistic theology. It was these theological implications that contributed to the emergence of a rival philosophy, atomism.

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1.2. Democritus and Epicurus

Around the same time as Aristotle, we have the competing philosphy of atomism due to Democritus, developed later by Epicurus. Very little information is preserved about Democritus, more on Epicurus, with perhaps the best exposition being a poem written four centuries later by Titus Lucretius Carus, *De Rerum Natura*. Reading Lucretius,[2] which is enjoyable, informative and highly recommended, reveals that Epicurus had noble and very humanistic goals in challenging Aristotle, including the desire to free mankind from the onerous demands of arbitrary gods. It is a criticism of his disciples and not the founder that the epithet "epicurian" came to mean "eat, drink and be merry, for tomorrow we die" (1Cor15:32). Despite nearly two millennia of bad press, ultimately epicurean atomism became the dominant philosophy of science by the end of the 19th century, with most of the successes of the enlightenment science re-attributed to materialism.

In contrast to Aristotle, Democritus and Epicurus developed the view that objects are inorganic, composed of dead collections of tiny atoms in multitude combinations that explain the variety observed in nature. Further, the motion of atoms reflected no purpose or mover, but an incessant and unstoppable agitation. Natural phenomena are then the consequences of collisions and recombinations of blind atoms, without any appeal to purpose or teleology. Accordingly, the only causes that survive atomist explanations are the "what" and "how", with both "who" and "why" causes rejected as inapplicable to senseless particles. Therefore by not permitting teleological explanations, the causal chain terminating with god is broken.

Even with this atomic reductionism to two causes, one might still introduce (as indeed, enlightenment philosophy did) a god who created the atoms and gave them their initial motion. Therefore Lucretius takes great pains to establish three more assumptions intended to preserve the autonomy of atoms, to liberate them from teleology. Strictly speaking, these three additional hypotheses are not required to be an atomist, but they are required to be a materialist or an atheist. This is why we regard epicurean philosophy as more than a scientific development of atomism, but a theological response to Aristotle. We quote Lucretius:

> [I:150]In tackling this theme, our starting point will be this principle: Nothing can ever be created by divine power out of nothing. [I:220] The second great principle is this: nature resolves everything into its component atoms and never reduces anything to nothing. [II:1080] ...nature is free and uncontrolled by proud masters and runs the universe by herself without the aid of the gods.

We can summarize these three principles as "Eternal existence", "indestructible atoms", "non-contingent universe". The first principle removes the need for a creator-god by arguing that the universe has existed forever. The second principle argues that atoms are indestructible, or else a small decay, persisting forever, would lead to nothingness and require a creator-god again. The third principle argues that purpose or contingency cannot affect atoms, or else a creator-god could be invoked again to explain phenomena. Thus a creator-god is banned from the beginning, the end, and the middle of history.

1.3. Augustine

Augustine of Hippo was a teacher of philosophy in the 4th century AD, when he converted to Christianity, and went on to be the most influential theologian of the Church, perhaps through the sheer volume of writings he produced. In his autobiographical work, *Confessions*,[3] he wraps up his life history with three concluding chapters on philosophy, having a distinct, trinitarian emphasis. In each of those chapters, he establishes a theological principle that directly counters materialism,

> [11.15] For thou madest that very time itself, and periods could not pass by before thou madest the whole temporal procession. [12.7]...thou didst create something and that out of nothing (*ex nihilo*). [13.2]Indeed, it is from the fullness of thy goodness that thy creation exists at all; ...that the inchoate and the formless, whether spiritual or corporeal, would deserve to be held in being despite the fact that they tend toward disorder....

Again we summarize Augustine by saying time was created by God; matter was created by God, and both matter and mind are "held in being" by a creator-God against entropic decay. Note that a weak atomism is compatible with Augustine, but not materialism. Few, however, made the distinction and consequently both atomism and materialism vanished for the next 1200 years as the Church dominated the intellectual climate of the West.

1.4. Enlightenment and 19th Century Physics

The Crusades reintroduced Europe to the writings of Aristotle, and very quickly aristotelean arguments circulated in all the leading universities. Perhaps in response to this near hero-worship, or perhaps in response to his treatment by the Jesuits, Pierre Gassendi christianized and promoted the greek atomists from 1617 until his death in 1655, though without the full complement of materialist assumptions. Atomism gained credibility with chemists in the ensuing century, and by the 1800's was winning over physicists as well. In that century, James Clerk-Maxwell stands out as both an ardent Christian and strong proponent of the new atomism. He gave this lecture on atoms to the British Association for the Advancement of Science in 1873, in which he apparently includes one of the three materialist assumptions as well.[4]

> They continue this day as they were created, perfect in number and measure and weight, and from the ineffaceable characters impressed on them, we may learn that those aspirations after accuracy in measurement, truth in statement and justice in action, which we reckon among our noblest attributes as men, are ours because they are essential constituents of the image of Him Who in the beginning created, not only the heaven and the earth, but the materials of which heaven and earth consist.

