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Physics and the Real World

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Physics and chemistry underlie the nature of all the world around us, including human brains. Consequently some suggest that in causal terms, physics is all there is. However, we live in an environment dominated by objects embodying the outcomes of intentional design (buildings, computers, teaspoons). The present day subject of physics has nothing to say about the intentionality resulting in existence of such objects, even though this intentionality is clearly causally effective. This paper examines the claim that the underlying physics uniquely causally determines what happens, even though we cannot predict the outcome. It suggests that what occurs is the contextual emergence of complexity: the higher levels in the hierarchy of complexity have autonomous causal powers, functionally independent of lower level processes. This is possible because top-down causation takes place as well as bottom-up action, with higher level contexts determining the outcome of lower level functioning and even modifying the nature of lower level constituents. Stored information plays a key role, resulting in non-linear dynamics that is non-local in space and time. Brain functioning is causally affected by abstractions such as the value of money and the theory of the laser. These are realised as brain states in individuals, but are not equivalent to them. Consequently physics per se cannot causally determine the outcome of human creativity, rather it creates the possibility space allowing human intelligence to function autonomously. The challenge to physics is to develop a realistic description of causality in truly complex hierarchical structures, with top-down causation and memory effects allowing autonomous higher levels of order to emerge with genuine causal powers.

KEY WORDS: Physics; emergence; causality.

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

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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; biological systems are open systems,(19) and in the real world, context matters as much as laws.(13) The physics approach tends to ignore three crucial features that enable the emergence of biological complexity out of the underlying physical substratum:(13, 34) namely, top-down action in the hierarchy of complexity, which affects both the operational context and nature of constituent parts; the causal efficacy of goals and information; and the origin of biological structure and information through evolutionary adaptation. These features enable the causal efficacy of emergent biological order, described by phenomenological laws of behaviour at each level of the hierarchy. What occurs is *contextual emergence* of complexity,(13) crucial to the nature of the everyday world around us.

The higher level laws emerge out of the underlying physics, which establishes a possibility landscape(33) delineating possible ways of creating biological functionality.(23, 94). However, the higher level properties are largely independent of that underlying physics,(4) which is why biologists do not need to study quantum field theory, the standard model of particle physics, or nuclear 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 (e.g., future prices on the New York Stock Exchange), where human intentionality is causally effective. Physics *per se* does not even causally determine the specific outcome of the higher level functioning.

I will 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, e.g., Refs. 49, 76, 78, 79).

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*.[15, 87] They are *structured* in that their physical nature reflects a precise ordering as in very large intricate networks, for example the microconnections 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.[19, 71] Figure 1 gives a simplified representation of the hierarchy; for a more detailed description see, Ref. 68. 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.[2] 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,[19]

"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 cannot 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.[47] 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

[2] A clear example of such a language hierarchy occurs in digital computers.[91]

Level 8: Sociology/Economics/Politics
Level 7: Psychology
Level 6: Physiology
Level 5: Cell biology
Level 4: Biochemistry
Level 3: Chemistry
Level 2: Atomic Physics
Level 1: Particle physics

Fig. 1. A hierarchy of structure and causation. A simplified representation of the hierarchy of structure and causation for human beings. Each lower level underlies what happens at each higher level, in terms of physical causation. For a more detailed exploration of this hierarchy, see http://www.mth.uct.ac.za/~ellis/cos0.html.

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 such 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.[15] 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. Modules can be modified and adapted to fulfil new functions, enabling great flexibility as complex structures adapt to a changing environment.

2.2. Higher Level Variables and Coarse Graining

The essential key to understanding emergent properties is *correct choice of higher level concepts and associated 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.[61, 62] 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 Schr¨odinger 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" (Ref. 85, 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). Thus higher level variables can be considered as active agents in determining the causal outcome (a higher voltage produces a higher current, giving more heat, etc).

The loss of lower level information associated with this coarse graining (if we only know the current is 10 A, we do not know the detailed electron distribution) is the source of entropy—many lower level states correspond to the same higher level state (Ref. 72 pp. 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 concepts and variables, however, are associated with collective effects that appear to be more than just coarse-grainings or aggregates (see, e.g., Ref. 13 for the case of downward causation in convective fluid dynamics). Their very nature depends on the higher level structure. Furthermore some higher level variables are not physical variables at all, but rather are *of a mental or abstract nature*, for example feelings of hate, the concept of a country, the concept of an electromagnetic field, differential and integral calculus and the theory of the laser. They are themselves hierarchically structured, and are causally

effective because they are key elements in the functioning of the human mind in either a social or technological context.

