NECESSITY, PURPOSE, AND CHANCE: THE ROLE OF RANDOMNESS AND INDETERMINISM IN NATURE FROM COMPLEX MACROSCOPIC SYSTEMS TO RELATIVISTIC COSMOLOGY

George F R Ellis[i]
Mathematics Department, University of Cape Town

1. CAUSATION AND RANDOMNESS IN NATURE

Various kinds of causation occur in nature. Famously, Jacques Monod (1972) characterised the only options as chance and necessity. But he missed a key further kind of causation that certainly occurs in the real universe: namely purpose or goal-seeking (Ellis 2005). By omitting this key causal category – which *inter alia* explained why he wrote his book - his analysis was prevented from relating adequately to deep philosophical issues, even though he claimed to answer them. The same comment applies to more recent books by Susskind, Hawking and Mlodinow, Krauss, and others.

This paper will consider a broader context: the interplay between necessity, purpose, and chance. The first has an inexorable impersonal quality. It is the heart of physics and chemistry. It can be successfully described by mathematical equations. The second is the core of human being, as well indeed of all life. All living entities embody some kind of purpose or function in their structure and actions (Campbell and Reece 2005). The third embodies the idea of randomness, implying a lack of purpose or meaning. Things just happen that way, not because it's inevitable, but because it's possible, and maybe probable. It is prevalent in the real universe because of the large number of unrelated causes that influence events, and in particular because of the vast numbers of micro-events that underlie all macroscopic outcomes. All three kinds of causation occur in an intricate interplay in the real universe.

Denis Noble (2013a) says the following re randomness: "*Defining what is meant by 'random' is itself a major field of enquiry in mathematics, computation and in science generally. The question whether there are truly random events in the universe is a vexed one, lying at the heart of theories of quantum mechanics. Probably, we will never know, perhaps cannot know in principle, the answer to that kind of question."* I'm not going to pursue those fundamental issues, but rather will consider first how randomness is basic to quantum physics and second how it relates to complex systems and the existence of life.

When one has social or engineering systems, randomness is a problem to be handled and as far as possible limited by careful design, so that the desired outcome will be attained despite random events intervening in the dynamics. This is not always successful: in particular, digital computers are notoriously susceptible to the smallest error: a single wrong full-stop can bring an immensely complex program to a crashing halt. However social systems such as the economic and legal systems and technological artefacts such as modern aircraft are generally more robust: they are designed to handle reasonable classes of random events without disaster occurring. Feedback control in cybernetic or homeostatic systems is specifically designed to tame randomness, but it remains an enemy to be handled with care. It has the potential to derail everything and prevent attaining the desired goal.
At the micro level, biological systems do not live in a carefully controlled environment: they face rampant randomness all the time. It turns out that they take advantage of the storm of

randomness encountered at the molecular level: there is much evidence that molecular machinery in biology is designed to use that randomness to attain its desired results (Hoffmann 2012). This is true also in terms of macro levels of behaviour, and in particular as regards how the brain functions (Glimcher 2005, Deco, Rolls, and Romo 2009, Rolls and Deco 2010). Randomness is harnessed through the process of adaptive selection, which allows higher levels of order and meaning to emerge. It is then a virtue, not a vice; it allows purpose to be an active agent by selecting desired outcomes from a range of possibilities.

Irreducible randomness occurs in physics at the quantum level, thereby influencing cosmology and the existence of life on Earth. If it were not for this randomness, we would be stuck in the vice of determinism and outcomes would be limited and uninteresting. But it is there, as part of the design of the universe. It is a key feature in allowing autonomous higher levels of order to come into being. It is remarkable that many writings on quantum physics (for example regarding the black hole `information paradox') claim its dynamics are deterministic: only unitary transformations can occur. These texts, which explicitly or implicitly deny that state vector reduction takes place, give no way whereby the Born rule – the key relation that predicts probabilities of different classical outcomes to experiments - can ever take effect: for they deny that specific classical outcomes occur. They simply do not reflect the nature of the paradigmatic two-slit experiment where the quantum mechanical interference pattern is built up photon by photon as individual photons arrive at a detector in an indeterministic way (Figure 1). [ii]

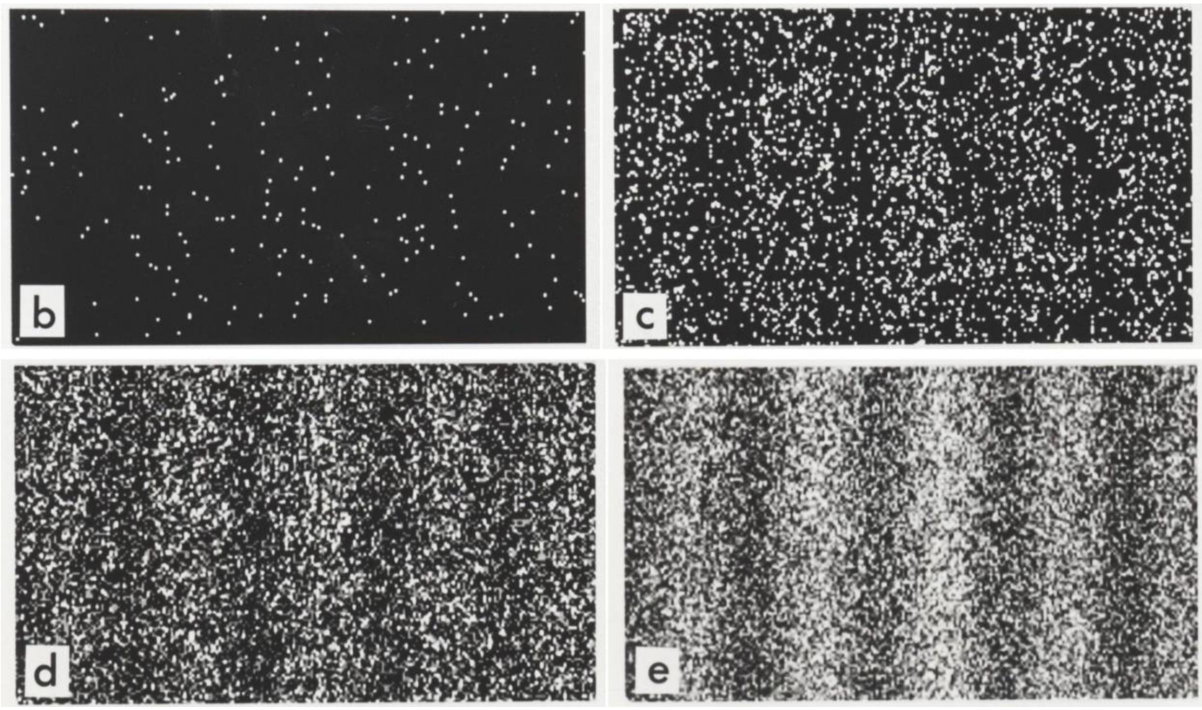

Figure 1: Quantum Uncertainty. *Double-slit-experiment performed by Dr. Tonomura showing the build-up of an interference pattern of single electrons. The numbers of electrons are (b) 200, (c) 6000, (d) 40000, (e) 140000. From Wikimedia Commons.*

This paper by contrast takes that experiment seriously as genuine evidence regarding the nature of the universe. Irreversible unpredictable quantum effects do indeed take place in the real universe. This foundational indeterminism is a key aspect of the nature of physical reality. Its existence is based in deeper levels of being – the possibility spaces that determine what is and what is not possible in the physical universe. It is part of the design of the things: one of the features one has to explain, if one claims to explain on any basis whatever the nature of the physical universe.

> *Why do both chance and necessity occur? Who or what ordered them both? And how does purpose fit in?*

An element of randomness at the bottom does not mean all that happens is just pure chance – rather it is one of the foundations that, together with necessity, opens up the possibilities of mental and spiritual life, realised through physical existence. It does not have to have the connotation of meaningless so often ascribed to it. It is the gateway to variety and possibility. That is what will be explored in this article.

2. RANDOMNESS IN QUANTUM PHYSICS

The standard view is that quantum physics, which introduced the quantum principle that only discrete energy states occur, particle/wave duality, the uncertainty principle, quantum tunnelling, superposition of states, and entanglement, involves a foundationally indeterminate dynamics: probabilities can be predicted, but not specific outcomes.

2.1 The Standard View

The basic postulate of quantum mechanics (Morrison 1990, Rae1994, Isham 1995, Greenstein and Zajonc 2006) is that before a measurement is made, the vector $|\psi>$ describing the quantum state of the system can be written as a linear combination of unit orthogonal basis vectors representing different possible measurement outcomes:

$$| \psi_1> = \Sigma_n c_n |u_n(x)>, \qquad (1)$$

where $|u_n(x)>$ is an eigenstate of some observable $\hat{A}$. The evolution of the system can be completely described by a unitary operator $\hat{U}(t_2, t_1)$, and so the state vector evolves as

$$|\psi_2> = \hat{U}(t_2, t_1) ||\psi_1> \qquad (2)$$

Here $\hat{U}(t_2, t_1)$ is determined by the evolution equation

$$ih\, d|\psi_t>/dt = H |\psi_t>. \qquad (3)$$

where H is the Hamiltonian (substitute (2) into (3) to see how H determines $\hat{U}$). This is a unitary evolution: no surprises occur, the initial state uniquely determines the final state at all later times. Physics is determinate: necessity rules.

