Physics, Information and Life: Towards a Universal Theory

1. Physics

From the onset of the twentieth century to its closing, physics reigned as the queen of the natural sciences. The discipline represented how successful the application of the scientific method could be. The advances made in understanding the nature of our physical Universe, from the smallest fundamental particles to the entire cosmos itself and almost everything in between, sparked the enormous technological developments that have forever changed the world. One would be hard pressed to name another discipline that has altered not only the way we view our own Universe but the way we live our lives as well. The most sophisticated tools ever created have provided us with the ability to observe the different constituents of the Universe with great precision. In addition theoretical advances allowed us to create models with great explanatory power capable of not only describing the measurements made but able to make predictions regarding those that were yet to be made.

What made physics so powerful was that it went beyond philosophy and mathematics to be a science based upon measurement. Without a quantifiable means of making observations, physics would not have reached the stature that it now occupies. From knowledge and understanding came the ability to control the processes that at one time were totally enigmatic. While some have deplored what might be considered a loss of mystery, it can be said that the mystery arising out of ignorance has been replaced by an even greater mystery that occurs in light of what is known. This is what has driven science, particularly physics, to search for ultimate truths, however simple they may be.

Physicists believe that the processes we observe on the Earth and their descriptions encoded in physical models and theories are not unique to out terrestrial environment. That they are universal has allowed us to translate our knowledge of what happens on Earth into an understanding of the processes occurring in the remotest regions of our Cosmos. Newton's theory of gravity has provided the paradigm for this. The realization that the very reason why an apple falls to the ground also explains why the planets orbit the Sun along elliptical trajectories pushed physics into an exalted position that rivalled religion.

Similarly quantum mechanics originally designed to describe the behaviour of atoms and molecules, has been successful in not only describing fundamental building blocks such as quarks and lepton but also provided clues to identifying the enormous energy sources that have powered the Sun and other stars for billions of years.

Clearly the recent history of physics will be a hard act to follow. In spite of the advances in understanding made between 1900 and 2000, twentieth century physics has left 21st century physicists with some difficult tasks. An explanation of why the Universe seems to be now expanding much more rapidly than our standard cosmological models predict will be required. The two cornerstones of 20th century physics, general relativity and quantum theory have yet to be made compatible, and we still do not have an good explanation of how the masses of the elementary particles are determined. The climate is changing rapidly and energy sources are not meeting the needs of a growing population. While physicists will continue to work on these problems and will with all likelihood be able to succeed in solving them, it should not go unnoticed that already the marquee science of the 21st century is biology.

Over the past half century, since the discovery of the structure of DNA, we have witnessed the advances in genome sequencing and anticipate the results of functional magnetic resonance imaging to give us insight into how the brain works. The new understanding obtained from studying biological systems at the molecular level has led to medical breakthroughs that have dramatically improved our chances for living long healthy lives. These successes, it must be remembered have been enabled by the instrumentation developed by earlier generations of experimental physicists whose goals were to observe the non-biotic world. In addition, quantum physics provides the foundations for molecular biology in both the laboratory and on blackboards.

Given that 2009 has seen the simultaneous celebration of the 200th anniversary of Darwin's birth and the 150th anniversary of the publication of the *Origin of the Species* it is appropriate that physics should take note of this and begin to concern itself with life on earth (and elsewhere in the Universe.) Traditionally it was always assumed that the biotic Universe was much too complicated and too irreproducible to be of interest to physicists. But the old joke about the theoretical physicist who begins a lecture on the physics of biological systems with the statement "Consider a spherical cow ..." has to be set aside. Physicists need to be challenged into taking a head-on approach toward studying complexities of the biological sciences.

There are a number of indications that this has already begun. The discipline of complex systems research which grew out of studies in statistical physics, catastrophe theory and the analysis of chaotic behaviour, attempts to understand systems consisting of many constituents whose dynamics are governed by complicated, nonlinear interactions. Such systems range from large scale turbulent flow, to chemical reactions undergoing spatio-temporal pattern formation, from the onset of avalanches to the rise and fall of financial systems. No longer is the cow being considered, spherical. Now it is a cow's cow.