3. BOTTOM-UP AND TOP-DOWN ACTION

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

3.1. 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 physicalist 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" (Ref. 27, p. 714).

3.2. 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* (18) and *contextual emergence*. (13) 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.

3.3. The Effects of Top–Down Action

Top-down action affects the nature of causality significantly, because *inter-level feedback loops become possible* (Fig. 2). Additionally, *top-down*

Level 3
Level 2
Level 1
Bottom-up action only. Bottom-up and Top-down action.
(a) (b)
Fig. 2. Bottom-up and Top-down action. The fundamental importance of top-down action is that it changes the causal relation between upper and lower levels in the hierarchy of structure and organisation (cf. the difference between Fig. 2a and Fig. 2b).

(*contextual*) *effects modify 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". (65) A dramatic example is the properties of neutrons, which together with protons form atomic nuclei: they are unstable with a half-life of 11 minutes when unbound, but stable with a half-life of billions of years when bound into a nucleus. This plays a key role in underlying the stability of chemical elements, thus allowing the existence of life. Crucial to daily physics is the fact that electrons interact strongly with photons (via Thomson scattering) when free, but only weakly when bound into atoms; the interaction of matter and light is completely different when electrons are free compared with when they are incorporated in ordinary matter. The resulting transition from strong to weak coupling as matter and radiation cool in the early universe underlies the decoupling of matter and radiation, allowing the start of structure formation by gravitational attraction. (29, 86) A change of context results in a major difference in the physical behaviour of constituent elements, with a different physical understanding of the interactions (Thomson scattering gets replaced by spectral theory) described by quite different equations. At a much higher level of complexity, an individual human mind is crucially affected by the society in which it develops; (12) for example the language it uses as a basis for understanding is culturally determined. Indeed you cannot understand a mind in isolation, because the specific form of the modern mind has been determined largely by culture. (30, 80) At the largest scales, the cosmological context influences the nature of local physics through top-down action. (32, 37) At the foundations, classical physics emerges from quantum physics through an 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. (53, 97) Thus *complex systems are not just conglomerates of unchanged elementary constituents; rather by their specific structuring, at all scales they profoundly affect the nature of the constituents out of which they are made*.

3.4. Examples of Top-Down Action

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

3.4.1. 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.

3.4.2. 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 the average density of baryons in the universe—a key cosmological parameter. (29, 86) Similarly the linearised equations for cosmological structure formation depend on the averaged quantities in the background universe (its density and expansion rate, for example), which therefore determine the nature of the perturbation solutions and the resulting formation of structure in the expanding universe. (29, 58)

3.4.3. 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. (50, 72, 73) 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. The von Neumann interpretation of quantum mechanics emphasises the role of the mind in setting up the experiment. (89)

3.4.4. The Arrow of Time

Top-down action occurs in the determination of the arrow of time. (25, 96) 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 alone. 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. (37, 72) Global context makes a fundamentally important difference to local physical behaviour.

3.4.5. Evolution

Top-down action is central to two main themes of molecular biology: first, the *development of DNA codings* (the particular sequence of base pairs) in the DNA occurs through an evolutionary process which results in adaptation of an organism to its ecological niche. (18, 19) 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 or explain this coding on the basis of biochemistry or microphysics alone*.

3.4.6. 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. [56] 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. [41, 95] Thus the crucial developmental mechanism determining the type of each cell in the body is controlled in an explicitly top-down way. The key issue in development is not so much which genes occur in DNA, but rather which of the genes in the DNA get switched on where and when. Context controls the outcome.

3.4.7. 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. Macroprocesses at the planetary level cannot be understood without explicitly accounting for human activity. [83]

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 (CAD), 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. [38] 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 Fig. 3). 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.

Cosmology Ethics
Astronomy Sociology
Earth Science Psychology
Geology Physiology
Materials Biochemistry
Chemistry
Atomic Physics
Particle physics

Fig. 3. Branching hierarchy of causal relations. The hierarchy of physical relations (Fig. 2) extended to a branching hierarchy of causal relations. The left-hand side involves only (unconscious) natural systems; the right-hand side involves conscious choices, which are causally effective. In particular, the highest level of intention (ethics) is causally effective.

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; large-scale physical devastation of the earth will result if thermonuclear war takes place.