Immediately after a measurement is made at a time $t = t*$, however, the relevant part of the wavefunction is found to be in one of the eigenstates representing a specific measurement outcome:

$$|\psi_2> = c_N |u_N(x)> \qquad (4)$$

for some specific index N. This is where the quantization of entities and energy comes from (the discreteness principle): only discrete eigenstates can result from a measurement. The eigenvalue c_N – the outcome of the measurement -- is unrelated to the initial wave function (1). It cannot be a unitary evolution (2). The data for $t < t*$ do not determine either N or c_N; they merely determine a probability for each possible outcome (4), labelled by N, through the fundamental equation

$$p_N = c^2_N = \langle e_N|\psi_1\rangle^2 \qquad (5)$$

where $|\psi_1\rangle$ is the wave function before the measurement. This is the Born rule for measurement probabilities, which gives the wave function its physical meaning. One can think of this process as the probabilistic time-irreversible reduction of the wave function where the initial indeterminate state changes to a final determinate classical state:

$$|\psi_1\rangle = \Sigma_n\, c_n\, |u_n(x)\rangle \rightarrow |\psi_2\rangle = c_N\, u_N(x). \qquad (6)$$

This is the event where the uncertainties of quantum theory become manifest (up to this time the evolution is determinate and time reversible). It will not be a unitary transformation unless the initial state was already an eigenstate of $\hat{A}$, in which case we have the identity projection

$$|\psi_1\rangle = c_N\, u_N(x) \rightarrow |\psi 2\rangle = c_N\, u_N(x) \qquad (7)$$

This discussion presents the simplest idealized case of a measurement (Penrose 2004: 542-549). More generally, one has projection into a subspace of eigenvectors (Isham 1995:136; Wiseman and Milburn 2010:10-12) or a transformation of density matrices (Isham 1995:137), or any other of a large set of possibilities (Wiseman and Milburn 2010:8-42), but the essential feature of non-unitary evolution remains the core of the process.

Thus there is a deterministic prescription for evolution of the quantum state determining probabilities of outcomes of measurements, but indeterminacy of the specific outcomes of those measurements, even if the quantum state is fully known.

Examples are radioactive decay: we can't predict when a nucleus will decay or what the velocities of the resultant particles will be, and the foundational two-slit experiments: we can't predict precisely where a photon, electron, neutron, or atom will end up on the screen (Feynman 1963, Greenstein and Zajonc 2006). Each individual photon arrives at an unpredictable place, but the predicted overall interference pattern gradually builds up over time, see Figure 1.

The fact that such unpredictable measurement events happen at the quantum level does not prevent them from having macro-level effects. Many systems can act to amplify them to macro levels, including photomultipliers (whose output can be used in computers or electronic control systems). Quantum fluctuations can change the genetic inheritance of animals (Percival 1991) and so influence the course of evolutionary history on Earth; and they have changed the course of structure formation in the universe (Section 3).

2.2 Alternative possibilities

The above is the standard view: according to Heisenberg, Dirac, von Neumann, Feynmann, *et. al,,* : irreducible randomness occurs in quantum theory. Determinism does not hold in the real world, at the micro-level. This was very worrying to many people, in particular Albert Einstein, and all possible alternatives have been carefully explored.

- **Hidden variables?** Many investigations have tried to see if physicists have somehow missed some hidden variables. This involved the Bohr-Einstein debate, a famous paper by Einstein, Rosen, and Podolsky (1935), see (Fine 2013) for a discussion, and a set of inequalities by Bell (1964, 1987). These have shown this idea is incompatible with usual concepts of realism and causation.

- **Many worlds**? Everything that is possible occurs, as possibilities multiply and the wave function splits into innumerable branches (Everett 1957); see Isham (1995) for a summary of the various proposals as to how this happens. But this has no cash value: it does not change the experimental situation described above, which is what we experience in the real world. Any number of hypothetical other worlds that are supposed to be realised somewhere else make no difference to this outcome.

- **Pilot wave theory** (Bohm 1952) is a deterministic theory that gives exactly the same results as the standard theory. Again it makes no difference to the outcome. If one could observe the underlying hidden variables, one would be able to signal faster than light, which according to special relativity leads to temporal paradoxes (Kofler and Zeilinger 2010).

- **Decoherence**: Some have suggested that the measurement problem is solved by environmental decoherence (Zurek 2004). However while this diagonalizes the density matrix, it leaves a superposition of states, and so does not lead to a specific classical outcome. It does not predict where the individual spots in Figure 1 will occur; and neither does any other statistical result from quantum physics.

All these options are discussed by Isham (1995), and many of the original papers are presented with commentaries in Wheeler and Zurek (1983).

2.3 The outcome

There are various alternatives to the standard view, but in the end they amount to proposing some kind of machinery hidden behind the scenes that makes no difference to the practical outcomes described by equations (4) – (7). You have no ensemble to which you can apply statistics unless you have the individual events that make up the ensemble; and those are what quantum physics is unable to predict.

The irreducible uncertainty of specific events, as shown in the two-slit experiment in Figure 1, is what we have to deal with in all experienced quantum phenomena. There is indeed genuine unpredictability in the real world, even though we can predict statistics of microevents with precision.

3. Cosmological Unpredictability

This uncertainty applies in the cosmological context. To make this quite clear, one can pose the following question: is it possible the content of this paper is uniquely determined by the initial state of the universe? That would be the case if necessity held sway.

3.1 The cosmic context

The expansion history of the universe is represented in Figure 2. Time runs from left to right. An extraordinarily rapid initial accelerating period of expansion ("inflation") gives way to a hot big bang era, until matter and radiation decouple at the Last Scattering Surface ("LSS"), 300,000 years after the hot big bang. This is followed by dark ages until the first stars form and galaxies come into being through gravitational attraction. Some massive first generation stars meet a fiery end as a supernova, spreading clouds of heavy elements in space that then allow second generations stars to form that are surrounded by planets.

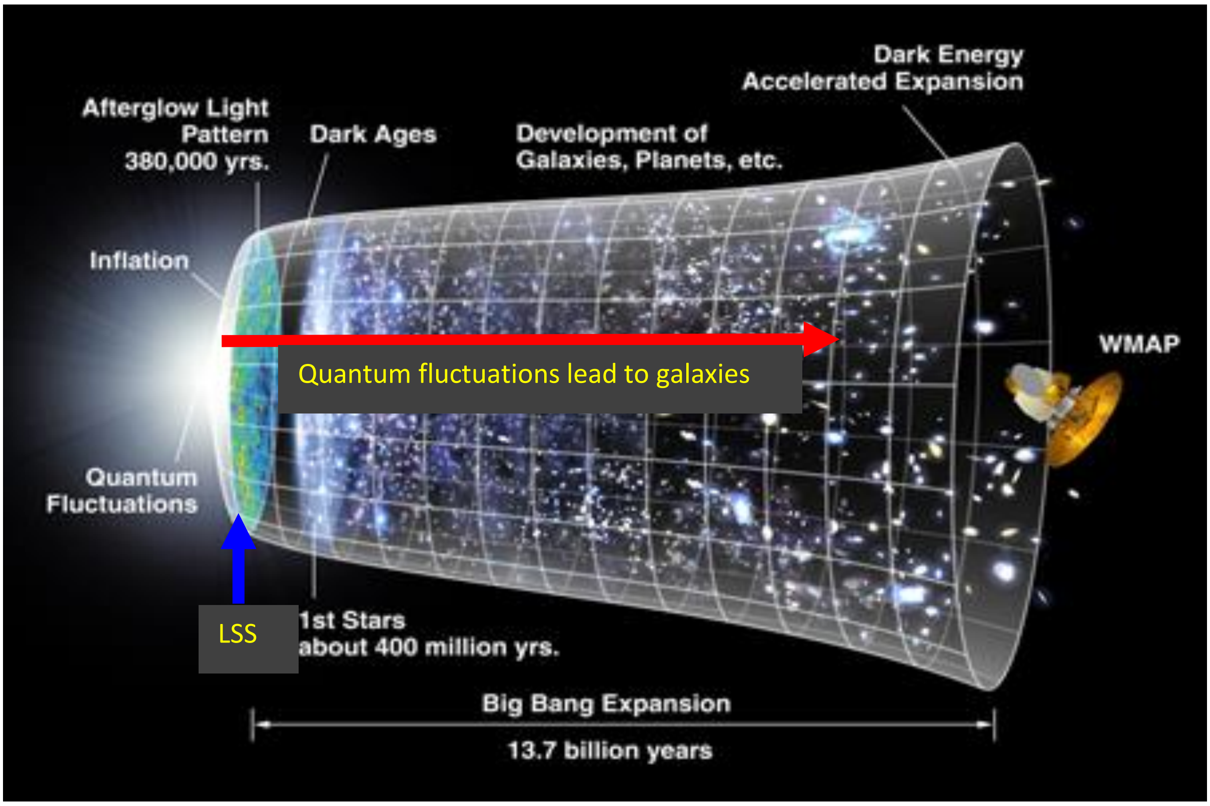

Figure 2: The unpredictability of the universe. *Quantum fluctuations lead to the existence of galaxies.*

Thus the expanding universe is the environment creating the conditions for life to exist today. The cosmic background radiation (CBR) sky we observe today (Figure 3) is an image of the density fluctuations on the LSS that are the precursors of all the galaxies that exist today, because this radiation was released at the LSS and then travelled freely towards us. It is an image of the early universe that has led to present state today.

Now the question is this: *is all the future history of the universe uniquely encoded in the fluctuations on the LSS*? If we had future satellites far more powerful than Planck, that could detect every micro-fluctuation on the LSS, could one then in principle run that data forwards to predict the specific words on the page you are reading now? And going back even earlier, are these words implied by the state of the universe at the start of inflation?

In short: is it true that in the real universe, the future is uniquely predicted by the past?

