Paper Title: Physics and the Real World
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Abstract:
This talk will point out some of the ways that physics underlies the functioning of complex systems, including the human mind. The limits of reductionist physics in describing such systems will be considered. In particular it will be pointed out how present day physics gives a causally incomplete understanding of the real every-day world, because it does not comprehend human volition, which is clearly causally effective. Various aspects of and attitudes to this causal incompleteness will be considered.

Biography:
George F. R. Ellis, Ph.D., is professor of Applied Mathematics at the University of Cape Town. After completing his Ph.D. at Cambridge University with Dennis Sciama as supervisor, he lectured at Cambridge and has been visiting Professor at Texas University, the University of Chicago, Hamburg University, Boston University, the University of Alberta, and Queen Mary College (London University). He has written many papers on relativity theory and cosmology, among them *The Large Scale Structure of Space Time* co-authored with Stephen Hawking (Cambridge University Press,1973); *Before the Beginning: Cosmology Explained* (Merion Boyars, 1993); *Is the Universe Open or Closed? The Density of Matter in the Universe* with Peter Coles (Cambridge University Press, 1997); and *Dynamical Systems in Cosmology* with John Wainwright. He has also written on science policy and developmental issues, science education, and science and religion issues. He is co-author with Nancey Murphy of *On the Moral Nature of the Universe* (Fortress Press, 1996) and editor of *The Far-flung Universe: Eschatology from a Cosmic Perspective* (Templeton Foundation Press, 2002). He is past president of the International Society of General Relativity and Gravitation and of the Royal Society of South Africa and fellow of the Royal Astronomical Society and the Institute of Mathematics and its Applications. Among the prizes and honorary degrees he has received are the Claude Harris Leon Foundation Achievement Award, the Gold Medal of the South African Association for the Advancement of Science, and the Star of South Africa Medal, which was presented to him in 1999 by President Nelson Mandela. He is the recipient of the 2004 Templeton Prize.

Paper Text:

1: Physics and the everyday world

Physics is the model of what a successful science should be. It provides the base for the all other physical sciences and biology because all objects we see around us, including ourselves, are made of the same fundamental particles whose interactions are governed by the fundamental forces identified and investigated by physics.

The extraordinarily successful reductionist approach of present day physics is based on the concept of an isolated system. Experiments carried out on such systems enable the physicist to isolate and understand the fundamental causal elements underlying physical reality. However no real physical or biological system is in fact isolated, either physically or historically; in the real world, context matters as much as laws (Bishop 2005c). The physics approach tends to ignore three crucial features that enable the emergence of biological complexity out of the underlying physical substratum (Ellis 2004, 2005, Bishop 2005a): namely, top-down action in the hierarchy of complexity which affects both the context and nature of constituent parts, the causal efficacy of stored information (`memory effects'), and the origin of biological information through evolutionary adaptation (see Figure 1). These features enable the causal efficacy of emergent biological order, described by phenomenological laws of behaviour at each level of the hierarchy. Thus what occurs is *contextual emergence* of complexity (Bishop 2005a).

The higher level laws emerge out of the underlying physics, which establishes a possibility landscape (Ellis 2004) delineating possible ways of creating biological functionality (Vogel 1998, Conway Morris 2003). However the higher level properties are to a large degree independent of that underlying physics (Anderson 2005), which is why biologists don't need to study quantum field theory or the standard model of particle physics.

In this article I look at aspects of the properties of emergence, and consider some of its consequences for our understanding of causality. The key take-home message is that the *higher levels in the hierarchy of complexity have real autonomous causal powers, functionally independent of lower-level processes*. The underlying physics both enables and constrains what is possible at the higher levels, creating the possibility space of outcomes, but does not enable us to actually predict events in the everyday world around us, where human intentionality is causally effective. Physics does not causally determine the specific outcome of the higher level functioning that occurs in practice. I will clearly demonstrate this by considering the relation between initial data in the very early universe and the existence and functioning at the present time of truly complex systems that embody purposive action (such as ourselves).

I do not pursue here the further crucial issue of what features of fundamental physics make the emergence of complexity possible; for that discussion see for example Hogan (2000), Rees (2001a, 2001b), Quigg (2005).

2: Complexity and Hierarchical Structure

2.1 Hierarchy. True complexity, with the emergence of higher levels of order and meaning, including life, occurs in *modular hierarchical structures* (Simon 1962, Booch 1994). They are *structured* in that their physical nature reflects a precise ordering as in very large intricate networks, for example the micro-connections in a VLSI computer chip or amongst neurons in the human brain. Such systems are not complex merely because they are complicated; "order" means organization, in contrast to randomness or disorder. They are *hierarchical* in that layers of emergent order and complexity build up on each other, with physics underlying chemistry, chemistry underlying biochemistry, and so on (Peacocke 1990, Campbell 1991). Figure 2 gives a simplified representation of the hierarchy; for more detailed descriptions see Ellis (2002), Morowitz (2002). Each level is described in terms of concepts relevant to that level of structure (particle physics deals with quarks and gluons, chemistry with atoms and molecules, and so on), so a different descriptive language applies at each level. Thus we can talk of different levels of meaning embodied in the same complex structure.

This is the phenomenon of *emergent order*, with the higher levels displaying new properties not evident at the lower levels. As expressed by Campbell (1991, pp.2-3), *"With each upward step in the hierarchy of biological order, novel properties emerge that were not present at the simpler levels of organisation. These emergent properties arise from interactions between the components ... Unique properties of organized matter arise from how the parts are arranged and interact ... [consequently] we cannot fully explain a higher level of organisation by breaking it down to its parts".* One can't even describe the higher levels in terms of lower level language. Effective theories such as the Fermi theory of weak interactions, the gas laws, and Ohm's law give a phenomenological understanding of behaviour at higher levels (Hartmann 2001). The higher levels are more complex and less predictable than the lower levels: we have reliable phenomenological laws describing behaviour at the levels of physics and chemistry, but not at the levels of psychology and sociology. Thus this is a hierarchy of complexity.