3.5. Summary

Overall, top-down action is how context affects what happens. It is like setting a set of hardware of software switches for an electronic apparatus, which then decide the mode of operation of that machine at that time, giving different possible sets of outputs in response to the same input (for example, determining if a computer will operate in wordprocessing, spread-sheet or image processing mode). Quite different modes of action occur depending on the context, even though the underlying physical operations are identical in all cases.

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 and enable information driven interactions.

4.1. Information, Feedback Control and the Causal Efficacy of Goals

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.[6,8,9] 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 (Fig. 4). Examples are controlling the heat of a shower, the direction of an automobile, the speed of an engine or the running of an organisation.

A key feature is that such systems damp out the effects of fluctuating initial data: they are designed precisely to give the same output whatever

information feedback
loop
System State comparator
Controller
Goals

Fig. 4. The basic feedback control process. The comparator determines the difference between the system state and the goal; an error signal from the comparator activates the controller to correct the error. [8] This is the way that abstract variables such as goals become causally effective in the physical world and damp out uncertainty or variations in the initial conditions. The goals determine the outcome, rather than the initial data.

initial state occurs (within the limited domain that the system is designed to handle). *The system output is determined by its goals rather than the initial data.* Thus the way physical effects lead to resultant behaviour ("output") is quite different when feedback systems are involved. The usual understanding of how physics works is summarised as follows:

(*Physical laws, equations of state, boundary conditions, initial data*) −→ Output

or taking for granted the context of the physical laws, equations of state and boundary conditions, simply

(*Initial data*) −→ Output.

In the case of a structured system with feedback control, this becomes quite different:

(*Physical laws, structure, boundary conditions, goals*) −→ Output

or taking for granted the context of the physical laws, physical structure and boundary conditions, simply

(*Goals*) −→ Output.

Rather then giving an output depending on the initial state or boundary conditions, the system is designed precisely to give the same output whatever the initial state. You are ill if your body temperature differs significantly from 98.4F; many bodily systems function to keep the temperature at that value irrespective of outside conditions. Thus in order to predict the behaviour of goal-seeking systems, you need to know the goals, not the ambient conditions.

Because truly complex systems are necessarily hierarchically structured, their behaviour is determined by a *control hierarchy*. This occurs for example in fluid convection, [13] in individual human lives and in society at

large. Thus, if I plan to build a factory, I have to employ builders; they have to order components from manufacturers; the manufacturers must plan a production schedule, etc. Managing large systems is essentially an exercise in hierarchical control management [81] and the human nervous system is a classic example of hierarchical decentralised control. [9]

4.2. The Role of Goals and Information

The series of goals in a feedback control system are clearly causally effective. They embody information about the system's desired behaviour or responses. Knowledge about goals and the environment can be exchanged between agents by means of information transfer, and can lead to changes in the goals and hence in behaviour. Here, *pragmatic information*[3] is related to *abstract patterns* and *has a purpose*—to cause some specific change. [82] *Information driven interactions* involve control by pattern-dependent operations rather than physically based responses:

"A specific one-to-one correspondence is established between a spatial or temporal feature or pattern in system A and a specific change triggered in system B. This correspondence depends only on the presence of the pattern in question . . . information is the agent that embodies the above described correspondence and is always there for a purpose. . . the much-sought boundary between physical and biological phenomena can be found wherever a force-driven complex interaction

becomes information driven by natural means" (Ref. 82, pp.111–120).
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. (66) They are effected through

3 Information has syntactic, semantic and pragmatic aspects (Ref. 59, pp. 31–56).

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, having been inbuilt through the process of Darwinian evolution (selection processes acting on random variations), and embodies practical solutions to optimisation problems faced by our animal and human ancestors. Thus their nature and implications may sometimes be inferred by considering optimisation as a natural process leading to predicable conclusions. (90) It does not follow from physics *per se.*

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; (59, 82) 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 (Ref. 11 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*. (39, 45) This is a highly nonlinear process, which is non-local in space (because of senses such as vision and hearing, and technologies such as television and cell phones) and in time (because of memory effects in the brain, and preservation of information through writing and electronic recording). It is enabled by the pattern recognition capacities of the brain, enabling *information driven interactions*. (82) 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. [26] 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. [11] Together these form a culture that crucially affects human behaviour and alters the course of human history. Indeed the true situation is that there is gene-culture co-evolution. [80]

Non-physical entities such as the theory of thermodynamics and technology policy underlie the development and use of technology that enables transformation of the environment. They are created and maintained through social interaction and teaching, and are codified in books and perhaps legislation. 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, e.g., 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 often socially agreed to, and exist in the context of a world of social constructions. [33]