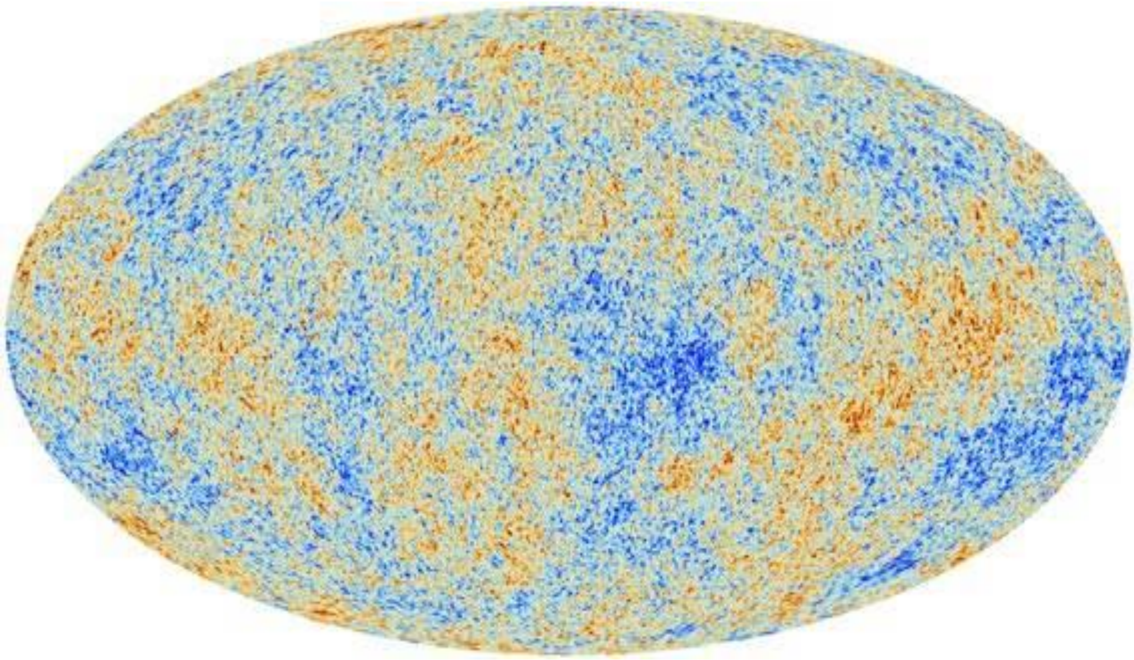

Figure 3: ***CMB Sky*** *measured by the Planck Satellite. Image credit: ESA–Planck Collaboration.*

3.2 Not possible because of inflationary perturbations

This is not possible even in principle for two reasons. First, the inhomogeneities that occurred on the LSS were the outcome of quantum fluctuations during inflation (Dodelson 2003, Mukhanov 2005). They were not determined uniquely by the state of the universe at the start of inflation, because until the relevant quantum fluctuations had become crystalized in classical fluctuations, the outcome was unpredictable, even in principle, because of the quantum uncertainty described in the last section.

Thus the state of the LSS is not uniquely determined by the state of the universe at the start of inflation; but it was that state that determined what specific structures formed in the universe at later times. Hence the existence of our specific Galaxy, and the Sun and Earth in it, is also not so determined. They are the outcome of unpredictable random events.

As the existence of the Earth is not a specific outcome of that initial data, of course what is written in this book cannot possibility be so either. Because of chance, necessity cannot explain the details of the present day universe.

3.3 Not possible because of effect of cosmic rays on evolution

Second, suppose we knew every detail of the state of the Earth and the life on it two billion years ago. That would not uniquely predict that humans would exist today, because the random quantum events leading to cosmic ray emission can change the genetic inheritance of animals (Percival 1991) and so influence the outcomes of Darwinian evolution.

Indeed that is what occurred when cosmic rays altered evolutionary history through causing genetic mutations and so influenced the course of evolutionary history on Earth:

> "*The near universality of specialized mechanisms for DNA repair, including repair of specifically radiation induced damage, from prokaryotes to humans, suggests that the earth has always been subject to damage/repair events above the rate of intrinsic replication errors ….. radiation may have been the dominant generator of genetic diversity in the terrestrial past*" (Scalo et al 2001).

The emission of a specific cosmic ray at a particular time and place is a quantum event, unpredictable even in principle, as per the last section. The outcome was determined as it happened.

Consequently the specific evolutionary outcomes of life on Earth (the existence of dinosaurs, giraffes, humans) cannot even in principle be uniquely determined by causal evolution from conditions in the early universe, or from detailed data at the start of life on Earth. Quantum uncertainty prevents this, because it significantly affected the occurrence of radiation-induced mutations in this evolutionary history. The specific outcome that actually occurred was determined as it happened, when quantum emission of the relevant photons took place: the prior uncertainty in their trajectories was resolved by the historical occurrence of the emission event, resulting in a specific photon emission time and trajectory that was not determined beforehand, with consequent damage to a specific gene in a particular cell at a particular time and place that cannot be predicted even in principle.

3.4 Conclusion: Genuine emergence MUST occur.

Because of the expansion history of the universe shown in Figure 2, where quantum fluctuations play a key role, randomness and indeterminism in cosmology prevent predictability of the Laplacan kind. A Laplacian demon who could calculate with infinite precision would not be able to predict our existence, much less what is written on this page, from the initial state of the universe: none of this is written into that initial state shown in Figure 2. Hence the contents of this paper can't possibly be encoded in CBR data: quantum uncertainty prevents this from being the case.

So how do scientifically meaningful events, like Darwin developing the theory of evolution or Einstein developing the theory of relativity, happen?

The answer has to be that what appears to be the case is indeed the case: processes of evolution and development lead to emergence of brains and minds with their own causal powers not uniquely determined by the underlying microphysics. Genuine emergence in time MUST occur and lead to the macro levels of order and meaning we see. If we had a much more powerful telescope than in the Planck Satellite and could see every micro detail of the LSS, we would not somehow find the General Theory of Relativity encoded there. Actually this proposal is absurd: what we have there are random Gaussian fluctuations. They do not encode the present day uniquely: rather they encode the possibility of today developing.

What we have to examine in order to understand this is the processes that lead to genuine emergence of higher levels of causation and meaning, encoded in language and symbolism, which undoubtedly have come into existence in the real universe.

4. The Emergence of Complexity

So how did complexity arise? It is possible because as well as bottom up causation, top down causation occurs in the hierarchy of complexity, whereby higher levels of emergent complexity can causally affect what happens at the lower levels – which then affects what happens at the higher levels (Ellis, Noble and O'Connor 2012). In particular adaptive evolutionary and developmental processes lead to the existence of genuine complexity, where higher levels of structure – including brains – come into being and cause outcomes in the physical world. The possibility for this to happen is because of the randomness at lower levels that allows for selection of functionality on the basis of higher level selection criteria.

Higher level purposes structure events – for example by creating computers that then have the power to change the world. This outcome is not predictable from microphysics alone, and is not uniquely implied by the initial data, as was shown in the last section.

4.1 The hierarchy of structure and causation

On both the natural sciences and life sciences side, complexity is based in modular hierarchical structures (Murphy and Ellis 1995; Ellis 2008, 2012). Higher levels of structure and causation emerge from complex combinations of lower level entities (Figure 4).

LEVEL	NATURAL SCIENCE	LIFE SCIENCE
level 8	Cosmology	Sociology/economics/politics
level 7	Astronomy	Psychology
level 6	Space science	Physiology
level 5	Geology, earth science	Cell biology
level 4	Materials science	Biochemistry
level 3	Physical chemistry	Organic chemistry
level 2	Atomic physics	Atomic physics
level 1	Particle physics	Particle physics
Level 0	M-theory?	M-theory?

Figure 4: The hierarchy of structure and causation. *The natural sciences and life sciences hierarchies are based in the same elementary constituents.*

On the natural sciences side, this emergence is in terms of physical scale (which is inverse to the energies involved). However on the life sciences side, the higher levels are not purely physical: they involve causal factors such as intentions, ideas, and social constructions.

4.1 Top down action in complex systems

The emergence of higher level causal powers is possible because of the existence of both bottom-up and top-down causation in complex systems. Contextual effects occur when the higher levels of the hierarchy causally effect what happens at the lower levels in a coordinated way; thus the higher level have real causal powers (Noble 2006).

There are three basic kinds of top-down causation: TD1, algorithmic; TD2, feedback control, and TD3, adaptive selection (Ellis 2008, Ellis 2012). Two further higher forms of top down causation are built on the basis of TD3: namely TD4, adaptive selection of feedback control goals, and TD5, adaptive selection of adaptive selection criteria.

How is this related to physics? How is there causal room at the bottom for top down causation to take place? And does top down causation take place in physics also? I look at these issues at the end.

TD1: Algorithmic Top-Down effects. Algorithmic top-down causation occurs when high-level variables have causal power over lower level dynamics through system structuring, so that the outcome depends uniquely on the higher level structural and boundary conditions and initial conditions. The lower level variables determine the outcome in an algorithmic way from the initial and boundary conditions (for example, the software loaded in a computer) as a consequence of the structural relations that hold (for example, the wiring in a computer or interconnections of neurons). Changing these structural conditions leads to different lower level events and dynamical outcomes.

Provided the lower level interactions mesh together in a coherent way, the constrained operation of lower level forces, operating in a law-like/algorithmic way, leads to reliable higher level behaviour whose outcome depends on the nature of the constraints and initial conditions. These are often in the form of networks of interactions (Barabási and Oltvai 2004), usually including recurring network motifs (Alon 2007). These are higher level features because they cannot be described in terms of lower level concepts (for example, the specific connections between transistors in a computer cannot be described in terms of properties of electrons) and the system ceases to function if the higher level relationships are disrupted, even though the individual lower level elements are unchanged.

Suitable engineering design damps out the effect of chance events if structures are of sufficient size that quantum fluctuations lie below activation thresholds. Together with designed safety margins and friction effects that damp out perturbations, this confers stability on functioning. The canonical example is digital computers: the low-level gates and transistors act in accord with the data and the program loaded (word processor, music program, image processing program, etc.), which is a high-level concept whose structure and function cannot be explained in lower level terms. The hardware and software are each hierarchically structured in a symbiotic way so as to allow this higher level functionality (Tanenbaum 1990). Computer systems are highly reliable: randomness is tamed.

TD2: Feedback control systems with fixed goals. In non-adaptive feedback control, higher level entities influence lower level entities, so as to attain specific fixed goals through the existence of feedback control loops, whereby information on the difference between the system's actual state and desired state is used to lessen this discrepancy (Beer 1996, 1972). Unlike the previous case, the outcome is not determined by the boundary or initial conditions; rather it is determined by the goals. Indeed the whole purpose of such systems is to make initial conditions irrelevant.

A different outcome will occur if the goal is changed. Thus, the nature of causality is quite different than the previous case, when feedback control systems are guided by goals, which are higher level entities. This contrasts dramatically with how physics is usually considered to operate, but is fully in accord with engineering and biological precepts. The goals are established through the process of natural selection and genetically embodied, in the case of biological systems, or are embodied via engineering design and subsequent user choice, in the case of manufactured systems.

An example is a thermostat controlling the temperature in a room; the goal is set by setting a desired temperature on an input panel. All of biology embodies numerous genetically determined homeostatic systems, based on the principle of feedback control. In particular, this is true of the human body: homeostasis is the key to physiological research (Rhoades and Pflanzer 1989). Thus, for example, we have inbuilt bodily systems that interact to maintain body temperature at 98.4 F to high accuracy. Such cybernetic systems are specifically designed to damp out the effects of fluctuations and random events.