While many of the systems described above are made up of "non-biotic things", research into the origins of life and the evolution of living organisms will likely receive a great impetus from the participation of physicists. Indeed the ability to physically measure atomic, molecular and cellular processes, to assign reproducible data to those measurements, and to even perform manipulations on such structures begins to bring the biological sciences into the realm of physics.

It has been argued that biology cannot be reduced to physics. One of the proponents of this idea, Stuart Kauffman, has expressed his doubts in his most recent book *Reinventing the Sacred* [1]. Kauffman's arguments (and those of others) are based on the idea that physics is basically reductionist and that biological systems are so complex and evolve in such unanticipated ways that any reductionist attempts to break biological systems down into simple components and operations such that the system is equivalent to the sum of its parts is doomed to failure.

Kauffman of course invented random boolean networks (RBN's) which consist of a finite set of Boolean elements whose on or off state is determined by the other elements in the network. The rules are discrete and the evolution occurs at discrete times. The RBN's were designed as models for genetic regulatory networks. Such networks which include cellular automata systems might be called reductionist in the sense that the state of each individual objects is simple (either a 1 or a 0) and the rules that govern their interactions are simple and causal. Be that as it may the system undergoes many different kinds of behaviour, including regular periodic, unpredictable chaotic and emergent quasi-stable behaviours, the latter occurring at the boundary between stable and chaotic evolution as determined by the parameters that govern the system's dynamics. Kauffman goes on to claim that biological systems exist in the critical regime defined by this boundary and that reductionism is unable to explain this.

While It has often been argued that concepts such as self-organisation, critical behaviour, emergence, auto-catalysis, etc. cannot be included in the reductionist world view, much depends upon one's definition of reductionism. However rather than get bogged down in semantics, what is clear is that physics can play a role in understanding life and biological evolution without reducing biology to physics. Although quantum mechanics has explained the basis of atomic and molecular structure, chemistry has not been reduced to physics. In fact chemists now use quantum mechanics to do chemistry better than ever given the knowledge they have gained from quantum mechanical descriptions. When chemists enter the laboratory to perform their experiments, it is likely that they are do so without concerning themselves about quantum chromodynamics (QCD) and its description of how up and down quarks form the nuclei of the atoms about to undergo chemical manipulation. Although QCD provides a fundamentally a lower level description of atomic structure, its relevance to chemical reactions is negligible.

The same holds true for computing the flow of air over the wing of a modern jet airplane. In spite of the fact that the air is made of molecules of oxygen, nitrogen, carbon dioxide, water, and a host of other atoms and molecules, computational hydrodynamics is still presented with challenges in solving the the Navier-Stokes equations governing fluid motion. Also the designer of telescope lenses and mirrors for intended for the capture of light from distance sources is not concerned about the quantum nature of light.

Even if physics is able to provide a model of living organisms, biologists like chemists can rest assured that their jobs will not be lost. In fact it can be expected that the new understanding gained from a "physical theory of life" will provide biologists with even greater powers than they currently have.

2. Information

One suggestion of a possible profitable approach to understanding biological systems is to use an information theoretic analysis. In fact much of science is based upon an approach that uses information gained from experiment or observation in order to make inferences and models to explain those measurements. Statistical physics and the discipline of quantum information science are good examples of how powerful this approach has become.

The scientific method begins with measurement and the acquisition of data in order to obtain information. How this is used to develop knowledge is best described by systems theorist Russell Ackoff [2]. Ackoff presented a hierarchy of processes that must occur in the human mind while travelling the along the path to understanding. Briefly they are:

(1) measurement/observation or the collection of data in the form of symbols

(2) information formation or the processing of data to create relationships

(3) knowledge formation or employing the data and information to construct plausible models

(4) development of understanding - using the models to make explanations and predictions

(5) development of wisdom, where universal principles are created

John Wheeler's approach to this is even simpler:

> "All things physical are information theoretic in origin and this is a participatory universe ... Observer participancy gives rise to information; and information gives rise to physics." [3]

But we must also realize that there are many participants who also are collecting information, storing it and processing it. Some of those participants may even be the objects we are studying. Having collected the data from measurements and/or observations, models are created that compress the information and data into its most useful and fundamental form. Here more processing is required to place the data into some context which becomes Ackoff's knowledge creation.