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, [21, 40] and "explains" the behaviour or properties of an entity by determining its role or function within the higher levels of structure. [1] 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 16 h35 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 involving goal choices rely on the existence of the lower level explanations involving physical mechanisms 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. Physics and Human Intentionality

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*. Thus it gives a causally incomplete account of the world. Even if we were to attain a "theory of everything" such as string/M-theory, i.e., a comprehensive theory of fundamental physics, as described in Refs. 43 and 73, this situation would remain unchanged: physics would still fail to include within its domain 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.*

There are three different aspects to this causal incompleteness of physics. First, 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.

Second, 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. 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 do not know enough about brains to make the calculation. The thing is doable in principle, though not in practice. In the end, physics is all there is, by itself controlling 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. (54, 75)

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.

It may be claimed that physical laws alone give *either a unique outcome* (determinism), or *uniquely determine the chances of outcomes* (indeterminism), thereby fully accounting for deterministic and indeterministic possibilities in nature. I consider these options in the next two sections, suggesting neither by itself accounts for the existence and effectiveness of biological information. Section 6.4 will suggest that *physical indeterminism combined with adaptive selection*—a biological mechanism—is the basis for explaining the accumulation of biological order and emergence of associated purpose.

6.2. Physical Determinism

The claim made by determinism is *physical causal completeness*: *for any specific physical system, including human minds, physical laws alone give a unique outcome for each set of initial data*. In effect the claim is that quantum uncertainty—which of course we know is present—only affects micro-events but is not important as regards macro-events, for which a classically determinist view is both valid and sufficient to fully determine outcomes.

To see the improbability of this claim, one can contemplate what is required from this viewpoint when placed in its proper cosmic context (see Fig. 5). The implication is that the particles that existed at the time of decoupling of the cosmic background radiation in the early universe (29, 86) just happened to be placed so precisely as to make 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.

In my view, this is absurd. It is inconceivable that truly random quantum fluctuations in the inflationary era—the supposed source of later emergent structure (29, 58)—can have had implicitly 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

T4
T3
T2
T1
Decoupling of matter
and radiation (LSS)
Our past worldline
Past light cone
Here and now

End of inflation

Fig. 5. Spacetime diagram of the cosmological context of the development of complexity. Random fluctuations at the end of inflation generated random fluctuations at the surface of decoupling of matter and radiation. First generation stars (without planets) formed at time T_1, second generation stars (with planets) at time T_2. First life appeared at T_3. The present time is T_4. The higher level order and meaning at times T_3 and T_4 is not explicitly coded into the initial data at the end of inflation or at the surface of last scattering. Thus they come into being during the evolution of complex structures; they are allowed by the initial data but not caused by it.

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.

The basic issue raised here is, *what is the relationship between the cosmic initial data and the higher level order that exists later*? To explore this further, consider the logically possible options (Fig. 6). The *first option* 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 order we see around us includes societies, languages, cities, communication systems, books, manufactured objects, communally shared theories of physics and so on. Its existence is plainly manifest.

The *second option* is that there was in fact a high level of order imbedded in the data at the time of decoupling leading to the order we see today, and originating in quantum fluctuations at the end of inflation that also had high levels of order imbedded in their structure. What I mean by "order" in this context is this: the high-level order that exists today has arisen out of the data for the visible universe that is present at the time of decoupling of matter and radiation, being the time development of

Possibilities	***Option 1***	***Option 2***	***Option 3***
Meaning at the LSS	No/Yes	Yes	No
Meaning today	No	Yes	Yes

Fig. 6. Logical options for the development of complexity in the cosmological context. One hypothetical possibility is that there is no meaningful order today (option 1). We reject that possibility as incoherent (you could not discuss it if it were true). Perhaps the order that is present today was present in some coded form at the time of decoupling (option 2). We reject this too because those perturbations are supposed to have been random (and if higher level order were indeed to have been present then, the major unresolved issue would be how it got there). The true situation is option 3: random data at the LSS lead to spontaneous processes of structure formation, creating order at later times that was not existent at earlier times in the history of the universe.