Homeostasis is the way biology handles random disturbances. Reasonable levels of randomness are tamed.

TD3: Adaptive selection. Adaptive processes (Holland 1992) take place when many entities interact, for example the cells in a body or the individuals in a population, and variation takes place in the properties of these entities, followed by selection of preferred entities that are better suited to their environment or context. Higher level environments provide niches that are either favourable or unfavourable to particular kinds of lower level entities; those variations that are better suited to the niche are preserved and the others decay away. Criteria of suitability in terms of fitting the niche can be thought of as fitness criteria guiding adaptive selection. On this basis, a selection agent or selector (the active element of the system) accepts some of the variations and rejects the rest; the selected entities then form the current system state that is the starting basis for the next round of selection, ultimately leading to the emergence and nature of adapted form and function.

A different lower level structure will result if the higher level context is changed. Thus, this is top-down causation from the context to the system. An equivalence class of lower level variables will be favoured by a particular niche structure in association with specific fitness criteria; if the top level conditions change, the outcome will change.

Unlike feedback control, this process does not attain pre-selected internal goals by a specific set of mechanisms or systems; rather it creates systems that favour the meta-goals embodied in the fitness criteria. This is an adaptive process rather than a control process. It is the way new information is generated that was not present before (Kuppers 1994), and enables emergence of complexity with an increase of embodied information, for the process searches the solution space in a way that is not pre-ordained and adapts to the context.

The outcome is not predictable either from the initial conditions or from the meta-goals, because of the random element involved, although both clearly influence the outcome. This underlies all life, including cells as well as plants and animals, and is the basis for building up biological information—the foundational difference between physics and biology (Roederer 2005). As will be discussed in the next section, this uses random events to advantage. The more complex forms of top down causation are built on this basis.

TD4: Adaptive feedback control. Adaptive information control takes place when there is adaptive selection of goals in a feedback control system, thus combining both feedback control and adaptive selection. The goals of the feedback control system are irreducible higher level variables determining the outcome, but are not fixed as in the case of non-adaptive feedback control; they can be adaptively changed in response to experience and information received. The overall process is guided by fitness criteria for selection of goals. The classical example is associative learning in animals, such as Pavlovian conditioning: an animal responds to a stimulus such as a sound, which is taken as a sign of something else and causes physical reactions implemented by motor neurons (Gray 2011). The training is causally effective by top-down action from the brain to cells in muscles. The fitness criterion is avoidance of negative stimuli; change of the associated goals (through a change in the environment) results in change of behaviour.

TD5: Adaptive selection of adaptive selection criteria. The most complex top down causation is when there is adaptive selection of adaptive selection goals. This includes intelligent top-down causation (i.e. the effect of the human mind on the physical world) - the special case of feedback control with adaptive choice of goals where the selection of goals involves the use of symbolic representation to investigate the outcome of goal choices. Here, a symbolic system is a set of structured patterns realized in time or space, arbitrarily chosen by an individual or group to represent objects, states and relationships (Deacon 1997). It will generally involve hierarchical structuring and recursion, as is required if it is to be useful in understanding complex situations, and has the potential to enable quantitative as well as qualitative investigation of outcomes. This is the process whereby creative impulses build on randomness to generate truly new artefacts that transform the world, such as dams, electrical power systems, aircraft, economic systems, computers, and the internet.

4.3 Adaptive selection as the key process underlying growth of complexity

Darwinian selection is the key to biological emergence where, through natural selection, top-down action from the environment codes information about appropriate responses to the environment into the detailed base sequence in each animal's DNA. But adaptive selection occurs much more widely than that. Its basic elements are shown in Figure 5.

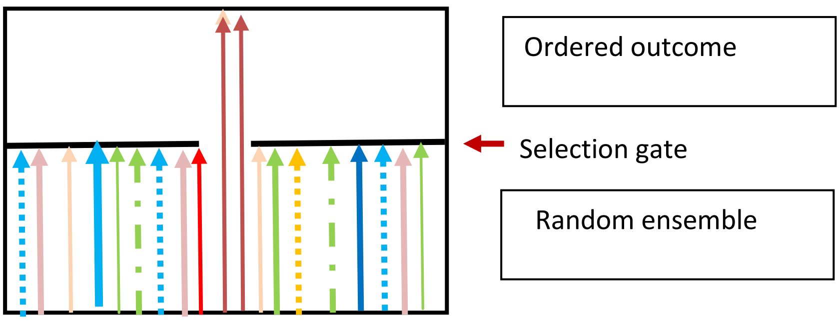

Figure 5: The basic selection process. *A selection gate creates order out of disorder by letting through only entities in a random initial ensemble that satisfy some selection criterion. This is an irreversible process: the initial state cannot be determined from the final state (the needed data is missing).*

The generic process of adaptive selection is the way meaningful information is created from a jumble of disordered objects, gained by discarding all the information received that is not meaningful. One can think of this as a selection gate creating order from disorder by deleting what is not wanted and keeping what is desirable in terms of meeting some higher level selection criterion. Irreversibility is introduced at the micro level by this process, whereby local entropy is decreasing as order increases, because the initial state cannot be determined from the final state: the informant needed is simply not there. As Landauer (1961) demonstrated, erasing unneeded information is an irreversible dissipative process.

This is the basic way that order is created from chaos, and useful information attained and stored. It occurs everywhere in biology and in the way our minds operate, where it is the basis of learning and the development of technology. It also occurs in chemistry and physics.

4.4 Key need for an ensemble of initial states from which to select

For adaptive selection to work, it needs some kind of random ensemble to work on. This must be generated by some kind of randomising process, as indicated in Figure 6.

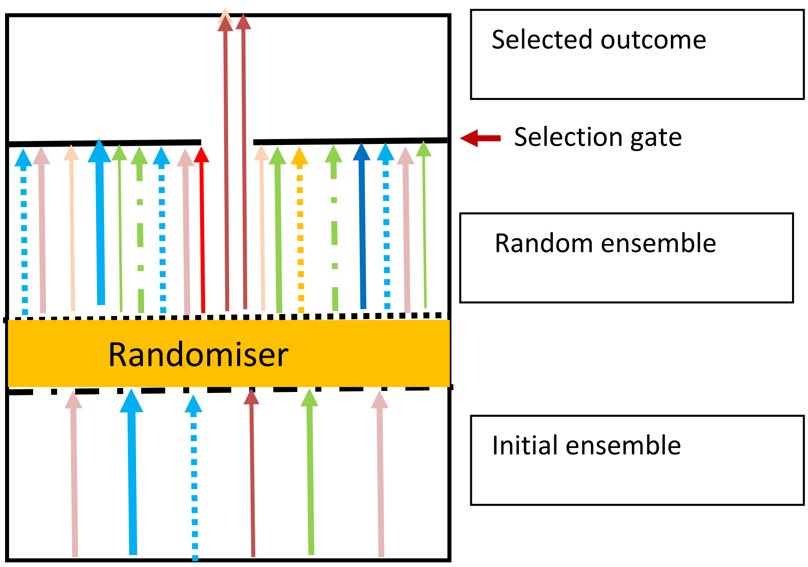

Figure 6: The randomizing process. *A randomizer provides the random ensemble form which selection takes place. This is what makes the process unpredictable*

According to Abbot, Davies, and Shalizi (2002),

> *"We now recognize that noise plays an indispensable role in many creative processes by providing a disturbing or enervating influence that can shunt a physical system randomly through a selection of states. In many systems, living and nonliving, there is an optimal state, defined according to some criterion of fitness (in the biological case that being the most suitable adapted organism). Noise will then enable the system to 'discover' the optimal state and maintain it. This principle of random shuffling toward an optimal state provides the basis for the powerful techniques of genetic algorithms, which have application to a wide range of practical design problems".*

There are essentially two ways the randomness can arise. Firstly, it may be due to irreversible quantum randomness, as discussed above. Acting on a given ensemble of initial states, it will produce an unpredictable ensemble of intermediate states from which the final ordered state may be chosen.

But secondly, randomness can also simply be the result of statistical interlevel relations in the hierarchy of complexity: the granular nature of lower level structures and large number of entities involved will result in fluctuations that can be selected from at the higher level, as in the way genetic randomness results in different phenotypes that can be selected from.

Thus although this is not foundational randomness, it is genuinely effective randomness in terms of interlevel relations, giving the basis for higher level outcomes not predictable on the basis of the initial data. This is the "chance" that Monod (1972) describes in his book.

4.5 Darwinian evolution

Both these kinds of randomness occur in Darwinian evolution: due to cosmic rays, as discusses dabove, on the one hand, and due to the random mixing of genes as sexual propagation of new genes takes place, on the other.

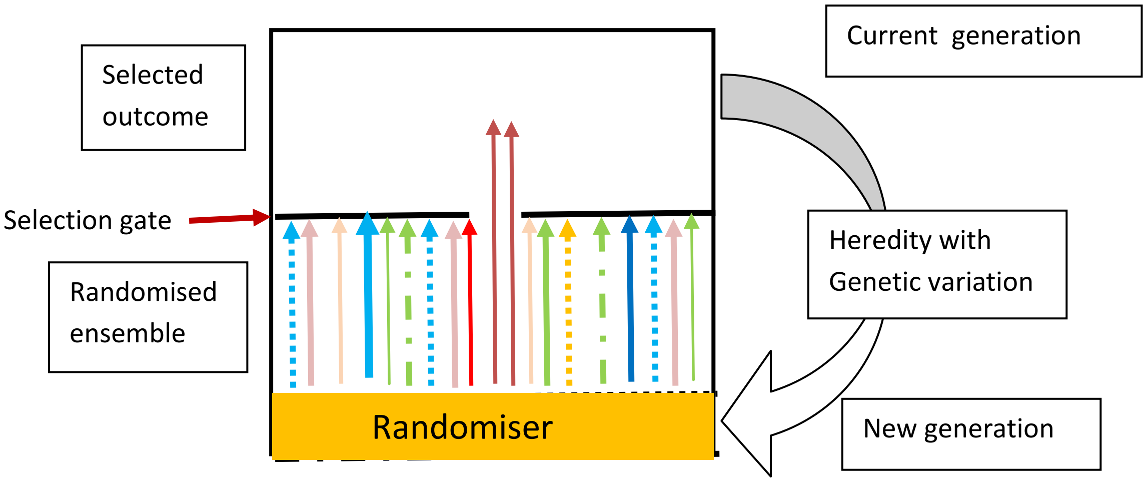

Figure 7: Darwinian selection. *The genetic randomizer takes the current state and provides the new random ensemble from which selection takes place. This is what makes the process unpredictable. Numerous repetitions give Darwinian processes their creative power.*

The great power of natural selection in this case derives from the continual repetition of the selection process with small variations repeatedly taking place, and eventually accumulating large changes that exquisitely adapt form, function, and behaviour to the physical, ecological, and social environment.