So far the process of collecting the data, and then making the interpretation as to the meaning of the data is common to all of the sciences. This is not just what natural scientists do but is what makes the social sciences (e.g. economics, linguistics, public administration, psychology, etc.) "scientific". What places it in the realm of physics can be summed up in the simple yet profound statement made by Rolf Landauer that "Information is physical" [4]. Information is transported, stored, retrieved and processed by physical entities, and those entities (paper, magnetic domains, DNA, electromagnetic waves, crystal orientations etc.), are by their nature, subject to the laws of physics and they must be understood within the context of both experimental and theoretical physics.

Accepting Kauffman's notion that life operates at the transition between stable and chaotic behaviour, and leads to emergent phenomena we must deal with this as a working hypothesis. Systems demonstrating emergent behaviour tend to be far from equilibrium. A number of these systems also tend toward showing what is known as power-law behaviour. Systems that exhibit power law behaviour in their probability distributions. (i.e. functions of the form $f(x) \approx x^{\alpha}$ for large values of x where in most cases $\alpha < 0$) include earthquakes, fluid turbulence, floods, commodity prices, word usage, solar flares, sizes of organisations just to name a few. This is quite different from the exponential probability Boltzmann distribution occurring in thermal equilibrium.

For large values of x the probability distributions decay to zero less rapidly than the exponential fall-off. How power law distributions arise remain a mystery since there seems to be no universal theory or model from which this behaviour can be derived. Certainly they cannot be explained by equilibrium statistical mechanics and it is for this reason that they are considered as being non-equilibrium systems.

One might expect that the standard Shannon-Gibbs-Boltzmann expression

$$H = -\sum_i p_i \log p_i$$

for entropy would require modification if not outright replacement. Here p_i is the probability distribution such that $\sum_i p_i = 1$ and the base of the logarithm is left unspecified to cover different situations (base 2 for Shannon, base e for Gibbs-Boltzmann).

One possibility is the use of Fisher information [5] developed in the 1920's by statistician and geneticist R.A. Fisher who defined information directly in terms of the data received by observer making a measurement.

The computation of I is defined in terms of a functional of the probability density function $p(x)$ i.e. it is an averaged value

$$I = \left\langle \left[\frac{d}{dx} \log p(x) \right]^2 \right\rangle$$

Therefore the "wider" the distribution of fluctuations the smaller is the derivative of its logarithm which creates a smaller value of I. I is therefore a quantitative measure of information. The properties of I are that is it monotonically decreasing function of t as opposed Boltzmann's entropy which is an increasing function of time.

A more recent possibility was introduced in 1988 by Tsallis [6] where the entropy of a system depends upon a parameter q.

$$S = \frac{1 - \sum_i p_i^q}{q - 1}$$

This can be shown to reduce to the Gibbs expression in the limit $q \to 1$. When the entropy is maximised, under suitable conditions the probability distributions are described by power laws when $q \neq 1$.

From such proposals and others it is clear that non-equilibrium systems will have valid information theoretic descriptions which ultimately will be governed by physical laws.

3. Life

Since living things are undergoing continuous evolution they exist in non-equilibrium states. It is clear that as long as the organism is living the Gibb's (or any) free-energy of the system cannot vanish ($\Delta G \neq 0$) since each organism must extract energy from the environment to grow and develop. Of course $\Delta G = 0$ is achievable, but this results in death. This in some sense introduces a universal law of biology, albeit a trivial one based upon classical thermodynamic theory. What is needed are non-trivial ones that most likely will reach out to a physical theory of information dynamics (that arguably has yet to be fully developed).