Despite his obvious efforts to rehabilitate materialism and make it compatible with Augustine, the other two materialist assumptions were not so easily abandonned, and by the turn of the 20th century, full-blown materialism had regained ascendancy among scientists. The last holdout of teleology was biology, which seemed best explained by aristotelean purpose. Thus it was Darwin's "Origin of the Species" in 1859 that finally provided a convincing materialist counter-argument for purposeless design, positing chance developments over eternal time.[5] Note how the three materialist assumptions were used; Maxwell's physics invoked the indestructibility of atoms, whereas Darwin's biology required eternal time, while both assumed chance alone directed their motion.

1.5. Metaphysical consequences

We have traced the historical dialectic of materialism above to give it a proper chronological perspective. Now we ignore the chronology and discuss the theoretical dialectic. Aristotle's organic, or purpose driven explanations work very well for animals and humans. But it gave a curious interpretation to inanimate objects, embuing them with some vague "life force" that was attractive in nature. In contrast, Epicurus' interpretation was ideally suited for inanimate objects whose primary interaction was a repulsive force. Tellingly, Lucretius expends great effort to explain the attraction of magnets as mediated by a repulsive force. Likewise, Newton's theory of gravity was opposed by Enlightenment materialists because it was attractive "spooky action at a distance" reminiscent of Aristotle. And Faraday's theory of electromagnetism was opposed by 19th century materialists because it invoked invisible "fields" that generated the attraction. The success of the theories of both Newton and Faraday should alert us that today's scientific materialism is not pure epicurean philosophy but synthesized with aspects of aristotelean thought.

This synthesis led to some irreconcilable paradoxes, such as Newton's problem that the attraction of gravity over an eternity of time should have reduced the universe to a single large body (black hole).[6] Newton also fretted that perturbations of the planetary orbits should destroy their orbits about the sun. Despite these problems, the three materialist assumptions were held inviolate, so as to prevent any return of teleology through acts of creation. As we will show later, this faith caused considerable difficulties for astrobiology.

2. 20TH CENTURY DEVELOPMENTS

2.1. The Loss of Materialism

2.1.1. Einstein and Special Relativity

In 1905, as Einstein struggled with the inconsistencies of the classical theory of electromagnetism, he struck upon the weird and wonderful world where the speed of light is a constant. One of the many materialist premises that this theory contradicted was the notion that a wave exists in a material medium that is "waving", such as water waves on the ocean, or sound waves in air. In contrast, Einstein argued that light, an electromagnetic phenomenon described by Maxwell, was waving in a vacuum, with no physical medium involved, which is why it always travels at the same speed. Indeed, the only reason light could travel as fast as it does, is that it has no mass at all. Even worse, matter and light were related to each other by the famous equation $E = mc^2$, so that light could be turned into matter, and matter into light at any time. Thus Einstein overturned one of Epicurus' foundation principles, that matter was indestructible.

Despite the elegance of Einstein's theory, it so contradicted common experience and philosophy that it encountered much opposition. Nevertheless it's success at predicting experimental results rapidly gave it credibility, even with materialists. It was, after all, this theory that predicted the energy released in Uranium fission would be a million times greater than that of a similar sized chemical bomb. Einstein's success would be the envy of lesser men, but he was deeply disturbed that his novel theory only addressed the energy, and not the forces so dear to a Newtonian physicist. Consequently in 1916 he generalized his theory, with great effort and mathematical sophistication, to handle forces, acceleration and gravity.

2.1.2. Einstein and General Relativity

This general theory predicted that gravity is just matter warping space-time, so that light travelled in curves, rather than straight lines. To test this theory, an expedition was mounted in 1919 to look for the curvature of starlight around the sun, which could only be observed during an eclipse. The success of this prediction propelled Einstein to everlasting fame and glory. It also introduced a small problem. If the universe is bent inward by the gravity of its contents, then it would collapse into a single point of unimaginable gravity, a black hole. Einstein attempted to resolve this problem by inserting an "anti-gravity" term into his theory that would give a static, motionless equilibrium. However when Slater and later Hubble showed that the majority of galaxies were receding from us, making us appear to be the center of a large explosion, Einstein realized that it wasn't necessary to have an equilibrium, an explosion would work just as well without an extra "anti-gravity" term. He then eliminated this term, calling it his "greatest mistake".