This process requires a downward flow of information from the environment into the organism, whereby information about environmental niches changes structure, function, and/or behaviour of the plant or animal. Hence development of such a downward flow of information is a key necessity in the evolutionary history of life (Davies 2012, Walker and

Davies 2013): without it, adaptive selection cannot start to take place. It is the implicit information flow that enables the process of adaptation.

Multilevel selection: It must be emphasized here that Darwinian selection is not a simple process of selection of genes on the basis of phenotype properties. Indeed there is no direct link from environmental fitness to gene properties. Rather selection of genes is a multi-step interlevel affair, whereby many levels of the hierarchy interact with each other (Cacioppo et al 2000) to select equivalence classes of genes that have a desired higher level effect – a classic case of top down causation (Martinez and Moyo 2011).

This is a complex and highly controversial subject; see Ellis (2013) for a brief motivation of this viewpoint, together with links to some of the large literature on the controversy and the Price equation that describes (Helanterä and Uller 2010). My own view is as follows:

A minimum for a realistic discussion of Darwinian selection in the case of higher animals is seven levels, see Figure 8, because ecosystem properties affect genetic selection through the intermediate levels shown there, rather than directly. Given this context, many examples occur where higher levels are selected for and then carry the lower levels along with them. In particular, once multicellular entities exist, selection cannot act directly on the gene level or even the cell level because there is no causal handle available for this to take place. It has to take place via higher levels (the group or the individual), this selection then acting down to the level of the genes. The point is that each cell depends on the organism for its existence.

Level 7	ecosystem level
Level 6	group level
Level 5	individual/animal level
Level 4	organ/systems level
Level 3	cell level
Level 2	multi-gene/DNA level
Level 1	individual gene level

Figure 8: *The biological levels involved in genetic selection in social animals.*

Thus the environmental context affects the organism and group viability, and selection is via these levels, not directly to the cell or gene level. Realistic discussion should refer to this full multi-level context, not just considering two levels.[iii] Any statistical approach used should reflect this causal mechanism. Furthermore, when selection takes place, it is not for specific genes, but for any families of genes in an equivalence class that produce the same higher level outcome that is selected for. The specific individual genes in the equivalence class that are realised do not matter, as far as the selection process is concerned.

It is this functional dependence on lower level equivalence classes that characterizes this process as top-down action (Auletta, Ellis, and Jaeger 2008).

Example: Formation of social groups. An important example of such multilevel selection is the formation of social groups, which is the key to the rise of society and technology. This gives major advantage at the group level which then confers benefits at the individual level that would not occur if the group did not exist. These key advantages – such as development of language, education of the young, and the growth of technology - is possible because individuals have an innate desire to form groups, which brings great behavioural advantage.

One can make the case (Ellis 2013) that this emotional desire to aggregate together arises from specific neurotransmitters at the cellular level, which operate within specific physical systems (the ascending systems) at the physiological level, selected for because they lead to group behaviour that is advantageous at the individual level. Gene clusters that select for these physiological systems are selected for because they lead to enhanced group performance, which then leads to greater survival prospects for the individuals and hence for the organs, cells, and genes that support this behaviour.

Drift and targeted change: In addition to adaptive selection, genetic drift based in underlying stochastic gene variation is a mechanism of importance in evolution (Masel 2011), with considerable debate taking place on the relative importance of the two effects (Barton et al 2007, Millstein, Skipper, and Dietrich 2009). [iv]

On the other side, it is not necessarily true that all evolutionary changes are random. There is now solid evidence of targeted DNA change that is functionally significant (Noble 2013. 2013a). Additionally, trans-generational inheritance occurs through epigenetic mechanisms (Noble 2013, 2013a). But once these have happened, they are tested by their survival value. Those that don't work are deleted; those that make no change can remain.

Thus these effects complicate the simple story of evolutionary processes. But in fact plants and animals end up with their hugely complex multilevel structure and function adapted beautifully to physical, ecological, and social environments: the overall effect is indeed adaptive selection. It is clear that many options must have been tested and many rejected to result in the exquisite adaptation that we see all around (Campbell and Reece 2005, Gray 2011). Through these various mechanisms, life is based in a process of trial and error which has extraordinary adaptive power when reiterated a huge number of times.

Randomness occurs at all the levels in Figure 8, and provides the opportunity to select for complex advantageous structure and behaviour. It is a key actor in the creation and function of the multiplicity of life we see around us.

4.6 Room at the bottom

But where does the causal slack lie enabling top-down action to take place? If the underlying physics is deterministic and determines all physics outcomes at the lower level, how is there freedom for higher level causation to be efficacious? Several key features are relevant (Ellis 2012)

1. **Causal Channelling by Structuring**: In considering specific physical and biological systems, the freedom lies partly in the choice of structuring of the system so as to attain higher level functions— constraints paradoxically create possibilities. For example, the specific connections in a computer (which could have been different) act as constraints on lower level dynamics, thus channelling how they function. Partly it lies in the boundary conditions that select specific solutions, together with openness of the system: new information can enter across the boundary and affect local outcomes.

Together these features set the environment in which the lower level components operate, and so determine their outcomes. No specific solution without boundary conditions!

2. **Altering elements**: Top-down causation can change the nature of the lower elements; for example cells get adapted to their specific roles in an animal's body. There is not just a situation of invariant lower level elements obeying fixed physical laws; rather we have the nature of lower level elements being changed by context. Often this ensures that the lower level elements function so as to fulfil higher level purposes: this is an aspect of adaptive selection (Campbell 1974). Thus, the nature of micro-causation is changed by top-down processes, profoundly altering the mechanistic view of how things work.

3. **Creating elements**: Top down causation due to a specific environment can create lower level entities that would not otherwise exist on their own. Examples are symbiotic entities in biology, the cells in the human body, and Cooper pairs that enable superfluidity in solid state physics. Effective lower level entities are caused to exist by the higher level context: they would not exist without that context.

4. **Deleting elements**: Adaptive selection can delete lower level entities, thus creating order out of disorder (see the previous sections). An example is deleting files or emails on a computer. What remains expresses the order entailed by the selection criteria. By throwing away unnecessary information one creates order that is useful for higher level purposes.

5. **Underlying Indeterminacy** The underlying microphysics is not determinate (see Section 2), although people often talk as if it is – even though quantum physics has been an established part of physics for nearly 100 years. The required freedom partly lies in micro-indeterminism (random outcomes of microphysical effects) as seen from the next level up. Combined with adaptive selection, random outcomes at the micro-level allow variation at the macro-level, which then leads to selection at the micro-level, but based on macro-level properties and meaning. Statistical variation and quantum indeterminacy provide a repertoire of variant systems that are then subjected to processes of adaptive selection, based on higher level qualities of the overall system

Because of the existence of these various effects, with irreducibly random processes occurring at the bottom level, there is sufficient causal slack to allow all the kinds of top-down causation Td1-TD5 to occur without violation of physical causation, and then affect macro level properties. For example, developmental biology amplifies molecular-level variation to system-level changes that are adapted to higher level purposes.

4.7 Top-Down effects in physics

Finally the significant further point is that top down causation also takes place in physics.

Top down causation TD1 (algorithmic) takes place in physics, as discussed in Ellis (2012a), but TD2 (feedback control) does not, except in the context of a designed system. What about TD3 (adaptive selection)? A key example of this process in physics is state vector preparation (Isham 1995), which is crucial to all quantum physics experiments. For example photons in a specific polarisation state are selected from an ensemble of random incoming polarisation states, either by separation and collimation, or by selective absorption, the others being discarded (neither is a unitary process: it is possible because the local context acts down in a non-unitary way on the state vector). It also occurs in the purification processes that underlie nanotechnology, chemistry, and chemical engineering.

Adaptive selection may well relate to how the quantum measurement process takes place in a contextual way (Ellis 2012a), as suggested by the transactional approach to quantum mechanics (Cramer 1986). It is in any case built into the Lagrangian view of dynamics, where the initial velocity is selected for by variation over the entire path from the initial to the final event. This is rather similar to the Feynman path integral approach to quantum physics (Feynman and Hibbs 1965), where the selection principle from the variety of paths explored is minimisation of the action along the path (Feynman 1988). There is work to be done developing this idea.

Because these forms of top down causation occur in the physics that underlies biology, it is hardly surprising that there is no problem with it occurring in biology as well.

4 RANDOMNESS AND THE PROCESSES OF BIOLOGY

That random processes are a core feature of biological functioning is indicated by many kinds of evidence (Glimcher 2005, Eldar and Elowitz 2010, Chouard 2011). In particular adaptive selection is a key process at all levels. This can only work because of the large gap between macro and microphysics, together with the huge number of micro-components involved (atoms in a cell, cells in a human body, etc.). Emergence of genuine complexity requires the vast numbers of entities at the lower levels as entailed in physical reality.

In particular randomness is a key feature of Darwinian evolution, as emphasized above, leading to the extraordinary variety of life we see today (Campbell and Reece 2005). As stated in Wikipedia,

> *"The modern evolutionary synthesis ascribes the observed diversity of life to natural selection, in which some random genetic mutations are retained in the gene pool due to the systematically improved chance for survival and reproduction that those mutated genes confer on individuals who possess them."*

In more detail, Elowitz et al (2002) comment

> "*Clonal populations of cells exhibit substantial phenotypic variation. Such heterogeneity can be essential for many biological processes and is conjectured to arise from stochasticity, or noise, in gene expression. McAdams and Arkin (1997) show that proteins are produced from an activated promoter in short bursts of variable numbers of proteins that occur at random time intervals. As a result, there can be large differences in the time between successive events in regulatory cascades across a cell population. In addition, the random pattern of expression of competitive effectors can produce probabilistic outcomes in switching mechanisms that select between alternative regulatory paths. The result can be a partitioning of the cell population into different phenotypes as the cells follow different paths*."