Just as the elementary particles, then nuclei, then atoms and eventually macroscopic objects evolved out of the hot "Big Bang" as the Universe cooled to permit their long term existence, life had to evolve out of a non-biotic world when the environment allowed it to do so. But where we think we understand the how the change in the magnitude of the ambient energy density of the expanding Universe allowed for different fundamental physical interactions to occur and survive, the transition from non-biotic to biotic behaviour remains mysterious. Some sort of selection process was present, in the most fundamental Darwinian sense. What ever started that evolutionary process, began something that continues to this day. So ubiquitous is biological evolution that Theodosius Dobzhansky has written an article entitled "Nothing in Biology Makes Sense Except in the Light of Evolution" [7] *The American Biology Teacher* 35, 125 (1973). This is used as the basis of the argument that to understand evolution is to understand life itself.

To go even further we might add that "nothing in evolution makes sense except in the light of information". What life and evolution is all about is the quasi-stable survival of self-replicating agents. This survival is differential in the sense that replicators must also compete against each other in addition to ensuring their survival in the ambient environment. In this sense selection is has both internal and external influences. This is a much different process than the simple condensation of elementary particles into nuclei into atoms into molecules and so on. These new objects must be capable of not only self-replicating but also ensuring their own survival against other similar objects and the prevailing environment.

In following Richard Dawkins who introduced the term "meme" in his book *The Selfish Gene*, to represent replicators of ideas or fashions or beliefs or anything that can be transmitted and replicated through communication (such as speech, rituals, the internet, etc.). Therefore genes (in the form of DNA, RNA) and memes (in the form of blueprints, recipes) are simply the media by which instructions are stored and transmitted. The instructions represent the information but the behaviour of the carriers which for living organisms consist of genetic material are as stated before, subject to the laws of physics. It would appear that what is true for genes is also true for memes. Computer viruses provide a good example of the latter. They carry instructional information from one host to another, they are self-replicating and they are able to fend off threats to their survival. Fortunately we can change their environment and/or through our own evolutionary abilities were are able to destroy them.

A law that mutating, replicators some how progress from a lower evolutionary state to a higher one through natural selection should be applicable not only here on Earth but through out the Universe. It might also apply to other systems, such as cultural evolution, the evolution of organisations such as clubs, financial institutions, governments, and networks ranging from the internet to terrorist cells and espionage agencies. While deceptively simple its full justification is likely to be extremely complex. It will require a theory that incorporates dissipative structures in non-equilibrium thermodynamics, auto-catalytic, self-replicating chemical processes, information generation, propagation, and reception in nonequlibrium situations, communication up and down the different hieracical scales, non-linear dynamics, internal and external selection criteria, and general mathematical theory of nonlinear systems.

It can be expected that to attempt to understand life will be one of the greatest challenges presented to physics. In doing so it is also likely that new insights and even new disciplines will emerge. With the appropriate processes in place, knowledge will evolve into understanding. Our understanding of Newtonian physics has allowed us to create structures for better living, and our understanding of quantum mechanics has provided us with "better living through chemistry", Hopefully our understanding of fundamental biology will provide even further prospects better living . But if we follow Ackoff's hierarchy discussed earlier what just might be ultimately possible in physics is the acceptance of the limitations physics presents and along with that wisdom.

References

1 Kauffman, S.A. it Reinventing the Sacred Basic Books, New York, (2009).

2 Ackoff, R. L., "From Data to Wisdom", Journal of Applied Systems Analysis, 16, 3, (1989) p 3-9.

3 Wheeler, J.A., "Information, Physics, and the Quantum", in *Complexity, Entropy and the Physics of Information* (W. Zurek, editor) Addison Wesley, Reading., MA, (1990).

4 Landauer, R. "Information is Physical", Physics Today, 44, 23 (1991)

5 Friedan, B. R. *Science From Fisher Information*, Cambridge Univ. Press, Cambridge, UK, (2004)

6 Tsallis, C. "Possible generalization of Boltzmann-Gibbs Statistics", J. Stat. Phys. 52, 479. (1988).

7 Dobzhansky T. 'Nothing in Biology Makes Sense Except in the Light of Evolution" The American Biology Teacher 35, 125 (1973). itself.