This massive explosion, derisively named "the Big Bang", suggested that there was a beginning to the universe. And if space had a beginning, so did time. Again there were great misgivings from scientists about this second onslaught on materialism, as documented in Jastrow's book "God and the Astronomers",[7] with many objections and alternative theories presented. Nevertheless, the discovery of the 2.73K blackbody radiation in 1963 as predicted by the theory, clinched it for most scientists, and after several billion dollars spent on satellite measurements, today astronomers believe the universe to be 13.7 Gy old, plus or minus 200My.[8] Thus the second pillar of materialism crumbled, which held the universe to be eternal.

2.1.3. Carter and the Anthropic Principle

Less noticed, perhaps, than the the destruction of these two pillars of materialism, was the destruction of the third pillar, non-contingency. As cosmologists fine-tuned their models, they noted that if any of the arbitrary constants of physics were adjusted slightly, the universe would look very different. This included the fine structure constant, the proton-to-electron mass ratio, the electrical-to-gravitational force ratio and so on. Brandon Carter compiled a number of these delicate balances,[9] but one example of this category should suffice to illustrate the problem.

If the Big Bang had exploded a bit more violently, then protons would be too far from each other to have begun to accrete into galaxies and stars, so that our universe would consist of slowly cooling gas, without stars, without planets, and without us. Conversely if the Big Bang and been a bit less violent, then gravity would have overwhelmed the expansion, leading to "the Big Crunch" and a black hole would have formed in much less time than 13.7Gy. In order for the universe to look as it does to our eyes, the explosive force of the Big Bang is sensitive to one part in 10^{60}. To give a feel for that number, note that there are roughly 10^{80} atoms in the observable universe. So inhomogeneities on the scale of $10^{80}/10^{60} = 10^{20}$ atoms were significant, or roughly the size of a grain of salt. One grain of salt more, or one less in the universe, and we wouldn't be here to discuss it.

Now an epicurean materialist would argue that because contingency is disallowed, there can only be two explanations for any phenomena: law or chance. But if there were a law that determines the fine-tuning of these arbitrary physical constants, it has not been found. Even were it to be found, laws often require deeper symmetries that merely remove the contingency to a deeper level.[10] But if it is not law, then it should be chance, and for every finely tuned constant, there should be a dozen "poorly tuned" constants. Carter was unable to find any such balance of "bad tuning" that would support the chance hypothesis. Now if neither law nor chance explain the phenomena under scrutiny, scientists have historically invoked design, purpose, or teleology. But this is no ordinary contingency, this is the universe!

So Carter argued that our peculiar universe is only an "apparent" contingency, because this selection is necessary for humans to evolve and observe it. He coined the phrase "The Anthropic Principle" to describe the non-random character of a universe that contains us. As many able philosophers have pointed out, however, Carter's logic is an improper negation of the correct syllogism "we should not be surprised to not observe a universe hostile to life". Another attempt to remove the contingency involves assuming the existence of an infinite number of universes, so that the improbability of ours is multiplied by a very large number so as to generate a probability equal to one. Since none of this infinity of other "multiverses" is observable, such an assertion must be taken as a faith statement, buttressing the third pillar of materialism with non-transparent, naively optimistic bracing.

2.1.4. Metaphysical consequences

Therefore at the end of the 20th century, the aristotelean versus materialism debate has reopened with a vengeance.[11] The existence of atoms is accepted by both sides, but the three additional materialist pillars are in serious trouble. All three pillars have to do with creation, with Augustine's philosophy, with Aquinas' proofs of God's existence. The finite lifetime of the universe hampers those who want to explain life as a chance chemical reaction occuring after long periods of time. The creation and destruction of atoms in stellar nuclear furnaces removes 99.9% of the visible matter from participating in this life process and raises philosophical questions about their existence at all. And the contingency of the laws of physics that support life suggest even more hidden factors yet to be discovered that don't give entropy a chance. The late Sir Fred Hoyle concluded that there wasn't enough time since the Big Bang,[12] and therefore insisted in a steady state universe much older than the standard chronology.[13] Paul Davies[14] suggests that peculiar laws of physics required life to form, but were not themselves evidence of contingency. So it appeared that there was a desire to defend at least one of the materialist pillars, but no consensus on which or how to construct a defense.

Nowhere is this more evident than in the astrobiology debate, where evidence for life elsewhere in the solar system or galaxy is fiercely contested. Do absorption bands in the microwave emission from galactic nebulae[15] indicate life or non-life? Did the evolution of carbon dioxide from the biology experiment on the Mars Viking lander[16, 17] indicate living organisms or peculiar chemistry? Do small chains of bubbles in Martian meteorites[18] indicate biology or abiology? Do strange colors on the icecaps of Mars and Europa suggest colonies of algae or mineral deposits? With recent planetary missions both at NASA and ESA, the debate is quickly becoming international. Does methane on Mars[19] imply methanogens or not? Is Mars Express finding evidence of water on Mars[20, 21]? What about evidence for an ice-filled crater[22]?