that data when evolved according to the applicable dynamical laws. Now it may be that what happens today is *directly* dependent on the initial data on that surface so that there is a function f relating initial data q to the outcome p today:

$$p = f(q). \quad (1)$$

Then rerunning the whole with the same data will lead to identical outcomes, and small alterations of positions and velocities of particles there make a corresponding real difference in the results today. For example, if some of those particles are perturbed a bit Einstein would have developed the theory of relativity in 1906 instead of 1905, or would have written the famous equation $E = ma^2$ instead of $E = mc^2$. This kind of effect would occur if details of what happens today depend linearly on small enough initial perturbations, which will for example be true if the non-linear dynamical development of the initial data is analytic, or if it is non-analytic but there is a Taylor series relating the initial data to the final outcome:

$$p = p_0 + (\partial f/\partial q)_0 q + O(q^2). \quad (2)$$

Various non-linearities, e.g., existence of chaotic systems [7, 92] or the "catastrophies" characterised by Thom [93] can lead to much larger final changes for a small change in initial data: human beings would not exist, for example, so there would be no human theories to contemplate. Thus,

the dependence on initial data may be extremely fine-tuned, and the later order that occurs (such as the specific words in Einstein's 1905 paper) is both an outcome specifically determined by the initial data in the context of the relevant dynamics, and would not have occurred in the specific form it did with marginally different initial data. Then it is reasonable to say that the resultant higher order meanings that emerge later were latent or implicit in that data. This is what I mean by saying that order was imbedded in the initial fluctuations. This is not to say I take a "blueprint" view of how things work in relation to the initial data: one the contrary, the way the initial value theorems of physics work is more like a "recipe" than a "blueprint". Within this context, physics by itself cannot plausibly create higher level meanings out of random initial data: there is nothing in any of the physics "uniqueness and existence" theorems that even hints at such a possibility.

Consequently if physical determinism were true, Einstein's 1905 paper on Special Relativity would be hidden in the perturbations at the time of decoupling in the early universe. If this were the case, it could have happened either by pure chance, or because some agency placed that ordered structure 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 upper bound for the probability that things like the Mona lisa or the general theory of relativity are encoded into the random quantum fluctuations of the early universe at the time of radiation decoupling is something like on the order of 10^{-100} (probably smaller). 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.

But in any case, consideration of quantum uncertainty shows this option would not work. We could not fine-tune the initial data precisely so as to give the desired higher level outputs today, because the required degree of precise predictability relating the initial data to the present day out comes is not present. [45] Furthermore, there is growing evidence of an important role of indeterminacy in brain and behaviour, from the neuronal to the social level. [42] Physics and biology must take indeterminism seriously.

6.3. Physical Indeterminism: Randomness and Attractors

It is a profound feature of physics that there is quantum uncertainty at the micro-level: what happens is determined by deterministic equations

for the evolution of the wave function, plus a measurement process whose outcome is only determined in a probabilistic way. [72, 73] The deterministic equation (1) is replaced by a family of possible outputs:

$$p = f(q, r), \quad (3)$$

where r is a random variable. Physics determines the chances of outcomes, but not a specific outcome. The inability to precisely 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 measurement processes as time progresses. Quantum theory denies the possibility of determining a single physical outcome from given initial data, and the longer the time involved, the greater is this uncertainty. In many circumstances statistical physics results will apply on a large scale 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 a CCD providing digital images from single photons that can then be amplified digitally or electronically. One case where this is significant in biology is the effects of quantum fluctuations on DNA, where the biological developmental process acts as the amplifier. (74) This result alone already shows that in the biological context quantum uncertainty is crucial, in that it determines a whole family of possible outcomes from given initial data rather than a single biological outcome.

In the cosmological context, taking quantum uncertainty into account, the predicted probability for all allowed physical outcomes in a particular context will soon be complete uncertainty. Considering for example, change of share prices in the New York Stock Exchange,

"Since a rise tomorrow is an event in the history of the universe, a quantum mechanical probability could in principle be calculated for it from a theory of everything (Although I suspect that is well beyond our present powers of computation). But it's likely that, after all that work, the predicted probability would be 50% for an upward tick. That is why you can't get rich knowing the wave function of the universe". (45)

Two competing effects complicate the situation. First *there are attractors in the physical possibility space*—a key aspect of the context in which this all occurs. For example, self-gravitating dark matter structures have a universal velocity distribution function, which is an attractor in the possibility space. This kind of structure will almost inevitably occur irrespective of the details of the initial data within a wide basin of attraction in parameter space, with only a few macroscopic parameters dependent on the initial conditions. (44) Thus *to a large degree it is not the initial data that determines these outcomes, but the structure of possibility space*.