Complex structures are *modular* in that each level is made up of more or less independent modules whose structure and behaviour can be studied in their own right - molecules are made of atoms, living bodies are made of cells, and so on; one can study atoms and living cells in their own right, and then see how they fit together to make molecules and bodies. There is no clear theoretical definition of true complexity, but for practical purposes it is a system that involves more than say 10^6 interacting active components.

A modular hierarchy represents a decomposition of a complex problem into constituent parts and processes to handle those constituent parts, each requiring less data and processing and more restricted operations than the problem as a whole (Booch 1994). This is clear for example in complex computer programs, which may have 15 million lines of code; they are only understandable because they are written in a modular way with numerous separate subroutines that can be each understood on their own. The success of hierarchical structuring depends both on implementing modules to handle lower-level processes, and on integration of these modules into a higher-level structure.

2.2 Higher Level Variables and Coarse Graining. The essential key to understanding emergent properties is *correct choice of higher-level variables*. It is not possible to understand or explain the emergent properties in terms of the lower level concepts and variables alone. Superfluidity, for example, cannot be deduced from the lower level properties of the quantum fluid alone (Laughlin 1999, 2005). The Hodgkin-Huxley equations governing membrane current propagation in neurons in the brain similarly do not follow from lower level properties alone: "The equations are not `ordinary laws of physics' (as Schrödinger pointed out) but `new laws' that emerge at the hierarchical level of the axon to govern the dynamics of nerve impulses. One cannot derive these new laws from physics and chemistry because they depend on the detailed organisation of the intrinsic proteins that mediate sodium and potassium current across the membrane and upon the geometric structures of the nerve fibers" (Scott 1995, pp. 52-53). In each case one can indeed derive physical arguments for the higher-level properties, but only by introducing suitable higher-level concepts not implied by the underlying physics.

Many higher level variables are functions of aggregated lower level variables, determined by them but by their nature abstracting important properties of the hierarchy that are otherwise hidden. These higher level variables are thus *coarse-grained versions of the lower level variables*: they represent the system as seen from the higher level view with many lower level (fine-grained) details averaged over. For example, gas pressure and density are macro-variables result from averaging over relevant micro-variables: numbers, masses, and momenta of constituent molecules in a given volume. A current flowing in a wire is represented at a macro-level by a number of amperes, representing the aggregate amount of charge flowing in the wire, but at the micro-level is described by a distribution of electrons in the wire. Stating the number of amperes flowing provides a useful coarse-grained description of the micro-situation. Together with the related resistance and energy variables, this choice gives phenomenological understanding of the higher level behaviour (the flow of current in a wire is related to the voltage and resistance). The loss of lower level information associated with this coarse graining (if we only know the current is 10 amperes, we don't know the detailed electron distribution) is the source of entropy – many lower level states correspond to the same higher-level state (Penrose 1989, 310-314). Consequently the higher level states are relatively insensitive to many details of the lower level state of the system.

Some causally effective higher-level variables however are not aggregated physical variables, but rather are *of a mental or abstract nature*, for example feelings of hate, the concept of a country, integral calculus, or the theory of the laser. They are causally effective because they are key elements in the functioning of the human mind in either a social or technological context. This is discussed below in Sections 3.7 and 4.4.

3 Bottom-up and Top-down action in the Hierarchy

The first key issue underlying complex emergent behaviour is the occurrence of both bottom-up and top-down action in the hierarchy.

Bottom-up action. What happens at each higher level is based on causal functioning at the level below, hence what happens at the highest level is based on physical functioning at the bottom-most level. When I move my arm, it moves because many millions of electrons attract many millions of protons in my muscles, as described by Maxwell's equations. Thus microphysics underlies macro effects. The successive levels of order entail chemistry being based on physics, material science on physics and chemistry, geology on material science, and so on. This is the profound basis for reductionist worldviews:

> "*The underlying physical laws necessary for the mathematical theory of a large part of physics and the whole of chemistry are thus completely known, and the difficulty is only that the exact application of these laws leads to equations much too complicated to be soluble*" (Dirac 1929, p.714, quoted in Bishop 2005a).

Top-down action. However additionally, higher-level structure together with the system's environment (which sets boundary conditions for physical variables) enable higher-level variables to influence lower-level variables by setting the context in which they function. This leads to downward causation (Campbell 1974) and contextual emergence (Bishop 2005a). For example, when I move my arm, it moves because I have decided to move it, thus in effect my intention is causally effective in terms of instructing many millions of electrons and protons what to do. This is possible because the detailed physical structuring of the hierarchical system, in this case the physiology of the nervous system, provides the context in which the lower level causality functions.

Top-down action affects the nature of causality significantly, because *inter-level feedback loops become possible* (Figure 3), *thereby modifying the properties of the constitutive elements at the lower levels*. For example, "the emergence of the novel entity water obliges the two component elements to a relatedness (chemical bonding and the corresponding mixing of the electronic orbitals) that profoundly affects the properties of both hydrogen and oxygen" (Luis 2002). A dramatic example is neutrons: they are unstable with a half life of 11 minutes when unbound, but stable with a half life of millions of years when bound into a nucleus. Electrons interact strongly with photons via Thomson scattering when free, but only weakly when bound into atoms (this transition from strong to weak coupling underlies the decoupling of matter and radiation in the early universe, allowing the start of structure formation by gravitational attraction). At a much higher level of complexity, an individual human mind is crucially affected by the society in which it develops (Berger and Luckmann 1967); you cannot understand a mind in isolation, because "the specific form of the modern mind has been determined largely by culture" (Donald 2001, p.153). At the foundations, classical physics emerges from quantum physics through the irreversible process of quantum decoherence, providing the basis for the very existence of independent component elements. This occurs through interactions with the environment that result from holistic features of quantum theory (Joos 1998, Zurek 2003). Thus complex systems are not just conglomerates of unchanged elementary constituents; rather by their constitution they profoundly affect the nature of the constituents out of which they are made.