Some view the evidence for life on other planets as support for Hoyle's panspermia hypothesis. Others see it as evidence for the spontaneous evolution of Davies. Still others might hold to a transpermia hypothesis, a spread of life throughout the solar system from a single infection. But no matter which hypothesis is presented, it challenges the materialist assumptions, and brings attention to the fragility of the status quo paradigm.

2.2. Information Theory

2.2.1. Claude Shannon

In 1948, Claude Shannon, a Bell Labs physicist was attempting to calculate the maximum amount of data that AT&T could send through their telephone lines. He abstracted the data as a pattern of bits, of 1's and 0's, and calling it information, as so began the field of information theory.[23] As every phone user knows, It is important to distinguish signal from noise, and this required the characterization of noise. This had been accomplished by Boltzmann around 1877, when he discussed the exponential nature of thermal noise, and established a firm mathematical foundation for the concept of entropy. Engraved on his tombstone is his proud achievement, $S = k \log W$, entropy is a constant times the logarithm of the number of states. Today the constant k is called "Boltzmann's constant", which arbitrarily converts combinatorial mathematics into conventional thermodynamic quantities. If the number of states is proportional to the number of combinations of particles, $W \propto N!$, then we can use Stirling's approximation to derive the Gibbs entropy, $S \sim S_G = kN \log N$. So when Shannon needed to talk about information, replacing the particles with bits, he defined information as the negative of the entropy, $I = -S = -kN \log N$, termed negentropy.

Now the pinnacle of 19th century physics was thermodynamics, the physics of heat, work and energy. One of the three laws of thermodynamics is that the entropy of a closed system must either remain constant or increase, it cannot spontaneously decrease. In Shannon's terminology, information is either static or a decreasing function of time. But if a biologist takes a petri dish of agar, places one microscopic bacterium on it, and closes up the system, it rapidly transforms into a state far from equilibrium, as bacterial colonies spread over the top of the agar. What is going on? The careful physicist would argue that the entropy of the carbon dioxide liberated by the digestion of agar more than makes up for the low-entropy carbohydrates and proteins manufactured in the bacteria. So the biologist repeats the experiment with filtered water containing no complex sugars or proteins and a single blue-green algae. Again, the water clouds with millions of complex organisms. The scrupulous physicist then argues that sunlight penetrating the petri dish is suppying an energy source, so the system is not strictly closed.

Although the physicist may be correct, the bookkeeping has never been conclusively calculated to measure whether the entropy has actually increased in either case. Thus the biologist harbors a certain uneasiness about the law of entropy, suspecting that life may violate it in subtle ways. This is easily demonstrated by taking that cloudy water or the scummy petri dish and exposing it to an intense ultraviolet light, effectively sterilizing it without heating or changing the composition in any way. From a physical viewpoint, the entropy is nearly the same as before, the same chemicals in the same amounts, but from a biology viewpoint, it has been converted to abiotic soup. Nothing in Boltzmann's calculations indicate what entropic threshold separates life from non-life, exasperating biologists who look to physicists for mathematical precision.

The answer, however, may be in Shannon's telephone lines. Shannon didn't just measure the information existing in a mile of copper wire at some arbitrary picosecond, he measured the signal as it propagated through the wire. For Shannon, a signal is a time sequence, not a spatial sequence. Of course, multiplying a time sequence by a velocity will give a spatial sequence, so many physicists ignored the difference, talking about "the propagation of information" as if the information were a spatial quantity that travelled at some finite velocity less than or equal to the speed of light.

This interpretation of information as spatial permeates the field, so that the existence of organic chemicals, or complex topologies are often taken as evidence of life, whereas temporal signatures, such as carbon dioxide evolution, or circadian rhythms are considered less reliable indicators. Furthermore, the discovery that information propagates at variable speeds, or faster than the speed of light is greatly complicating the spatial interpretation, requiring a new paradigm for both information and life. This complication arose in the 20th century from Quantum Mechanics (QM), which attacked, not the foundations of Epicurus' materialism, but the foundations of Democritus' atomism.

2.2.2. Werner Heisenberg

Strangely, the assault on atomism began with the discovery of a new atom, an atom (or quanta) of energy. The same year as Einstein's earth-shaking Special Theory of Relativity, he also published a paper explaining a curious property of hot objects, which emit light and electricity as a consequence of the atomic nature of energy. Hot objects, such as horseshoes in a furnace or tungsten wires in a light bulb, will glow brightly when heated, starting with red, moving up to yellow, and then white heat. The problem physicists faced was that the well accepted theory of electromagnetic emission predicted the opposite, that they should all be emitting white light at room temperature, becoming redder as they got hotter. Max Planck spent the entire winter of 1900 fitting arbitrary mathematical functions to these color plots, until he uncovered a curious function that fit exactly. It seemed to imply that the color of the wire, and the amount of light emitted, was proportional to the temperature divided by a unit of very small size, which came to be called "Planck's constant". Einstein explained this as the quantization of energy into little packets, and explained that electricity could not be generated in metals exposed to light, until each packet of light had enough energy to liberate a single atom of electricity, an electron.