It can be argued that the nature of the possibility landscape, based on the underlying physics and chemistry as functioning in this context, strongly restricts the possible physical mechanisms whereby the functionality of life can be achieved, so that while the variety of life may be very different on other planets in the visible universe, the underlying biochemical structures enabling their functioning may be very similar. (23) The inevitable outworkings of the underlying physical laws then almost inevitably lead to a specific class of structures (stars and star clusters, e.g., as well as basically similar living systems), with only detailed parameters determined by the initial conditions; initial data is only weakly relevant provided it lies in the basin of attraction, indeed memory of much of the initial data is lost due to friction and dissipation effects.

However, the higher order meanings embodied in the mind and resultant physical objects produced through mental activity are not of this kind. The parameter space for combinations of letters on a page does not contain such physically determined attractors; a vast number of combinations of letters are allowed by the printing process which are not words in any known language. No purely physical channelling structure will lead to a sequence of letters and punctuation marks that make sense. The possibility space of all written text does not specifically encode mathematical theorems or physics theories—these certainly exist in this space, as they have indeed been written down, but as small islands of meaning in a vast sea of meaningless text, and no purely physics-based process has any way of telling which is which. *Thus if a purely physical evolution determines what* *happens, these meanings will not be probable outcomes of the way the possibility space is structured.*

Second, *chaotic systems* (7, 92) *exist in significant biological contexts*, for example, the physical processes governing the weather on earth, so the initial data can never be known precisely enough to determine a specific outcome. This can have a major impact on the evolution of life because climate and weather do indeed seriously affect animal survival probabilities. 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 lead to random fluctuations in the data in the classical limit, ensuring that effective classical initial data cannot even in principle be prescribed to the required level of accuracy to obtain a specific outcome. (14) Thus, although chaos is damped in quantum systems, chaotic systems can act as amplifiers of the uncertainty introduced by quantum processes into the classical limit, where they result in a spectrum of Gaussian fluctuations (the inflationary universe theory is an example of this process (29, 58)). Similar effects occur close to the edges in parameter space characterizing catastrophes: (93)

a very small change in initial data leads to very large changes in outcome. Causation of precise outcomes by purely physical processes from specific initial data in the very early universe is not even theoretically possible when such systems are significant, because at its foundations physics is stochastic.

6.4. Physical Indeterminism and Biology: Adaptive Selection

It is far more likely that the *third option* in Fig. 6 is the true situation: the later higher level outcome were not the consequences of specific aspects of the initial data, even though they arose out of them. 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 life and ultimately minds that are autonomously effective, able to create higher level order without any fine dependence on initial data. The higher level understandings in the mind were not specifically implied by the initial data in the early universe, neither were their physical outcomes such as television sets and cellphones.

This is possible if there is a large-scale context that is causally channelling the development of fluctuations "in the right direction" for them to eventually contribute to the existence of minds creating such things as the Mona lisa. This channelling is provided by the combination of the nature of the underlying possibility landscape (23, 33) and the developing order accumulating through Darwinian evolutionary processes, selecting between variations provided by chance effects on the large-scale and quantum uncertainty on the small-scale. Random variation followed by selection is a powerful mechanism that can accumulate biological order and information related to specific purposes. (82) At the micro level, it can be characterised as the *Molecular-Darwinistic approach*. (59) According to Glimcher, (42) it is apparent in neuroscience and behaviour:

> "The theory of games makes it clear that an organism with the ability to produce apparently indeterminate patterns of behavior would have a selective advantage over an animal that lacked this ability . . . at the level of action potential generation, cortical neurons could be described as essentially stochastic . . . the evidence that we have today suggests that membrane voltage can be influenced by quantum level events, like the random movement of individual calcium ions . . . the vertebrate nervous system is sensitive to the actions of single quantum particles. At the lowest levels of perceptual threshold, the quantum dynamics of photons, more than anything else, governs whether or not a human observer sees a light".

A key feature here is that while this process of variation and selection proceeds in a physical way, it also involves abstract patterns that are not

physical phenomena—for selection processes operating in biological systems develop in such a way as to recognise abstract patterns, which then become part of the causal processes in operation.(82) Thus

"material learning processes can in principle solve the problem of the origin of information. . . meaningful information can indeed arise from a meaningless initial sequence as a result of random variation and selection.. natural selection defines a gradient of evolution, not a detailed path, for reaching the (nearest) maximum" (Ref. 59, pp. 83, 86).

Overall, this mechanism is the way top-down action shapes the lower level components to fulfil their higher level roles. The selection process utilizes higher level information about the environment—which may or may not correspond to coarse-grained variables—to shape the micro-level outcomes.