Top-down action is prevalent in the real physical world and in biology. I will illustrate this with a series of examples.

3.1 Interaction potentials. Potentials in the Schrödinger equation, or in the action for the system, represent the summed effects of other particles and forces, and hence are the way the nature of both simple and complex structures can be described (from a particle in a box to the detailed structure of a computer or a set of brain connections). These potentials describe the summed interactions between microstates, enabling top-down effects by creating an ordered structure underlying causal relations (electrons flow in specific wires connecting specific components, neurons connect to specific other neurons, etc.). Additionally one may have external potentials representing top-down effects from the environment on the system, for example the gravitational field due to a massive planet alters the motions of particles in a laboratory located on the surface of the planet.

3.2 Nucleosynthesis and structure creation in the early universe. The rates of nuclear interactions depend on the density and temperature of the interaction medium. The nuclear reactions that take place in the early universe, and hence the elements produced in nucleosynthesis then, therefore depend on the rate of expansion of the universe, determined by macroscopic cosmological variables. Hence the resulting nuclear abundances can be used to determine to determine the average density of baryons in the universe – a key cosmological parameter (Silk 2001, p.144). Similarly the linearised equations for cosmological structure formation depend on the averaged quantities in the background cosmology (its density and expansion rate, for example), which therefore determine the nature of the perturbation solutions and the resulting formation of structure.

3.3 Quantum measurement. Top-down action occurs in the quantum measurement process - the collapse of the wave function to an eigenstate of a chosen measurement system (Penrose 1989, Isham 1997). The experimenter chooses the details of the measurement apparatus – for example, aligning the axes of polarisation measurement equipment - and that decides what set of microstates can result from a measurement process, and so crucially influences the possible outcomes of the interactions that happen. The choice of Hilbert space and the associated operators is made to reflect the experimenter's choice of measurement process and apparatus, thus reflecting this top-down action. Additionally top-down action occurs in state preparation: choosing and then enforcing the specific initial state of the system at the start of the experiment.

3.4 The arrow of time. Top-down action occurs in the determination of the arrow of time (Davies 1974, Zeh 1992). One cannot tell how a macro-system will behave in the future on the basis of the laws of fundamental physics and the properties of the particles that make up the system alone, because time-reversible micro-physics equally allows two solutions - one the time reverse of the other; but only entropy-increasing solutions in one direction of time occur at the macro-level. This does not follow from the micro-physical laws. Physically, the only solution to this arrow of time problem seems to be that there is top-down action by the universe as a whole, effective through boundary conditions at beginning and end of space-time, that allows the one solution and disallows the other (Penrose 1989).

3.5 Evolution. Top-down action is central to two main themes of molecular biology: first, the d*evelopment of DNA codings* (the particular sequence of base pairs in the DNA, see Figure 1) occurs through an evolutionary process which results in adaptation of an organism to its ecological niche (Campbell 1991). As a specific example: a polar bear *Ursus maritimus* has genes for white fur in order to adapt to the polar environment, whereas a black bear *Ursus americanus* has genes for black fur in order to be adapted to the North American forest. The detailed DNA coding differs in the two cases because of the different environments in which the respective animals live. This is a classic case of top-down action from the environment to detailed biological microstructure - through the process of evolutionary adaptation, the environment (along with other causal factors) fixes the specific DNA coding. *There is no way you could predict this coding on the basis of biochemistry or microphysics alone*.

3.6 Biological development. A second main theme of molecular biology is the reading of DNA in the cells in an organism during the processes of biological development. This is not a mechanistic process, but is context dependent all the way down (Keller 2000). The central process of developmental biology, whereby positional information determines which genes get switched on and which do not in each cell, so determining their developmental fate, is a top-down process from the developing organism to the cell, based on the existence of gradients of positional indicators (morphogens) in the body (Gilbert 1991, Wolpert 1998). Thus the crucial developmental mechanism determining the type of each cell in the body is controlled in an explicitly top-down way.

3.7 Mind on the world. When a human being has a plan in mind (say a proposal for a bridge being built) and this is implemented, then enormous numbers of micro-particles (comprising the protons, neutrons, and electrons in the sand, concrete, bricks, etc. that become the bridge) are moved around as a consequence of this plan and in conformity with it. Thus in the real world, the detailed micro-configurations of many objects (which electrons and protons go where) is determined by the plans humans have for what will happen, and the way they implement them. An example is the effect of human actions on the earth's atmosphere, moving many micro-particles (specifically, CFC's) around, thereby affecting the global climate. Macro-processes at the planetary level cannot be understood without explicitly accounting for human activity (Schellnhuber 2000).

The effectiveness of rationality: Concepts such as the plans for a Jumbo Jet, worked out on a rational basis through a process of computer aided design, are not the same as any specific brain states, for they can be represented in many different ways (in words, writing, diagrams, in computer memories associated with CAD programs, etc). Rather they are an abstract entity: an equivalence class of such representations. They are causally effective because they determine the nature of physical objects in the world: they guide the manufacture of material objects.