One would have thought that this discovery would strengthen, rather than weaken atomism. But in showing that light waves, which Huygens and Young had experimentally proved was the same wave later described by Maxwell's elegant theory, possessed the properties of an atom, it was only a small step to show that atoms possessed the same properties as waves. In 1923 deBroglie described the wavelength of an atom, which Bohr had used to explain the spectra of hydrogen, and in 1926 Schroedinger wrote the wave equation for atoms. All the mathematics developed over the previous two centuries to describe waves could now be used on atoms, and the highly successful field of Quantum Mechanics came into existence.

Heisenberg derived his important "Uncertainty Theorem" by considering the properties of waves, which can be described either as a position that oscillates in time, or as a frequency on a spectrum. That is, a radio signal is either an electric field that jiggles with time like the human voice, or it occupies a certain position on the radio dial with some spread on each side. The mathematical technique that converts time plots to frequency plots was developed in 1807 by Fourier, and came to be known as a fourier transform. A consequence of this transform, is a mathematical corollary due to Parseval, that the width of the wave in space-time multiplied by the width of the wave in frequency-space must be some multiple of the constant π. Heisenberg applied this type of conservation law to atom-waves, and showed that the position of an atom in space, multiplied by its momentum (or frequency as deBroglie argued) must also be a multiple of Planck's constant. This is to say, that if one knows the position of an atom very accurately, then one has no idea how fast it is going. Conversely, if one knows the energy or speed of an atom very accurately, no one knows where it is. Why is this important? Because Newton had argued that if one knows the initial position and speed of an object, one can integrate the equation $F = ma$ twice to predict precisely where it will be in the future. This result of Heisenberg's meant we can never pin atoms down, we can never predict their behavior with more than general accuracy, because we can't simultaneously know their position and speed.

As a consequence, atoms could no longer be visualized as Democritus had intended, as small objects with differing surface texture. Rather, atoms became a fuzzy, non-localized wave until they interacted with some detector and become point-like again. Einstein rebelled at such attacks on atomism, and constructed several thought experiments to disprove QM, each time being rebutted by Bohr, until his last thought experiment (EPR),[24] which discusses the long range effects of two-particle waves, was accepted by Bohr as a valid prediction of QM. It was a prediction Einstein could never accept.

Recent theorems derived by Bell[25] allowed the experimental test of Einstein's thought experiment, confirming that this atomic smear can occupy large volumes of space, entire laboratories or the visible universe. EPR predicted that measurement of one particle in the two-particle wave causes the other to instantaneously become a specific particle, no matter how far away. Even more bizarre is that if the first measurement is "thrown away", so as to erase all knowledge of the measurement (the "quantum eraser" experiment[26]), the second particle reverts to a wave. Information has real physical consequences, a real physical existence. Atoms are not simple particles blindly moving through space, but are a hybrid of a bleary waves multiplied by information. There are many metaphysical interpretations of that information, from Wigner's "consciousness", to Everett's "many-worlds". We choose to take a Shannon's interpretation of information as a quantifiable negentropy.

2.2.3. Metaphysical consequences

So developing Shannon's information theory to encompass QM, we arrive at a definition of information as the thing that converts waves into particles, that which collapses a wavefunction. Treating it as multiplicative, *Info* $\times \Psi(x,p) =$ *Atom*, then information is the specific measurement of a wave state divided by the broad probabilities of all other possible states supported by the wavefunction of those atoms, which is approximately Shannon's definition of negentropy. It differs from Shannon's, however, in that it includes all the entangled states, all the long range correlations not included in the Boltzmann entropy. Conversely, we can broaden the Boltzmann definition of entropy so as to include long-range interactions, attempting a statistical approach to these entangled wave states. Tsallis[27] has suggested just such a "non-extensive" entropy that has provoked much recent excitement in the field. In either case, the non-local nature of QM coherence suggests that information is also non-local, giving new measures to distinguish life.

If we contrast this with atomism, we see that the coherence length, the non-local nature of information reintroduces aristotelean attraction, not mediated by particles. Further, the quantifiable nature of information gives it a real existence for materialists, which we equate with aristotelean purpose. That is, a forensic pathologist determines whether a death was accidental or pre-meditated by attempting to isolate highly unlikely coincidences that indicate purpose. So there is a rough equivalence between purpose and negentropy, as Dembski[28] argues.