Rao, Wolf and Arkin (2002) comment that noise has many roles in biological function, including generation of errors in DNA replication leading to mutation and evolution, noise-driven divergence of cell fates, noise-induced amplification of signals, and maintenance of the quantitative individuality of cells. Promoter decoding of transcription factor dynamics involves a trade-off between noise and control of gene expression (Hansen and O'Shea 2013); the control circuits are adapted to take this into account.

The pattern is clear: randomness provides a basis for selection, enabling adaptation. Thus randomness is indeed key to the existence of complex life forms, and is important in molecular and developmental processes.

5.1 Handling randomness

As mentioned above, randomness can be an enemy disrupting the orderly functioning of biological systems, so top-down processes TD1 and TD2 in biology are designed to handle randomness at both the organ and cellular levels (Rhoades and Pflanzer 1989).

As far as TD1 is concerned, algorithmic processes embody attractors, activation thresholds, and dissipative damping that enables life to survive disruptive perturbations. Additionally the homeostatic processes characterised by TD2 are specifically designed to ensure that congenial internal environments are maintained: blood pressure, body temperature, ion levels, and so on are all regulated with great precision by physiological systems (Rhoades and Pflanzer 1989, Noble 2006), as are cell processes. Cells operate within strict parameters requiring precise homeostatic control of the internal environment: noise is largely filtered by the system.

Thus the effect of chance is controlled and limited by the relevant structures and processes, built into life for this purpose through Darwinian evolution. But more than that, it is often used to advantage.

5.2 Using randomness

At the molecular and cellular level, random processes are used to advantage by micro processes subject to a molecular storm, which results in huge numbers of collisions between molecules every second (Hoffman 2012). This is important both in molecular machinery and in supramolecular chemistry, thus playing a key role in cell processes.

Molecular Machinery This firstly provides random energy that can be used to extract useful energy by suitable molecular machinery, where it is key to many cell processes and to the way muscles work, using Brownian ratchets to extract energy from the molecular storm. This does not violate the second law of thermodynamics because of the ratchet-like shape of the energy landscape together with a reset step powered by ATP (Hoffman 2012). The extraordinary requisite molecules such as kinesin-1 and myosin V are there because they have been selected for through Darwinian processes in evolutionary history.[v]

Supramolecular chemistry and cell processes Secondly, it provides a random set of biomolecules from which the needed or meaningful ones can be selected as needed. This is crucial in supramolecular chemistry and cell processes.

The key factor here is molecular recognition (Gellman 1997), the “lock and key” mechanism of molecular biology which is the basis for supermolecular chemistry (Lehn 1995; Ariga and Kunitake 2006, Ariga, Hill, and Endo 2007). It occurs between receptors and ligands, antigens and antibodies, in enzyme substrate interactions catalysing formation of molecules, in the DNA to protein system where it implements the genetic code, between sugars and lectins, between RNA and ribosomes, and so on. It also plays a key role in the clonal selection theory of acquired immunity (Burnet 1995). Thus it is crucial to all life.

Adaptive selection is the core mechanism in all these cases, enabled by the incoming ensemble of molecules to choose from. This ensemble is random in that in includes a vast variety of molecules irrelevant to the current need; but it is highly specific in that it does indeed include specific molecules needed for particular current biological purposes. They are there because of a combination the evolutionary and physiological context; and that is where the top-down, goal-directed part of the causal nexus occurs. A fine mixture of chance and natural design enables the mechanisms to work in all these contexts.

5.3 Prevalence of randomness in molecular and cell biology

As a consequence, there is much evidence of the importance of randomness (or `noise’) in molecular and cell biology, for example playing a functional role in genetic circuits (Eldar and Elowitz 2010). The nature of these random fluctuations in genetic networks is discussed by Paulsson (2004) and Raser and O'Shea (2005). According to Buiatti and Longo (2013),

> **“***Biological randomness is not only an essential component of the heterogeneous determination and intrinsic unpredictability proper to life phenomena, due to the nesting of, and interaction between many levels of organization, but also a key component of its structural stability.*”

Samoilov, Price, and Arkin, (2006) state:

> “*There are fundamental physical reasons why biochemical processes might be subject to noise and stochastic fluctuations. Indeed, it has long been understood that random molecular-scale mechanisms, such as those that drive genetic mutation, lie at the heart of population-scale evolutionary dynamics. What we can now appreciate is how stochastic fluctuations inherent in biochemical processes contribute to cellular and organismal phenotypes. Advancements in techniques for empirically measuring single cells and in corresponding theoretical methods have enabled the rigorous design and interpretation of experiments that provide incontrovertible proof that there are important endogenous sources of stochasticity that drive biological processes at the scale of individual organisms. Recently, some studies have progressed beyond merely ascertaining the presence of noise in biological systems; they trace its role in cellular physiology as it is passed through and processed by the biomolecular pathways—from the underlying origins of stochastic fluctuations in random biomolecular interactions to their ultimate manifestations in characteristic species phenotypes.”*
>
> *“These emerging results suggest new biological network design principles that account for a constructive role played by noise in defining the structure, function, and fitness of biological systems. They further show that stochastic*

> *mechanisms open novel classes of regulatory, signaling, and organizational choices that can serve as efficient and effective biological solutions to problems that are more complex, less robust, or otherwise suboptimal to deal with in the context of purely deterministic systems. Research in Drosophila melanogaster eye color-vision development and Bacillus subtilis competence induction has elegantly traced the role of noise in vital physiological processes from fluctuations to phenotypes, and is used here to highlight these developments."*

In particular, randomness plays a key role in molecular machinery (Hoffman 2012). According to Hänggi and Marchesoni (2009),

> "*A solution common to most cell machinery is to have molecular motors operating on a track that constrains the motion to essentially one dimension along a periodic sequence of wells and barriers. The energy barriers significantly suppress diffusion, while thermal noise plays a constructive role by providing a mechanism, thermal activation, by which motors can escape over the barriers. The energy necessary for directed motion is supplied by asymmetrically raising and lowering the barriers and wells, either via an external time-dependent modulation e.g., due to the coupling with other motors_ or by energy input from a nonequilibrium source such as a chemical reaction, like ATP hydrolysis. Thus, in agreement with the reasoning underlying the analysis of the Smoluchowski-Feynman stylized ratchet engine, under appropriate nonequilibrium conditions structural anisotropy can sustain directed motion. Such a device does not violate the second law of thermodynamics because the very presence of nonequilibrium renders inoperative those limiting thermal equilibrium restrictions.*"

Chowdhury (2013) considers the various kinds of molecular machines: porters, sliders and rowers, pistons and hooks, exporters, importers, packers and movers as well as those that also synthesize, manipulate and degrade macromolecules of life. He shows that noise need not be a nuisance for a motor; instead, it can move forward by gainfully exploiting this noise. A noise-driven mechanism of molecular motor transport, which does not have any counterpart in the macroscopic world of man-made motors, is closely related to fundamental questions on the foundations of statistical physics.

Overall, randomness provides a variety of opportunities that cellular mechanisms can choose between to meet current needs by using biochemical processes. Chance enables goal-directed processes to use necessity to attain those goals.

5 RANDOMNESS AND THE PROCESSES OF THE BRAIN AND MIND

Adaptive processes occur at both the micro and the macro level and shape how brain plasticity develops in response to the physical and social environment.

Because the brain is based in molecular processes, all the mechanisms just discussed are at work in the brain at the micro level, enabling its biological functioning. However in addition, randomness occurs at the macro level. Some brain mechanisms are designed to handle this in a constructive way, by filtering out the relevant data from the noise. Additionally, adaptive selection is essential to brain processes at the macro level, for it is the basis of how we learn.

5.1 Handling Randomness

Our senses are continually bombarded by a huge volume of incoming data. The mind has to handle this by selecting what is meaningful in relation to survival first and chosen purposes second, discarding the rest (Beer 1972). You do not notice most of the details of what is in front of you, unless you make a conscious effort to do so. What data is deemed relevant is selected by a process of prediction on the basis of the current context, noticing what is needed and filtering out the rest, which is taken as a fixed background context to be taken for granted, and so is not even consciously noticed (Frith 2007). They need no attention because they contain no surprises. Unconscious processes predict their outcomes and handle them. Conscious effort is saved for handling the unexpected and novelty.

Confronted with a rich sensory environment, the brain must learn statistical regularities across sensory domains to construct causal models of the world. A paper by den Ouden et al (2009) used functional magnetic resonance imaging and dynamic causal modeling (DCM) to furnish neurophysiological evidence that statistical associations are learnt even when task-irrelevant. Activity in primary visual cortex and putamen reflected learning-dependent surprise: these areas responded progressively more to unpredicted, and progressively less to predicted visual stimuli. Consistent with predictive coding models of perception, associative learning is mediated by prediction-error dependent changes in connectivity. These results posit a dual role for prediction-error in encoding surprise and driving associative plasticity.

There is noise in the incoming internal and external data. Harris and Wolpert (1998) consider how signal-dependent noise determines motor planning .They present a unifying theory of eye and arm movements based on the single physiological assumption that the neural control signals are corrupted by noise whose variance increases with the size of the control signal. They propose that in the presence of such signal-dependent noise, the shape of a trajectory is selected to minimize the variance of the final eye or arm position. This minimum-variance theory accurately predicts the trajectories of both saccades and arm movements and the speed–accuracy trade-off described by Fitt's law. Their theory provides a simple and powerful unifying perspective for both eye and arm movement control.

Thus the mind is adapted to handle acceptable levels of randomness without having to continually make a conscious effort to do so. It unconsciously selects what is significant and discards the rest, which is handled automatically.

5.2 Using randomness

Additionally, an increasing literature emphasizes that, as in the case of microbiology, the brain uses randomness to advantage.

- McIntosh *et al* (2008, 2010) show that maturation appears to lead to a brain with greater functional variability, which is indicative of enhanced neural complexity. This variability may reflect a broader repertoire of metastable brain states and more fluid transitions among them that enable optimum responses. Brain maturation not only leads to more stable and accurate behaviour in the performance of a memory task, but correlates with increased brain signal variability. This doesn't mean the brain is working less efficiently. Such changes enhance information processing capacity, moving the brain from a deterministic system to one that is more stochastic. It shows greater functional variability, which is indicative of enhanced neural complexity. These findings suggest that the random activity that we think of as noise may actually be a central component of normal brain function.