The effectiveness of emotions: Emotions both influence immediate behaviour in obvious ways ("She acted in anger", etc.), and also underlie brain development and intellect. Higher levels of order and meaning are developed through the basic emotions setting up implicit goals in the developing brain, which then guide neural development by providing the value system for the processes of neural Darwinism (Ellis and Toronchuk 2005). In this way basic emotions can be causally effective. Just as in the case of qualia such as perceived colour or pain, these are not the same as brain states, although they are associated with them.

The effectiveness of social constructions: Socially devised rules and regulations (housing policy, health care systems, etc.) govern social relations and many resulting actions. The rules of football and of chess affect what happens in physical terms when the corresponding games are played. The effectiveness of money, which can cause physical change in the world such as the construction of buildings, is based in social agreement. These are abstract variables based in social interaction over an extended period of time, and are neither the same as individual brain states, nor equivalent to an aggregate of current values of lower level variables (although they may be represented by, and causally effective through, such states and variables).

Causal models of the real world will be incomplete unless they include these various effects. Multiple top-down action from the mind co-ordinates action at lower levels in the body in a coherent way, and so gives the mind its causal effectiveness. Because of this the causal hierarchy bifurcates (see Figure 4). The left hand side, representing causation in the natural world, does not involve goal choices. The right hand side, representing causation involving humans, is to do with choice of goals that lead to actions.

Ethics is the subject shaping goals at the highest level of the causal hierarchy, which deal with life purpose and appropriate choice of lower-level goals. By determining the nature of lower level goals chosen, and thence the nature of resulting actions, ethics is a set of abstract principles that are causally effective in the real physical world, indeed they crucially determine what happens. For example the jails in a country will contain physical apparatus such as a gallows or an electric chair only if the ethics of that country allow the imposition of the death penalty; they will not exist in countries where this is not regarded as acceptable. Wars will be waged or not depending on ethical stances.

4: Feedback control systems and information

The second key issue underlying complex emergent behaviour (already alluded to above) is the existence of a hierarchy of goals that are causally effective, because they are the key to the functioning of feedback control systems.

4.1 Feedback control. The central feature of organised action is *feedback control*, whereby setting of goals results in specific actions taking place that aim to achieve those goals (Ashby 1958, Beer 1966, 1972). A comparator compares the system state with the goals, and sends an error message to the system controller if needed to correct the state by making it a better approximation to the goals (Figure 5). Examples are controlling the heat of a shower, the direction of an automobile, or the speed of an engine.

4.2 The role of goals and information. The series of goals in a feedback control system are causally effective. They embody information about the system's desired behaviour or responses – indeed living systems are goal seeking ('teleonomic'). These goals are not the same as material states, although they will be represented by material states and become effective through such representations (e.g. the desired temperature of water may be set on a thermostat, and represented to the user on a dial; the thermostat setting is itself a representation of the desired goal). A complete causal description of such systems must necessarily take such goals into account.

The crucial issue now is what determines the goals: where do they come from? Two major cases need to be distinguished.

4.3 Homeostasis: In-built goals. There are numerous systems in all living cells, plants, and animals that automatically, without conscious guidance, maintain homeostasis - they keep the structures in equilibrium through multiple feedback loops that fight intruders (the immune system), control energy and material flows, breathing, the function of the heart, etc. (Milsum 1966). They are effected through numerous enzymes, anti-bodies, and regulatory circuits of all kinds, for example those that maintain body temperature and blood pressure. They have developed in the course of time through the adaptive processes of evolution, and so are historically determined in particular environmental context, and are unaffected by individual history. Their existence is genetically determined.

Not only are the feedback control systems themselves emergent systems, but also *the implied goals are emergent properties that guide numerous physical, chemical, and biochemical interactions in a teleological way*. They embody biological information guiding the development of plants and animals (Kuppers 1990); for example the information in DNA, embodied in the specific sequence of base pairs, guides the process of protein synthesis in cells through controlling construction of a specific sequence of amino acids according to the genetic code, thus determining cell type and function. A series of feedback control mechanisms check that this information is correctly read when proteins are made and correctly replicated when DNA is duplicated. Thus biological information is causally effective through feedback control processes.

4.4 Goal seeking: Socially and mentally determined goals. However at higher levels in humans and animals, important new features come into play: there are now individual behavioural goals that are not genetically determined. Many of them are conveyed to individuals through a variety of social mechanisms by which they become internalised (Berger 1963, Chapter 5); others are learnt or consciously chosen. *It is in the choice and implementation of such goals that explicit information processing comes into play*. Information arrives from the senses and is analysed, sorted, and either discarded or stored in long term and short term memory, from whence they help guide future behaviour. Thus humans are *information gathering and utilising systems* (Fernandez and Sole 2003; Hartle 2004). This is a highly non-linear process which is non-local in both space and time. Conscious and unconscious processing of this information sets up the goal hierarchy, which then controls purposeful action in individual and social life. They may or may not be explicitly formulated.

At the highest level, the process of analysis and understanding is driven by the power of symbolic abstraction, codified into language embodying both syntax and semantics (Deacon, 1997). This underpins other social creations such as specialised roles in society and the monetary system, and higher-level abstractions such as mathematics, physical theories, philosophy, and legal systems – all encoded in symbolic systems. They gain their meaning in the context of a shared world-view and cognitive framework that is imparted to each individual by the society in which they live through many social processes (Berger and Luckmann 1967).