Part of the developing order is the human brain itself. Its structure relates higher level variables to coarse-grained lower level variables, with feedback control implementing higher level goals in a teleonomic way. Both features damp out the effects of lower level statistical fluctuations and quantum uncertainty, replacing them with a tendency to achieve specific goals. Additionally, it is influenced by higher order variables, allowing autonomous functioning of the mind so as to handle high level abstract concepts represented by language and internal images:

$$p = f\ (q,\ m,\ p,\ a,\ e), \quad (4)$$

where m are memories (arising from previous events, and so non-local in time) and related emotions, p are perceptions (arising from the senses and incoming information, and so non-local in space) and related emotions, a are abstractions (higher order levels of thought which set the context for understanding and ordering lower level variables), and e are external memory supports invoked by a distributed mind, for example, notes jotted down in a diary.(64) All of these set the context in which the non-linear local operations of the mind interpret what is happening.

The adaptive process structures synaptic connection so that abstract pattern recognition takes place,(82) as beautifully demonstrated in mirrorneuron experiments by Quiroga *et al*,(77) where the representation of an abstract object is reduced to a single neuron.(22) It is through the variables a that non-material features such as Platonic mathematics,(73) can affect the operations of the mind. Additionally mental constructs such as theories of physics, based in and reflecting well the material nature of the world around us but still constructions of the mind in a social context,(33) are included in a. It is through the variables p that the non-material feature of qualia are causally effective. The mind gets to be structured in this

way through the kind of adaptive process outlined here, both in terms of its historical evolutionary emergence, and in terms of developmental processes acting in each individual brain.(38, 82)

Physics provides the necessary conditions for the existence of such higher level phenomena, but not the sufficient conditions to determine the resulting behaviour. These are affected by causally relevant higher level variables which attain meaning and causal effectiveness at their own level. A mind's behaviour is determined by its interaction with other minds(30) and 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. The key point is that human understandings and intentions are causally effective in terms of changing conditions in the physical world, [33] but are outside the domain of physics.

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 cannot 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 so as to produce the dance of a bee or the web of a spider. One can argue that 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 is not true because *the ever-higher 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 and matter conservation must hold.

Physics by itself cannot causally account for any animal behaviour that is adaptive and depends on context, for example, beaver dambuilding, 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.

At the micro-level, stochasticity occurs in gene expression preventing prediction of a unique outcome; but self-organisation due to the cell being a dynamic self-organising system of adaptive interacting agents nevertheless leads to the emergence of higher level order allowing cell plasticity. [60]

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. [63] 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.

7. EMERGENCE AND CAUSAL CLOSURE

7.1. Causal Closure

Some of the physical cases considered above refer to *Weak Emergence*: this is when in principle a system may be fully described by the microscopic degrees of freedom alone, but in practice one would rarely choose to do so, both because the attempt is not illuminating, and because one will usually be unable to do so in reality. However the more interesting cases are those where I have claimed we encounter *strong emergence*: *even in principle*, micro-level laws fail to fully determine outcomes of complex systems, so that causal closure is achieved only by appealing to downward causation. But this claim is clearly in trouble if the system is already causally closed at the micro-level, as is the case with most model systems considered by physicists. For higher levels to be causally efficacious over lower levels, there has to be some causal slack at the lower levels, otherwise the lower levels would be causally over-determined. Where does the causal slack lie? Four key features are relevant.

First, in considering specific physical and biological systems, it lies partly in the *openness of the system*: *new information can enter across the*

boundary and affect local outcomes. For example, cosmic rays may enter the solar system and alter the genetic heritage of individual humans; alteration in solar radiation can cause climate change on earth; telephone calls from afar convey vital information that changes how we act. Context is crucial to physical outcomes for local systems, and is embodied in both structural and boundary conditions; for example, this is crucial in structuring the brain. New influences, not present in the system to start with, help shape its future.

However, this does not solve the issue on the largest scales: one can always consider a bigger system, including more and more of the universe within its boundaries, until at the cosmological scale we consider all that exists and there is no longer a possibility of such boundary effects occurring.