If aristotelean purpose can now be quantified as information, or QM coherence, and detected, then life itself can detected and quantified as well, removing the chasm between epicurean physics and aristotelean biology. No longer are law and chance the only two explanations for natural phenomena, but information or purpose becomes a quantifiable free dimension, roughly correlated with the presence of life.

Like Newton, who defended his theory of gravity against staunch materialists, saying *hypotheses non fingo*, we also frame no hypotheses. Certainly the reintroduction of information as negentropy, coupled with the 2nd law of thermodynamics leads to the question of causal chains for information, which some might see as a reintroduction of Aquinas' proofs of God's existence. We would argue that it is far too early in the development of quantum information theory to be definitive about causal chains. Some have argued that QM information is best understood as "reverse causation",[29, 30] others as "many-universes" in which there is no causal chain of information. Still others view Heisenberg's uncertainty principle as a fundamental character of the universe, so that even God has limited QM information. How these QM theories relate to Tsallis' non-extensive entropy[31] is also an active area of research. Because the experiments and theories are currently in a state of flux, it is too early to tell whether causal chains can be developed, nevertheless it should be clear that the current paradigm of scientific materialism cannot include all these new effects. It should also be clear that science is ready for a new synthesis of aristotelean atomism that can lead us into the new millennium.

3. APPLICATIONS TO EXOBIOLOGY

We have presented these developments of QM information theory because they directly impact on the search for extra-terrestrial life. The debates are complex for many reasons, not least because many scientists have taken conflicting positions. For example, the late astronomer Carl Sagan rejected the results of the Mars Viking lander that suggested biological activity on Mars with the statement that "extraordinary claims require extraordinary evidence", yet he simultaneously supported the Search for Extraterrestrial Intelligence (SETI) using the large Arecibo telescope to search for radio communications from outer space. Evidently he considered radio signals to be more extraordinary than biology experiments. Conversely, many exobiologists consider remote sensing to be less compelling than *in situ* measurements by landers or meteoritic analysis. In this section we attempt to analyze these controversies with the preceding framework, and suggest a path forward.

3.1. Biofossils versus Artifacts

3.1.1. ALH84001

The Allen Hills meteorite collected from Antarctica was identified on the basis of the composition of its gas bubbles[32, 33] as conclusively coming from the surface of Mars. It generated controversy when David McKay published a paper[18] arguing that carbonate inclusions in the rock were fossil evidence of biology. He buttressed his claim with carbon isotope ratios, microscopic analysis of magnetite grains, and chains of 200 nm "bubbles". Most of his detractors attempted to show an abiotic pathway that could generate the same observation. Our study of the debate seems to indicate that spatial information–such as bubbles, carbonate boundaries, magnetite grains, carbon isotope ratios–was explained with a plausible abiotic causal chain. Rarely, however, was temporal information evaluated or considered important.

That is, life proceeds by a series of cycles or periods, from microseconds for chemical equilibria, to hours for cell mitosis, to days or years for cell death. Therefore a biotic explanation for carbonate inclusions must also be consistent with life cycles. For example, one should not assume an igneous explanation for carbonate granules followed by biotic modification. Indeed, early support for an abiotic interpretation assumed such an shock-induced igneous episode to form the granules and produce the polycyclic hydrocarbons. Regrettably, none of the detractors felt it was necessary to form a self-consistent abiotic interpretation, so that no temporal sequence could be constructed that accommodated all the abiotic scenarios. Since such a temporal sequence is precisely what is needed to look for biotic information, the debate tended to hinge on the support or lack of support for spatial information. Even more significantly, apparently none of the detractors attempted to construct a spatially coherent model that incorporated all the various information in the sample: the magnetite, the carbonates, and the hydrocarbons.

Thus we see the difficulty for any biological hypothesis; biology must be spatially and temporally coherent, it must find information at multiple spatial and time scales which are consistent with life. Abiotic counter-hypotheses, however, have no such limitation, and indeed, can have contradictory time-histories and spatial scales. Coherence is not considered necessary because there is a materialist presumption of decoherence. If, as we argued above, quantum mechanical systems demonstrate long range coherence, then scientific naturalism can no longer presume this essential randomness. As McKay says about magnetites, the simultaneous occurrence of six unlikely events should be strong evidence for life. The critical missing ingredient, he argues, is the quantitative evaluation of coherence, the probability of the observed information content being consistent with chance.