These are all non-physical entities that are causally effective in terms of guiding human actions, e.g. physical theories such as electromagnetic theory and thermodynamics underlie the development of technology that enables transformation of the environment. They are created and maintained through social interaction and teaching, and are codified in books and sometimes in legislation. Thus while they may be represented and understood in individual brains, their existence is not contained in any individual brain and they certainly are not equivalent to brain states (electromagnetic theory for example is not the same as any individual's brain state). Rather the latter serve as just one of many possible forms of embodiment of these features (they are also represented in books, journals, CDs, computer memory banks, diagrams, the spoken word, etc).

Thus concepts can exist in their own right, independent of any specific realisation or representation they may be given in specific circumstances. Indeed they can be transformed between many such different representations precisely because they are independent of any single one of them. They are socially agreed to, and exist in a world of social constructions (Ellis 2004).

5: The nature of causality and explanation

The key point about causality in this context is that simultaneous multiple causality (inter-level, as well as within each level) is always in operation in complex systems. Thus one can have a top-down system explanation as well as bottom-up and same level explanations*, all three being simultaneously applicable.*

Reductionist analysis `explains' the properties of the machine by analysing its behaviour in terms of the functioning of its component parts (the lower levels of structure). Systems thinking tries to understand the properties of the interconnected complex whole (Churchman 1968, Flood and Carson 1990), and `explains' the behaviour or properties of an entity by determining its role or function within the higher levels of structure (Ackoff 1999). For example, the question: `Why is an aircraft flying?' can be answered,

· In *bottom up terms*: it flies because air molecules impinge against the wing with slower moving molecules below creating a higher pressure as against that due to faster moving molecules above, leading to a pressure difference described by Bernoulli's law, this counteracts gravity, etc.;

· In terms of *same-level explanation*: it flies because the pilot is flying it, after a major process of training and testing that developed the necessary skills, and she is doing so because the airline's timetable dictates that there will be a flight today at 16h35 from London to Berlin, as worked out by the airline executives on the basis of need and carrying capacity at this time of year;

· In terms of *top-down explanation*: it flies because it is designed to fly! This was done by a team of engineers working in a historical context of the development of metallurgy, combustion, lubrication, aeronautics, machine tools, computer aided design, etc., all needed to make this possible, and in an economic context of a society with a transportation need and complex industrial organisations able to mobilise all the necessary resources for design and manufacture. A brick does not fly because it was not designed to fly.

These are all simultaneously true non-trivial explanations; *the plane would not be flying if they were not all true at the same time.* The higher level explanations rely on the existence of the lower level explanations in order that they can succeed, but are clearly of a quite different nature than the lower level ones, and are certainly not reducible to them nor dependent on their specific nature. The bottom-up kind of explanation would not apply to a specific context if the higher level explanations, the result of human intentions, had not created a situation that made it relevant.

6 Physics and higher level causality

6.1 Human Intentionality. The higher-level feature of human consciousness is clearly causally effective in the world around us: we live in an environment dominated by manufactured objects that embody the outcomes of intentional design (buildings, motor cars, books, computers, clothes, teaspoons). The issue then is that the present-day subject of physics has nothing to say about the intentionality resulting in existence of such objects. Even if we were to attain a "theory of everything" such as string/M-theory (that is, a comprehensive theory of fundamental physics, as described in Greene 2003) this situation would remain unchanged: physics would still fail to comprehend human purpose, and hence would provide a causally incomplete description of the real world around us. This situation is characterised by the self-referential incompleteness of physics: *there is no physics theory or experiment that can determine what will be the next experiment to be undertaken by the experimenter or theory to be created by the theorist.* If physics were causally complete, this would not be the case.

6.2 Aspects of causal incompleteness. There are three different aspects to this causal incompleteness of physics. Firstly, as regards the present day subject of physics, this is an incontrovertible statement of fact. There is no current physics theory or experiment that explains the nature of, or even the existence of, musical symphonies, football matches, teapots, or jumbo jet aircraft.

Secondly, one can ask if the present day subject of physics could be extended to actually incorporate such features? The minimum requirement in order to have any hope of doing so would be to extend physical theory to include relevant higher-level variables, as happened in the past when the higher level variables of entropy, specific heat, etc. were introduced into physics in order to explain the corresponding macroscopic physical effects. In the present case, the minimal need would be to include a function (`conscious intention'), to some degree dependent on lower-level variables, that would at least in principle be able to comprehend higher-level mental effects. One would then look for mathematical equations reliably predicting the evolution of this variable, or at least showing how it is related in principle to lower-level variables. I suspect that most physicists would regard this ambitious project as lying outside the proper scope of physics. It will in any case be too complex to be practicable.

However there is a third aspect – that of basic principle. Brains are networks of neural cells, so some claim there's nothing in principle to stop us from fully understanding them. You just need to know enough about the state of the brain and the person's previous experience to apply physics and predict future behaviour. There is no evidence that the mind is free of the determinism of biological and physical processes (there's no ghost in the machine). Thus one can propose that our universe is an immensely complicated system that could in principle be understood (though obviously not by mere human brains) by 'bottom up' physical causation alone. Predicting human intentionality is difficult only because we don't know enough about brains to make the calculation. The thing is doable in principle, though not in practice; physics causes all that happens even if the outcome is not predictable in practice. In the end, physics is all there is, and by itself controls the outputs of the brain. Free will is an illusion.

Despite its appeal to some, this kind of claim is in fact an unproveable philosophical supposition about the nature of causation, with zero predictive ability (no observable consequences follow from it) and no experimental proof directly supporting it. On the contrary, everyday experience regarding our intentional actions suggests this belief is wrong (Pink 2004). The key issue is whether the higher levels in the hierarchy of complexity have real autonomous causal powers, largely independent of the lower levels and indeed controlling their context and hence their outcomes, or whether all the real causal powers reside at the lower levels and the higher levels dance to their algorithmic tune, merely appearing to have autonomy.