- To learn and reason in the presence of uncertainty, the brain must be capable of imposing some form of regularization. Bouvrie and Slotine (2013) suggest, through theoretical and computational arguments, that the combination of noise with synchronization provides a plausible mechanism for regularization in the nervous system.
- Garrett, McIntosh and Grady (2013) and Garrett et al (2013) consider how moment-to-moment brain signal variability is a ubiquitous neural characteristic. Evidence indicates that heightened signal variability can index and aid efficient neural function.

Thus micro brain function can use noise constructively.

The macro level perspective. The mind works by adaptive prediction of what is likely to happen (Hawkins, 2004), updated on an ongoing basis. Predictions are made, tested, and altered where necessary; the relevant random ensemble is a time sequence of explicit or implicit hypotheses that are subject to testing.

This underlies most of our mental ability. For example, the process of perception is a predictive adaptive process using Bayesian statistics to update the current perception on the basis of prediction errors, thus this is an ongoing correction process in time with incorrect hypotheses replaced by correct ones as need be. This includes prediction of the intention of others, which is the basis of theories of other minds (Gray 2011).

All this is learnt by processes of adaptive selection that underlie brain plasticity at the micro level, with the "fire together and wire together" Hebbian mechanism (Gray 2011) supplemented by neuronal group selection on the basis of a neuro-transmitter based `value system' (Edelman 1989), see Section 5.3.

At the macro level, it is the way we learn individually and collectively: it is in essence another form of the mechanism indicated in Figure 7, with "Heredity with Genetic variation" replaced by "Varied Hypothesis Generation" (see Figure 9).

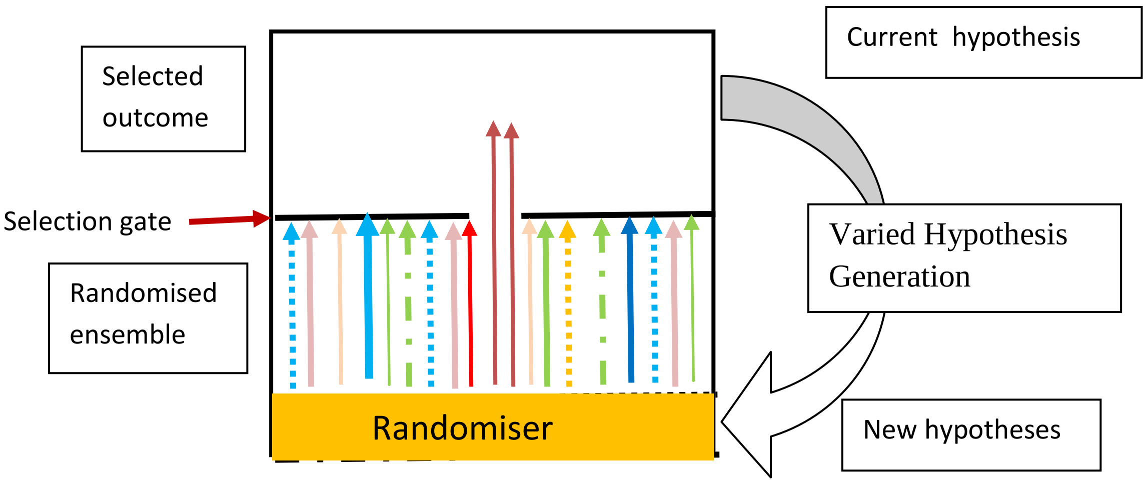

Figure 9: Learning processes. *Imagination creates new hypotheses as possibilities to replace a current inadequate hypothesis. Selection against the data, together with emotional and aesthetic criteria, rejects most of them, and results in new best understandings of the situation. This learning cycle repeats continually.*

This applies at the individual level as we negotiate the physical and social milieu in which we are imbedded. It is also applies at the communal level, being the basis of the social development of science and technology, and hence of the rise of civilisation (Bronowski 1973). Imagination creates theories and visions that we develop and test. We eventually keep those that work, and discard the rest.[vi]

Overall, this mechanism is the way top-down action shapes the lower level components (the neural connections) to fulfil their higher level roles. The selection process utilizes higher level data about the physical, ecological, and social environment to shape micro-level outcomes in structural and behavioural terms, leading to adapted higher level thought patterns and understandings of relations (Churchland 2013).

Creativity and play. The outcome of the random micro processes is creativity**,** developed by exploring the space of possibilities. Imagination, developed by play, opens up the ensemble of possibilities from which one can choose. Random ideas provide the palette of choice. Adaptive selection develops ideas, theories, and mental habits that shape how we think. An innate play system drives this process emotionally (Ellis and Toronchuk 2005). The importance of play in education (see Figure 10) derives from this process.[vii]

Figure 10: ***Creative play. From the Annex Project: http://theannexproject.com/playcreative-therapy/***

The central theme at both the macro and micro level is selection from an ensemble of opportunities and possibilities: creativity and learning take place by repeated trial and error, see Figure 9. This process occurs in all human thought and learning, and particularly in development of science and technology.[viii]

5.3 Underlying mechanisms

Selectionist and evolutionary mechanisms underlie brain function at the micro level, as explained by Fernando, Szathmáry and Husbands (2012). As stated by them,

> *"These processes include Edelman's theory of neuronal group selection, Changeux's theory of synaptic selection and selective stabilization of prerepresentations, Seung's Darwinian synapse, Loewenstein's synaptic melioration, Adam's selfish synapse, and Calvin's replicating activity patterns. Except for the last two, the proposed mechanisms are selectionist but not truly Darwinian, because no replicators with*

information transfer to copies and hereditary variation can be identified in them. All of them fit, however, a generalized selectionist framework conforming to the picture of Price's covariance formulation, which deliberately was not specific even to selection in biology, and therefore does not imply an algorithmic picture of biological evolution. Bayesian models and reinforcement learning are formally in agreement with selection dynamics."

Edelman in particular argues that generalised principles of Darwinian selection ("Neural Darwinism") must apply in the developmental process controlling detailed neural connections in each individual's brain (Edelman 1989, 1992; Edelman & Tononi 2001). The theory has three main elements:

1. Developmental selection,
2. Experiential selection,
3. Re-entry

(Edelman 1989:4-8; Edelman 1992:81-98; Edelman and Tononi 2001:79-92). The chemical gradients of molecules, which in some cases are the same as those used by the immune system, steer neurons in the generally right direction and these molecules may also prevent pre-programmed apoptosis. Competition for synapses then weeds out those which receive less use. In other words general tuning occurs by chemical gradients, but epigenetic experience provides specific tuning of those pathways.

The key feature is that, after developmental processes establish a great variety of connection patterns between neurons, a process of synaptic selection occurs within neuronal groups as a result of behavioural experiences that modify affective states. These changes occur because certain synapses are strengthened and others weakened without macroscopic changes in the anatomy, although there might be microscopic changes such as perforated synapses or changes in dendritic spines. "*This selectional process is constrained by brain signals that arise as a result of the activity of diffusely projecting value systems, a constraint that is continually modified by successful output*" (Edelman & Tononi, 2001, p.84; see also Deacon, 1997, p.202). An example of a value system is the noradrenergic system, originating in the locus coeruleus and projecting diffusely to the entire brain, releasing norepinephrine.

The unit of selection is neuronal groups (Edelman, 1989, pp.43-69; Edelman, 1992, pp.95-99). The "groups" that are selected experientially are those neurons which participate in ongoing, reciprocal signalling between widely separated regions of the brain (forming "re-entrant networks"). This parallel interchange allows for coordination and synchronous firing in the individual components of the neural group enabling coherent coordinated output. The value system is in effect the primary genetically determined emotional systems that Panksepp (1998) has identified, and so is a key link between emotion and intellect (Ellis and Toronchuk 2005).

This argument extends adaptive understanding from the evolutionary processes that historically led to the existence of the brain and shaped the genotype to also underpinning both brain developmental processes and brain functioning, thus directly affecting the phenotype. This is in accord with the way that such processes are now understood to underlie the functioning of the immune system through clonal selection[ix] (Burnet, 1959; Edelman, 1992, pp.77-78). Thus such principles are already known to occur in human physiological functioning in the immune system, giving the same benefits as discussed here: putting in place a mechanism that can deal efficiently with conditions already encountered, but that can also deal adequately with situations that have never before been encountered by the organism. Through this mechanism, "*In a very literal sense, each developing brain region adapts to the body in which it finds itself*" (Deacon, 1997, p.205).

Thus this provides a neural mechanism underlying traditional learning theory, also imbedding it in the broader understanding of the adaptive power of adaptive selection processes, seen as one of the most important mechanisms in biology.

This also applies to other aspects of the brain. A *biased competition mechanism* may be the neural basis of attention (Deco and Rolls 2005). According to this hypothesis, attention appears as a sometimes non-linear property that results from a top-down biassing effect that influences the competitive and cooperative interactions that work both within cortical areas and between cortical areas. The theme of competition and selection recurs continually.

5.4 Prevalence of Randomness in brain

Through these processes, randomness is crucial in the brain. According to Glimcher (2005), randomness is apparent in neuroscience at the microlevel and behaviour: at the macrolevel:

> *"Recent advances in the psychological, social, and neural sciences, however, have caused a number of scholars to begin to question the assumption that all of behavior can be regarded as fundamentally deterministic in character. … 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".*

Deco, Rolls, and Romo (2009 show that in the dynamics of neural processing, noise breaks deterministic computations and has many advantages. They show how computations can be performed through stochastic dynamical effects, including the role of noise in enabling probabilistic jumping across barriers in the energy landscape describing the flow of the dynamics in attractor networks.

The Noisy Brain: Stochastic Dynamics as a Principle of Brain Function (Rolls and Deco 2010) describes approaches that provide a foundation for this understanding, including integrate-and-fire models of brain and cognitive function that incorporate the stochastic spiking-related dynamics, and mean-field analyses that are consistent in terms of the parameters with these, but allow formal analysis of the networks which include some of the effects of noise on the operation of the system. Unlike digital computers, brain function cannot be understood as a deterministic noiseless system.