Second, it lies in *quantum indeterminism* (random outcomes of microphysical effects), *combined with adaptive selection*, as explained above: random outcomes at the micro-level allow variation at the macro-level, which then leads to selection at the micro-level but based in macro-level properties and meaning. Quantum uncertainty provides a repertoire of variant systems that are then subject to processes of Darwinian section, based on higher level qualities of the overall system. For this to work, one needs amplifying mechanisms in order to attain macroscopic variation from quantum fluctuations. This was explored above: some physical systems (such as photomultipliers and the human eye) amplify quantum effects to a macroscopic scale; some classically chaotic systems can amplify fluctuations in initial data that are of quantum origin;[4] some of the effects captured in Thom's catastrophe theory allow large amplification of microscopic changes; and some molecular biology processes (e.g., involving replication of mutated molecules) act as such amplifiers. (74) There is considerable evidence that these kinds of effects lead to indeterminacy in brain and behaviour. (42)

At a profound level the universe is indeterministic, allowing the needed causal slack. By itself that does not lead to emergence of higher level order; but it does allow this on the one hand through existence of attractors in possibility space, and on the other through the process of adaptive selection. (83)

The third key feature is that *top-down action changes the nature of the lower elements so that they are fitted to higher level purpose*. There is not just a situation of invariant lower level elements obeying physical laws; rather we have the nature of lower level elements being changed so

[4]When chaotic systems are quantised, their chaotic behaviour normally goes away, but that is not the context envisaged here.

that the way they obey physical laws fulfils higher level purposes. One should distinguish here different timescales of operation: physical functioning takes place on short-timescales, while this adaptation occurs both on developmental (medium term) timescales and on evolutionary (very longterm) timescales. It is through such processes that the efficacy of goals and abstract concepts can be implemented, with the efficacy of initial data being replaced by the causal power of inbuilt and chosen goals. Thus *the nature of micro causation is changed by these top-down processes*, profoundly altering the mechanistic view of how things work.

Finally, *one can argue that free will plays an autonomous causal role not determined by physics*; if so, that would be an important part of the causality in operation. This is clearly controversial territory, and some deny that free will truly exists. However, we should recognise 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 the academic subject of physics to exist*. The proposal that apparent rationality is illusory, being just the inevitable outcomes of micro-physics, cannot account for the existence of physics as a rational enterprise. But this enterprise does indeed make sense; thus one can provisionally recognise the possibility that free will too is an active causal factor, not directly determined by the underlying physics. It is possible that quantum processes play a key role here, as suggested for example by Stapp. (89) Those who claim physics alone underlies consciousness should take cognisance of the true difficulty of the "hard problem" of consciousness; (20) we do not know how to begin to tackle it. However, consideration of the causal effect of the human mind is not mandatory in order to argue that higher levels in the hierarchy can be autonomously causally effective; top-down action together with adaptive selection, as discussed above, may well be sufficient.

7.2. The Initial Value Problem

The technical challenge to physicists is to see how this all relates to the existence and uniqueness theorems of physics (see e.g. Ref. 48), 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, in addition to the fact that they are valid only locally in time. The 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 modular hierarchical physical structuring actually present in biological systems, nor do they reflect the complexities of adaptive evolution*. 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, (13) non-local influences in time because of memory effects, and alteration in microstructures through adaptation to macro purposes.

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, with higher levels of complexity having autonomous causal powers. 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. (2, 3) This allows new properties to emerge in a system as boundary conditions change. However, to relate to true complexity, it needs to be related to Darwinian processes of adaptation.

The kind of issue that comes up is first, the existence and function of various typical motifs that occur in networks at many levels, [10, 55] with associated modularity, [88] topology [57] and hierarchical structuring. [24, 51, 69] Second, the role of modularity [15] and feedback control [9] in hierarchical structures. Third, the role of memory effects, effectively non-local in time and information processing, filtering causal influences in sophisticated ways related to the goals directing the system. [82] 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. [82] These processes are tremendously effective at all levels, playing a role not merely in the emergence of biological order [19] but also in the emergence of classicality from the underlying quantum physics through quantum decoherence [97] and in protein folding. [16, 28] They underlie the functioning of the adaptive immune system [17] and structure neural connectivity in the brain. [38, 70] Thus a key element is the mathematical study of Darwinian evolutionary theory [5] and the study of evolutionary trajectories in rugged fitness landscapes, [52] the nature of those landscapes being determined by the underlying physical forces and potentials. [49]

How this all 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.

7.3. The Essential Issue

In the influential book *What is Life,* 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" (Ref. 84, p.81).

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 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". [4]

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. However, we can indeed understand these processes scientifically, provided we include the higher level effects appropriately. This paper tries to indicate how that can indeed be done.

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, [50, 72, 73] 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 key concluding point is that *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.

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