6.3 The cosmic context. To fully see the improbability of the latter view, one can contemplate what is required from this viewpoint when placed in its proper cosmic context (see Figure 6). The essential implied claim is that the particles that existed at the time of decoupling of the Cosmic Background Radiation in the early universe (Silk 2001) just happened to be placed so precisely that they made it inevitable that fourteen billion years later, human beings would exist and Crick and Watson would discover DNA, Townes would conceive of the laser, Witten would develop M-theory.

This is patently absurd. It is inconceivable that truly random quantum fluctuations in the inflationary era can have had coded in them the future inevitability of the Mona Lisa, Nelson's victory at Trafalgar, Einstein's 1905 theory of relativity. Such later creations of the mind are clearly not random, on the contrary they exhibit high levels of order embodying sophisticated understandings of painting, military tactics, and physics respectively, which cannot possibly have directly arisen from random initial data. This proposal simply does not account for the origin of such higher-level order.

6.4 The Logical Options. To explore this further, consider the logically possible options (Figure 7). The first is that the order we see today is only apparent, but is not real; in fact there is no order underlying what we see around us today. I include this only for completeness, because some people claim to support this view. However in my view it is simply incoherent; we could not be engaged in rational discussion if it were true..

The second is that there was in fact a high level of order imbedded in the data at the time of decoupling, originating in quantum fluctuations at the end of inflation that also explicitly had high levels of order imbedded in their structure. This could have happened either by pure chance, or because some agency placed that order there. The `chance' option is so unlikely that it is reasonable to discount it (`chance' initial data would have to fully account for every apparently rational human action in the past, present, and future). The `agency' option denies the standard assumption that quantum fluctuations are random, and will be rejected out of hand by most physicists because it introduces a causal element from outside physical theory into the early universe. Furthermore, the early universe perturbations could not even have been structured on purpose by any agent to give these later outcomes. Apart from the undoable computational task of determining the required initial positions and velocities for the particles to give this detailed later outcome, and the incredible fine tuning then required to place them correctly to make it happen, both quantum uncertainty on the one hand and the existence of chaotic systems that affect human life and biological evolution (such as the atmospheric physics underlying weather) on the other would prevent this Laplacian mechanical prediction from in fact working out. The computation would in effect broaden out into all possible Everett multiple universes, with corresponding uncertainty of outcome. The required detailed causality and predictability from the bottom up is unattainable even in principle.

Thus this option is not credible. There is a further nail in its coffin. If this option were true, then for example the data required to lead to Einstein's 1905 paper on Special Relativity would be hidden in the perturbations at the LSS in the early universe, and we would in principle be able to find its traces hidden in the Cosmic Background Radiation anisotropies measured by instruments in balloons/satellites such as COBE, WMAP, and Planck (Silk 2001). Indeed the data for all past, present and future theories of physics would be there. But if the holographic principle in cosmology is true as proposed by many physicists (Susskind and Lindesay 2005), then there is a strict bound to the amount of data that can be present on the LSS (Hogan 2004). Given that this data has to provide for predictions of all conscious events not only on this planet but on all other planets within our visual horizon, there simply is not enough data there to do the job.

It is far more likely that the third option is the true situation: conditions at the time of decoupling of the Cosmic Background Radiation in the early universe 14 billion years ago were such as to lead to the eventual development of minds that are autonomously effective as they seem to be, able to create higher-level order without any fine dependence on lower level physical laws or initial data because of the precise biological structuring of the brain. Coarse-graining in the brain relates many higher-level variables to lower-level variables and feedback control implements higher-level goals, both features damping out the effects of lower level statistical fluctuations and of quantum uncertainty, allowing autonomous functioning of the brain so as to handle high level abstract concepts.

One cannot understand or predict a mind's behaviour without taking into account its interaction with other minds and with symbolic entities such as language and news items. You don't even know what aspects of the world are relevant unless you understand this social context. Predicting probable outcomes of the workings of the brain would be possible only if we were to take into account the higher-level entities that in fact shape its outcomes, including abstractions such as the value of money, the rules of chess, local social customs, and socially accepted ethical values. These kinds of concepts are causally effective but are not physical variables – they all lie outside the conceptual domain of physics, and have only come into existence as emergent entities within the past few thousand years. They are not explicitly encoded in the physical initial data. You can't predict the future on the basis of the lower level structures alone, you have to also include the effects of causally relevant higher-level structures; but unless you understand those structures at their own level, you don't know what aspects of the lower level variables are relevant. Not only are they needed for any serious attempt at prediction, but they play an essential part in causation whether the outcome is predictable or not.

Reductive physics characterizes part of the causal nexus in operation in the workings of the brain - the bottom up aspects - but not all of it. It cannot comprehend crucial top-down influences in operation, such as those mentioned above, which determine which of the physically possible outcomes actually occur. And above all, we should not too hastily conclude we can understand what is going on in the brain on the basis of physics alone until we properly understand the issues of consciousness and free will. Despite some extravagant claims made by a few adventurous souls, we actually don't have a clue how consciousness emerges from the underlying physics; we don't even know the appropriate questions to ask (Chalmers 1997).

6.5 Other adaptive behaviours and contexts. What about animal minds? Many animals have sophisticated social and mechanical skills - they make tools for a purpose, form social hierarchies, etc. If physics can't account for human intentions, can it account for these behaviours? Reflection will show that the same argument above regarding the cosmic context applies here too: physical conditions at decoupling in the early universe cannot possibly have been fine-tuned enough so as to produce the dance of a bee or the web of a spider. But the physical conditions at decoupling, if fully known, could have been used to predict what would happen in the very next instant. And one might suppose that the events in that next instant could have been used to predict the next instant, and so on, right through to the dancing bee. But that isn't true because *the everhigher levels of interactions create results that are unpredictable from the vantage point of the lower levels, and indeed are not causally determined by them*, although the underlying physics implies constraints on what is possible, for example energy conservation must hold.