5.5 Input from Platonic entities

A key feature is that while this process of variation and selection proceeds in a way based in the underlying physics and neurobiology, human learning also involves abstract patterns that are not physical phenomena, but are nevertheless part of the underlying nature of existence.

Mathematical Relations: A key example is abstract mathematical relationships, which are not physical entities but rather have a Platonic nature, see Penrose (1989), Changeux and Connes (1995) for discussion.

Major parts of mathematics are discovered rather than invented (rational numbers, zero, irrational numbers and the Mandelbrot set being classic examples). They are not determined by physical experiment, but are rather arrived at by mathematical investigation. They have an abstract rather than embodied character; the same abstract quantity can be represented and embodied in many symbolic and physical ways, and these representations form an equivalence class. The underlying mathematical truths are independent of the existence and culture of human beings; it is plausible that the same features will be discovered by intelligent beings in the Andromeda galaxy as here, once their mathematical understanding is advanced enough (which is why these features are advocated as the basis for interstellar communication).

Selection processes operating in neural networks develop in such a way as to recognise such abstract patterns of logic (Churchland 2013), which then become part of the causal processes in operation in the brain. Through this mechanism, a different form of necessity is causally effective than is embodied in physical laws: it is the necessity of abstract logic and mathematics, which underlies associated logical structures such as algorithms and digital computer programs.

These features are discovered by humans, and represented by our mathematical theories; that representation is a cultural construct, but the underlying mathematical features they represent are not—indeed like physical laws, they are often unwillingly discovered, for example, the irrationality of the square root of 2 and the number π. These mathematical verities are causally efficacious through the actions of the human mind: one can, for example, print graphic versions of the Mandelbrot set in a book, resulting in a physical embodiment in the ink printed on the page.

Mathematics comprehension and utilization is thus a case of top-down causation from a logical possibility space (the world of mathematical abstractions) to the human mind, being realized through learning processes in details of neuronal connections (Churchland 2013), and then into the real world where it is causally effective both in terms of creating patterns on paper, and by underlying all physics, engineering, and planning.

Physics theories: Maxwell's theory of electromagnetism (an abstract entity described by Maxwell's equations) led to the development of radio, and then to existence of cell phones, TV and so on, based on manipulation of physical materials composed of atoms and electrons.

Maxwell's theory is not a physical entity, nor is it the same as any single person's brain state: it is an abstract pattern of understanding. It can be represented in many ways (on blackboards, in print, on computer screens, in spoken words) and in many formalisms (three-dimensional vectors or four-dimensional tensors, for example). These various representations together form an equivalence class, as they all lead to the same predicted outcomes.

How do you demonstrate causal efficacy of this theory? Design an artefact such as a cell-phone through the use of Maxwell's equations, and then construct it and operate it. The abstract theory will have altered physical configurations in the real world so as to lead to his desired output, and hence is causally effective. The theory is an irreducible higher level entity (it cannot be derived by coarse-graining any lower level variables) representing the nature of physical reality: it is an abstract representation of physical laws of behaviour that are eternal and omnipresent (physics is the same everywhere in the universe). It is the accuracy of this representation of the way the world works that gives the theory its causal powers: it is demonstrably a good representation of the underlying physical reality (namely, the consistent regularities in the behaviour of matter that underlies what happens in the physical universe).

Hence in this way, the causal regularities in the physical world can be represented as a set of abstract patterns, resulting in a mental theory that is causally efficacious. It is the underlying logical pattern that is the ultimate source of this causal efficacy, and hence through the mind (enabled by TDC5) has causal powers in the physical world, for example, by underlying engineering practice.

These two examples show how the patterns of possibilities embodied in these abstract patterns –a key part of necessity - are enabled to be causally effective through learning processes that are enabled by random processes followed by selection, as described above. Thus there is not only physical input into the universe: there is abstract input as well from these possibility spaces, which are knowable by the human mind, and represent crucial parts of necessity. And this changes things, e.g. by leading to the existence of digital computers.

5.6 Mental causation: dualism of mind and body

How does this happen? Minds with real causal powers can apprehend platonic realities (Churchland 2013) and thereby bring new input that was not in the physical initial data, but was present in eternal unchanging possibility spaces. Physics provides the necessary conditions for the existence of such higher-level outcomes, but not the sufficient conditions to determine the resulting behaviour. These are affected by 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 and the higher-level entities that in fact shape its outcomes, including abstractions such as understandings of mathematics, the value of money, the rules of chess, local social customs, and socially accepted ethical values.

These kinds of concepts and influences 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 in the universe. The key point is that human understandings and intentions are causally effective in terms of changing conditions in the physical world but are outside the domain of physics.

One of the intriguing aspects of present day views of the brain is the use of the digital computer as a metaphor. Now this is of course a very partial view, nevertheless (remembering that one can simulate any neural network on a digital computer) it does apply to some aspects of how the brain functions. The key point then is that a digital computer is a dualist machine: the hardware does nothing without the software, which is a non-physical entity that inhabits the hardware and controls what happens via its algorithms—which again are non-physical entities. Immaterial software shapes the outcomes of physics-driven hardware. Logic shapes what happens via algorithms. The physical underpinnings enable and facilitate this but do not control it. Hence the computer metaphor strongly supports the unfashionable idea of dualism of mind and brain.

Whether we accept this or not, in any case the mind is able to be causally effective because it operates at the higher levels of the hierarchy (Figure 4) in terms of the logic at that level, this being enabled by TD5 (doubly based in adaptive selection), and then acts down to control and shape lower levels in the hierarchy.

6 THE OUTCOME

The initial state of the universe allows all this to happen, but does not dictate the outcome. It cannot do so because of the randomness created by quantum uncertainty, which unfolds over time and creates possibilities out of which complexity can arise.

Layers of quantum indeterminateness at the bottom, classically determinate causation at higher levels, and indeterminate effects in emergent higher level structures at the top can embody higher level organisation and meaning through learning processes allowed by adaptive selection.

6.1 The bottom line

The outcome of the argument presented in this paper is as follows:

> ***Because of the processes discussed here, the occurrence of chance and randomness in the universe in addition to physical necessity does not mean that what happens is simply random. It opens up the space for higher levels of meaning to have real causal powers, and to embody abstract types of causation representing higher levels of meaning not written into the physical initial conditions in the universe. They are however enabled by abstract possibility spaces that enable their occurrence.***

This has all been supported in detail above, with many examples.

I close with three final comments.

6.2 The existential context

Where do the very causal categories of chance, necessity, and purpose come from? How do these concepts arise and have meaning, and what underlying ontological entities or causation do they represent? How can they even be relevant, as this whole discussion supposes, if there is no ontological referent that makes the dichotomy between them a meaningful issue? That itself surely cannot be shown to be necessary: for it is the very category of necessity that has to be explained.

They are written into the possibility spaces that underlie all that happens. The deep issues is why this is the case. That is a philosophical issue that cannot be determined by physics or indeed by science. I will not pursue it here; hints of a direction to go are in (Ellis 1993, 2011).

6.3 Multiverses and probability

I have not dealt here with probability measures for universe domains in a multiverse. Because the multiverse is not a scientifically testable theory, I do not see this as profitable, and will not enter that debate here. My arguments in this paper are all based in solid testable science.

6.4 The alternative: the demiurge

Suppose the argument presented at the start was not the case: forget quantum uncertainty and assume everything in the history of the earth is indeed written into the fluctuations on the LSS observed by Planck. We then have to explain how this paper, the theory of General Relativity, the Mona Lisa, the international banking system, etc. etc. could all have been encoded there in the initial data for the later universe.

This is simply unbelievable. Who or what could have set the molecules then just so as to get these results? To determine every thought that Maxwell, Einstein, Karl Marx had? This is not even remotely credible. It is fantasy. Suppose the initial data were ordered so as to produce these highly structured outcomes, what agent could have been responsible for this ordering? What kind of god or demiurge could have been responsible? Certainly not random quantum fluctuations, as envisaged in inflationary theory, which by its very nature only leads to random Gaussian processes. Such highly ordered logical systems cannot possibly be a unique outcome of Gaussian random processes in the early universe.

In fact, the only realistic possibility is emergence of brains with genuine causal powers that lead to these thoughts and resultant theories, such as General Relativity Theory and the theory of Evolution. These are creations of the mind that are not written into the initial data in the universe. They are wonderful products of emergent human intellect with its extraordinary imagination and causal powers. Their existence is not compatible with the deterministic picture, where all that exists is uniquely written into the Cauchy data at any arbitrary time.

They about come by imaginative investigation of possibilities, and discarding those that don't work: the adaptive process that is the theme of this paper, enabled by modicum of randomness at macro and micro levels.

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Endnotes

[i] email: george.ellis@uct.ac.za

[ii] See http://www.youtube.com/watch?v=DfPeprQ7oGc for a rather dynamic presentation of the issues.

[iii] It is quite extraordinary how some evolutionary theorists deny this, using the most vituperative terms, see http://whyevolutionistrue.wordpress.com/2013/08/25/famous-physiologist-embarrasses-himself-by-claiming-that-the-modern-theory-of-evolution-is-in-tatters/. A complete answer to the scientific issues raised in that blog is here: http://www.musicoflife.co.uk/pdfs/Answers-new1.pdf.

[iv] For a good discussion see http://en.wikipedia.org/wiki/Genetic_drift.

[v] Fir a video of the mechanism of kinesin walking, see http://www.youtube.com/watch?v=YAva4g3Pk6k, with the outcome shown here: http://www.youtube.com/watch?v=y-uuk4Pr2i8.

[vi] "Work" has emotional as well as intellectual components. They compete to determine outcomes.

[vii] See Peter Gray's blog at http://www.psychologytoday.com/blog/freedom-learn.

[viii] This leads to the idea of "memes" in analogy with genes. However this is just a weak analogy between rather different processes. In fact, "memetics" is a proposal with no testable outcomes and no predictive content. The well-developed area of cultural history is rather closer to a scientific theory.

[ix] An antigen selects particular lymphocytes out of a very diverse population of pre-existing lymphocytes for clonal expansion, enabling the immune system to respond to antigens that it has never encountered before.

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Robert Russell: RRussell@ctns.org

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