3.1.2. Carbonaceous chondrites fossils

Carbonaceous chondrites are a peculiar class of meteorites which are high in carbon content and have been water-modified. Like ALH84001, they are thought to be extraterrestrial, but unlike ALH84001 they are thought to be undifferentiated samples of proto-solar nebular material appearing as comets. Like ALH84001 they have been extensively analyzed, but unlike ALH84001, we have samples of carbonaceous chondrites going back 130 years, with a correspondingly longer history. Recent studies focus on electron microscopy of freshly fractured samples, showing an amazing zoo of fossilized structures.[34, 35] Like ALH84001, the large spatial information in their intricate shape are used infer exobiology, but unlike ALH84001, the spatial information is excellent enough to identify genus and species. Accordingly, effort has been expended to quantify the amount of spatial information in an image, so as to use computer classification to identify microfossils in an unbiassed way.[36] Such efforts have been shown to replicate, though not improve, on what a trained scientist can identify by eye, but have the additional feature of producing a probability statistic of certainty.

This approach has certainly given more credibility to the observations, which has caused the detractors to focus on two alternative hypotheses: terrestrial contamination, and the incompatibility of cometary environments. Forty years ago, it was commonly claimed that these meteoritic fossils[37, 38] were both intentional contamination (straw, coal) and unintentional (pollen, fungus).[39] Recent work has gone to great lengths to exclude both of these interpretations,[40] making those counter-arguments increasingly unlikely. Alternatively, detractors argue for hostility of the space environment, and the absence of liquid water on comets. Again, recent satellite rendezvous are generating a ferment of revised comet models, with at least one model predicting the ubiquitous presence of liquid water on short period comets.[41]

Once again, we see the same asymmetric debate illustrated for ALH84001, that biological hypotheses must have spatial and temporal coherence, whereas abiotic hypotheses have no such limitations. This asymmetry gives unfair advantage, as can be seen in a Baysean analysis of hypothesis testing.[42] Using the nomenclature that $prob(H1|D, I)$ is the probability of hypothesis one given data D and prior information I, then we can compare two hypotheses with the same data using Bayes identity:

$$\frac{prob(H1|D,I)}{prob(H2|D,I)} = \frac{prob(D|H1,I)}{prob(D|H2,I)} \times \frac{prob(H1|I)}{prob(H2|I)} \tag{1}$$

Now the second term on the right hand side is just our prior expectation of which hypothesis is better, so to be fair to both sides we can set it to one. This leaves the first term, the ability of the two different hypothesis to predict the same data. Now if H2 has one more adjustable parameter than H1, we would expect a proportionally better fit to the data, which would suggest that theories with many more parameters are to be preferred. This is not the only factor, however, since a procedure called marginalization allows us to integrate out extraneous variables in a hypothesis. Assuming that H2 has a single parameter more than H1, and assuming that it can take a range of values with roughly gaussian shape, we can integrate out this extra variable resulting in a term called the Ockham factor, named for the thirteenth century monk, William of Ockham who said *frustra fit per plura quod potest fieri per pauciora*, or roughly "it is vain to do with more what can be done with fewer". The marginalization procedure gives,

$$\frac{prob(H1|D,I)}{prob(H2|D,I)} = \frac{prob(D|H1,I)}{prob(D|\lambda,H2,I)} \times \frac{(\lambda_{max} - \lambda_{min})}{\delta\lambda\sqrt{2\pi}} \tag{2}$$

where the limits of the integral are λ_{max} and λ_{min}, and valid fits of λ have a width of $\delta\lambda$. Generally speaking, the limits of the integral are wider than the range of good fits, so that this last term is larger than one, and favors H1 over H2. So the abiotic hypothesis that can combine multiple time scenarios is effectively increasing the number of adjustable parameters needed to fit the data. Rather than producing a better hypothesis, Baysean analysis demonstrates that additional free parameters often reduce the probability of a such a hypothesis.

Supposing that the abiotic hypothesis is careful to use the same set of parameters as the biological hypothesis, how then does one compare the two? Assuming a free parameter, μ, for H1, and using the same marginalization technique for both, we can derive an Ockham factor of

$$\frac{\delta\mu(\lambda_{max} - \lambda_{min})}{\delta\lambda(\mu_{max} - \mu_{min})} \tag{3}$$

If both parameters have roughly the same range of validity, then it is the one with the wider fit error bars that wins, since the theory has a large range of validity. But if both give the same error bars on the fit, it is the one with the narrower range of prior limits on the integral that wins, since that hypothesis has some additional insight to be able to predict the value of the parameter more accurately.

Applying this Ockham factor to abiotic scenarios, we see that fits that require one region of the meteorite to reach 900°C and another not exceed 150°C have non-overlapping (negative?) error bars, and are therefore inferior to theories that are compatible with a 0-30°C range. Or if we say the two heating events are separated in time, then we can construct a time-temperature space for the two theories and ask which one has the larger fitted error bars. Conversely, if we argue that they both give the same fit errors, we might ask what prior temperature limits are consistent with abiotic hypotheses compared to biotic. Clearly biotic hypotheses have temperature limits between -273°C and 150°C, whereas abiotic have much higher temperature limits, giving the advantage to the theory having better predictive ability.