Physics by itself cannot causally account for any animal behaviour that is adaptive and depends on context, for example beaver dam-building, bird nest-building, or cooperative hunting by whales. These too emerge as higher-level autonomous behaviours of biological structures, made possible but not causally determined by the workings of the underlying physics and chemistry. Indeed physics and chemistry by themselves cannot even determine the development or functioning of a single living cell, for that depends on its biological context (where the cell is located in an animal and what the animal is presently doing, for example) - which can only be understood in terms of higher levels of description. In summary, the feature that "the whole is greater than the sum of the parts" is truly potent in the real world. In the influential book *What is Life* that played a key role in the molecular biology revolution, Erwin Schrödinger wrote:

> *"From all we have learnt about the structure of living matter, we must be prepared to find it working in a manner that cannot be reduced to the ordinary laws of physics. And that not on the ground that there is any `new force' or what not, directing the behaviour of the single atoms within a living organism, but because the construction is different from anything we have yet tested in a laboratory"* (Schrödinger 1967, p.81).

Where then is the cut-off point in the biological hierarchy above which reductive physics does not determine behaviour? It is the level of *supra-molecular chemistry*, the first level at which biological information becomes effective and adaptive evolution is possible (Lehn 1995). At and above this level, historical and biological context are the main determinants of what actually happens in living systems, out of all the possibilities allowed by the underlying physics; for example the detailed sequence of bases in a strand of DNA cannot be predicted by physics alone. The higher-level evolutionary context is a key determinant, which in the case of human DNA includes crucial cultural aspects such as the development of symbolic understanding. However the concept of emergence is important even in the relation of simple chemical systems to quantum mechanics (Bishop 2005a); according to Luisi (2002), "emergence is a basic characteristic of the molecular sciences in general and chemistry in particular" (see also Earley 2003). Another example where the key concepts of emergence characterised above occur (namely feedback loops, inter-level relations, wholes constraining and modifying the behaviour of their parts, and memory effects) is Rayleigh-Benard convection (Bishop 2005b).

6.6 Rationality and Science. Finally, we should recognize that the enterprise of science itself does not make sense if our minds cannot rationally choose between alternative theories on the basis of the available data, which is indeed the situation if one takes seriously the bottom-up mechanistic view that the mind simply dances to the commands of its constituent electrons and protons, algorithmically following the imperatives of Maxwell's equations and quantum physics. A reasoning mind able to make rational choices is a prerequisite for physics to exist.

Just as there is a measurement problem underlying quantum theory: in essence, quantum theory does not seem able to describe the workings of the macroscopic measuring apparatus (Penrose 1989), so is there one underlying physics overall. In essence, physics does not seem able to account for the ability of the experimenter first to choose what to do, then to set up the apparatus as desired and to voluntarily carry out the appropriate series of measurements, and finally to rationally determine the scientific implications of the results.

Physics underlies emergent biological complexity, including the physicist's mind, but does not comprehend it. The emergent higher levels of causation are indeed causally effective and underlie genuinely complex existence and action, even though these are not contained within the physics picture of the world. The essential proof that this is so is the fact that coherent, experimentally supported scientific theories, such as present-day theoretical physics, exist. They have emerged from a primordial state of the universe characterised by random perturbations that cannot in themselves have embodied such higher level meanings.

6.7 The essential issue. The topic discussed here is significant because it addresses an ultimate question: how deep in the layers do you need to go, beyond which physics cannot account for cause/ effect relations. The issue is not just that you go on until the messiness of nature gets in the way of uncovering the cause/effect chain in many processes, when they can't be isolated from the world. It is that the higher level properties themselves, including abstract theories and other social constructions, are key variables in the causal chain; you can't understand what is going on or make any predictions without approaching it at the correct causal level that makes clear what are the significant higher-level variables.

Paradoxically, while the higher-level properties emerge from the lower-level processes, they have a degree of causal independence from them: they operate according to their own higher-level logic. According to Physics Nobel Prize winner Philip Anderson, "*Large objects such as ourselves are the product of principles of organisation and of collective behaviour that cannot in any meaningful sense be reduced to the behaviour of our elementary constituents. Large objects are often more constrained by those principles than by what the principles act upon*" (Anderson 2005; see also Laughlin 2005).

Physics makes possible, but does not causally determine the higher-order layers of structure and meaning. It cannot replace psychology, sociology, politics, and economics as autonomous subjects of study.

7 The technical challenge

7.1 Existence and Uniqueness theorems. The technical challenge to physicists is to see how this all relates to the existence and uniqueness theorems of physics (see e.g. Hawking and Ellis 1973), which are the theoretical results underlying the belief that physics provides a complete causal description of all that happens, once we are given sufficient initial data. There are several ways in which these theorems are not applicable to the real physical world.

7.2 Quantum uncertainty. First, there is quantum uncertainty: at a micro level, what happens is determined by probabilistic equations, or more precisely by a set of deterministic equations determining the evolution of the wave function, plus a measurement process whose outcome is only determined in a probabilistic way (Penrose 1989). Thus the ability to predict the future on a micro scale leads to a rapidly diverging set of outcomes as we consider the result of more and more quantum processes as time progresses. They are in a sense the full family of Everett multiple universes, but the problem with the multiple universe scenario (i.e. the claim that they all exist physically) is that it does not help us predict which will be the single one that we will in fact experience (Isham 1997).

Thus quantum theory profoundly denies the possibility of determining a single physical outcome from given initial data, and the longer the time involved, the greater is this uncertainty. On a large scale, in many circumstances statistical physics results will apply and this uncertainty will wash out. However there are other circumstances where this is not the case, for example where there is a photomultiplier or other amplifying device active; a CCD will provide a digital image from single photons that can then be amplified digitally or electronically. One case where this is significant in biology is in the effects of quantum fluctuations on DNA, where the biological developmental process acts as the amplifier (Percival 1991). This result alone already shows that physics per se is causally incomplete in the biological context, in that it determines a whole family of possible outcomes from given initial data rather than a single biological outcome. It is certainly conceivable that quantum fluctuations will affect the outcome of brain micro-operations as well, for example quantum photo-detectors in the eye can react to individual photons.

7.3 Chaotic systems. Second, chaotic systems exist in significant biological contexts, for example the physical processes governing the weather on earth, where in-principle predictability is in fact not attainable because the data can never be known to the required level of accuracy. While one can still contemplate that the system is `in principle' deterministic despite this `in practice' unknown outcome, that is only possible when we ignore quantum fluctuations. In fact quantum randomness will ensure that effective classical initial data cannot even in principle be prescribed to indefinite accuracy. Thus chaotic systems act as amplifiers of quantum uncertainty. This can have a major impact on the evolution of life because climate and weather do indeed seriously affect animal survival probabilities.

7.4 Realistic physical descriptions. However, neither of these are crucial to what we are discussing here, nor is the literature on catastrophe theory, pattern formation due to the reaction diffusion equation, structure in sandpiles, properties at the edge of chaos, and so on, even though they do characterize important effects arising from non-linearity. The key issue is that the equations of state usually assumed in the existence and uniqueness theorems are highly simplified, and simply do not allow for the kinds of complex hierarchical physical structuring actually present in biological systems. Consequently they cannot account for top-down action in a hierarchy with coarse-graining of variables, feedback control loops, and stored information, resulting in structural influence of large-scale, non-local influences on parts (Bishop 2005b). The challenge is to derive equations that adequately represent causation in these systems, and then to see how they can allow true novelty to emerge that was not in fact inherent in the initial data.

The kind of issue that comes up is first the existence and function of various typical motifs that occur in networks at many levels (Kashtan et al 2003, Berg and Lassig 2004), with associated modularity (Sole and Fernandez 2003), topology (Klemm and Bornholdt 2004), and hierarchical structuring (Itzkovitz et al 2004, Costa 2005, Newman 2005). Second the study of evolutionary trajectories in rugged fitness landscapes (Jain and Krug 2005), the nature of those landscapes being determined by the underlying physical forces and potentials (Hogan 2000). An essential role is played by Darwinian-like processes of natural selection, resulting in the accumulation of order and information as hierarchical modular structures develop. These processes are tremendously effective at all levels, playing a role not merely in the emergence of biological order (Campbell 1991) but also in the emergence of classicality from the underlying quantum physics through quantum decoherence (Zurek 2003) and in protein folding (Dobson 2004, Boshoff et al 2004). They underlie the functioning of the adaptive immune system (Burnett 1959) and structure neural connectivity in the brain (Ottersen 2005, Ellis and Toronchuk 2005).

How this works in physics terms – what effective equations relate what variables in this context, and what are the properties of these equations - is the real challenge facing us in relating physics to complexity. The usual uniqueness theorems do not apply to such systems, precisely because the higher structural levels that come into being through this process (including protein folding, cell structure, and the structuring of the brain) are causally effective and lead to emergence of true novelty. A key physical concept in the development of complex systems is that of *broken symmetries*: the systems studied do not have the symmetries of their underlying equations (Anderson 1972, 1991). This allows new properties to emerge in a system over time as boundary conditions change. However to relate to true complexity, that process needs to be related to the Darwinian processes outlined above.

7.5 A Computational Example: Neural networks. A useful stepping stone is considering the case of neural networks implemented on digital computers, which are a particular case of hierarchically structured complex systems (Tannenbaum 1990). At the bottom-most (machine code) level, computers work in a purely algorithmic way: so the simulated neural networks are the outcome of the bottom-up action of deterministic binary machine operations. At the simulation level, there are no algorithms that can predict what the outcome of a neural net will be (if there were, there would be no need to construct the neural networks themselves).

This non-algorithmic outcome is possible because neural networks incorporate higher order goals into their operation through the process of training, where information from the environment is used to structure the network connection strengths on the basis of a chosen value system. A key issue here is that when neural networks have to determine this structure on the basis of two competing objective functions, the usual back-propagation algorithms for determining connection strengths do not work (J Greene, private communication). Rather one has to use a form of genetic algorithm (Mitchell

1998), showing yet again how Darwinian principles of selection are the crucial structuring feature in the organisation of complexity.

Consequently neural networks can be self-organising complexes (Carpenter and Grossberg 1991) whose final detailed structure is determined top-down by the interaction with the environment. Each micro-step at the lower levels is physically determined; taken together they allow the higher levels of behaviour (e.g. pattern recognition) to come into being. This result occurs because of the interactions between the underlying particles, forces, and potentials that underlie the computer's physical structure, but the outcome is dependent on the context in which the system functions as well as its specific structure.

Placing this in its cosmological context, the computer itself has come into being as an emergent entity allowing this kind of higher-level function, even though there was no pre-image of either the computer or its software imbedded in the density and velocity perturbations on the surface of last scattering in the early universe. Physical theory per se cannot explain either the existence or structure of digital computers – they are not the outcomes of any known kind of physics existence theorems. This must necessarily be the case, because they are not the causal outcome of the functioning of physical forces alone.

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