3.2. Deinococcus radiodurans

In 1956, when food preservation by pasteurizing with gamma rays was attempted, a strange organism was discovered that survived 1.5MRads of radiation. What is peculiar about this survival trait, is that nowhere on the Earth's surface does such a radiation environment exist. (Indeed, there are natural uranium reactors at Oklo, but they were thought to operate for a few years to a few hundred thousand years approximately 2 billion years ago, hardly sufficient time for evolution to work.) Given the magnetic field and atmosphere of the Earth, such a radiation environment has not occurred since the Earth was formed, yet here is an organism adapted for this environment. The biological mechanism turns out to involve duplicate strands of double DNA, or quadruple redundancy of the genome that enable it to survive repeated dislocations of its genes.

The exobiology hypothesis postulates that such a repair mechanism indicates evolution or adaption of the organism in extra-terrestrial environments, perhaps long journeys in interplanetary space where it would be exposed to galactic and solar cosmic rays. The terrestrial biology hypothesis postulates that this repair mechanism was designed for some other purpose, such as dehydration, and accidently found it useful for nuclear reactors.

This is a classic example of two hypothesis assuming the same mechanism, evolution, but with different prior assumptions, cosmic rays versus dehydration. Accordingly the theory that has the narrower range of limits would be preferred.

Given the additional assumption that radiodurans was transported via comets through the solar system, one can calculate a rough MRad upper limit for the radiation tolerance needed to survive a 10-100 ky journey. Were the bacterium in a suspended animation state, say, due to cold and dehydration, then the effect of galactic cosmic rays would accumulate, at about 10 or so Rad/year. But if the bacterium were actively duplicating and repairing its DNA, then the limit would be due to a single < 1 day dose, perhaps from a solar flare. In both cases, we obtain MRad levels of radiation resistance required.

Conversely, dehydration is an entirely different process of DNA destruction, with a potentially larger range of values for radiation tolerance. Not knowing the conversion from dehydration to radiation, it appears that only a weak upper limit can be placed on this method of radiation tolerance, making the first hypothesis more likely. This is just another way of saying that biogenic teleological hypotheses have more spatio-temporal coherence, and therefore a smaller range of predicted parameters than abiogenic or chance hypotheses.

3.3. The Viking Labelled-Release experiment

The LR experiment,[16] which attempted to grow Martian bacteria in the Viking lander and measure the carbon dioxide released, is notable for several reasons. In terrestrial tests, it was more sensitive than any other technique, being able to detect bacteria in Antarctic soils which looked sterile to others. Further, it contained a control, a sample of Martian soil baked at 350°C, which did not evolve carbon dioxide when incubated. Finally, it relied not on spatial information–biogenic structures, carbon isotopes, organic chemicals–but temporal evolution, with exponentially increasing carbon dioxide release as evidence of the multiplication of life. Despite the faultless performance of the experiment, the results were contested, perhaps because of a bias toward the spatial information of the mass spectrometer's negative results.[43] Thirty years later, additional work has revealed more temporal information in the signal, with circadian rhythms identified in the carbon dioxide evolution.[44] It is a telling commentary on the reigning materialist paradigm that temporal information is routinely underappreciated if not entirely ignored. Nevertheless, it is a relatively straightforward mathematical procedure to carry out hypothesis testing in the time domain, indeed, the entire SETI project depends upon it.

We merely point out that both time and space have information, so that the size of the Martian soil sample puts limits on the density of putative Martian bacteria, and therefore limits on the exponential increase of carbon dioxide, or the modulation by circadian rhythms. Life must be both spatially and temporally coherent, which act to further restrict the limits of any biogenic hypothesis. Therefore given a biogenic and abiogenic hypothesis involving superperoxides, the biogenic hypothesis has much stricter limits on the temporal evolution of the data, which must follow an exponential growth curve consistent with low microbial densities.[45] Once again we see an application of how spatial coherence produces superior "Ockham factors" in a comparison using temporal data.

4. CONCLUSIONS

We have attempted to sketch the historical development of organic and inorganic explanations in science from Aristotle to the present. We argued that 20th century developments in relativity, quantum mechanics and cosmology have seriously undermined the reigning paradigm of atomist, materialist naturalism. We have turned to quantum information theory as a way to include non-material information into materialism and non-local effects into atomism. These changes are consistent with an aristotelean description of purpose, or teleology, which we argue should be incorporated into the current scientific paradigm. We apply these criteria to the problem of exobiology using Baysean hypothesis testing as an instance of the problem, and suggest that spatial and temporal information are proxies for evidence of life. Without any great rigor, we demonstrate the consistency of biogenic hypotheses over abiogenic using Baysean probabilities, and hope that such calculations will become more common in the future of the field.

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