COMPLEXITY BIOLOGY-BASED INFORMATION STRUCTURES CAN EXPLAIN SUBJECTIVITY, OBJECTIVE REDUCTION OF WAVE PACKETS, AND NON-COMPUTABILITY

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ABSTRACT: **Background**: how mind functions is subject to continuing scientific discussion. A simplistic approach says that, since no convincing way has been found to model subjective experience, mind cannot exist. A second holds that, since mind cannot be described by classical physics, it ***must*** be described by quantum physics. Another perspective concerns mind's hypothesized ability to interact with the world of quanta: it should be responsible for reduction of quantum wave packets; physics producing 'Objective Reduction' is postulated to form the basis for mind-matter interactions. This presentation describes results derived from a new approach to these problems. It is based on well-established biology involving physics not previously applied to the fields of mind, or consciousness studies, that of *critical feedback instability*.

Methods: 'self-organized criticality' in complexity biology places system loci of control at critical instabilities, physical properties of which, including information properties, are presented. Their elucidation shows that they can model hitherto unexplained properties of experience.

Results: All results depend on physical properties of critical instabilities. First, at least one feedback or feed-forward loop must have feedback gain, $\mathbf{g} = 1$: information flows round the loop impress perfect images of system states back on themselves: they represent processes of *perfect self-observation*. This annihilates system quanta: system excitations are *instability fluctuations*, which cannot be quantized. Major results follow:
1. Information vectors representing criticality states must include at least one attached information loop denoting self-observation.
2. Such loop structures are attributed a function, 'registering the state's own existence', explaining
a. Subjective 'awareness of one's own presence'
b. How content-free states of awareness can be remembered (Jon Shear)
c. Subjective experience of time duration (Immanuel Kant)
d. The 'witness' property of experience – often mentioned by athletes 'in the zone'
e. The natural association between consciousness and intelligence
This novel, physically and biologically sound approach seems to satisfactorily model subjectivity.

Further significant results follow:

1. Registration of external information in excited states of systems at criticality reduces external wave-packets: the new model exhibits 'Objective Reduction' of wave packets.

2. High internal coherence (postulated by Domash & Penrose) leading to a. Non-separable information vector bundles. b. Non-reductive states (Chalmers's criterion for experience).

3. Information that is: a. encoded in coherence negentropy; b. non-digitizable, and therefore c. computationally without digital equivalent (posited by Penrose).

Discussion and Conclusions: instability physics implies anharmonic motion, preventing excitation quantization, and totally different from the quantum physics of simple harmonic motion at stability. Instability excitations are different from anything hitherto conceived in information science. They can model aspects of mind never previously treated, including genuine subjectivity, objective reduction of wave-packets, and inter alia all properties given above.

INTRODUCTION

In the early 1990's, after consulting myself, publisher Keith Sutherland recruited Professor Jonathan Shear to help him found the Journal of Consciousness Studies, thus bringing a new channel of publication to the field of consciousness research. Sutherland had been stimulated by Penrose's monumental book, the Emperor's New Mind, strongly arguing that analysis of the halting problem, and other aspects of computational theory, implied that human information processing was not computable (1). This point developed the suggestion by Penrose's Oxford colleague, J. Lucas, that metamathematical theorems imply the existence of consciousness, a point supported by Penrose, based on his experience of mathematical intuition, and its role in guiding discovery in mathematics.

   The rest is history: in 1994, David Chalmers published his magnificent JCS paper (2), amplified in his book, The Conscious Mind (3), which became the reference point for all subsequent work in the field, from Jon Shear's book of papers, 'Consciousness the Hard Problem' (4), in which Chalmers refuted all objections to his proposals, to the Penrose-Hameroff collaboration (5) now dominating the field. Key points made by Chalmers were, *inter alia*, (A) to deny conscious experience as an ingredient of creation is inadmissible i.e. the subjective aspect of mind, with its sense of 'self', whatever that may mean, is undeniable. (B) Consciousness needs to be admitted as an *a priori* ingredient of creation, as fundamental as the electron or matter-energy. (C) Since reductive explanations of consciousness had failed, the nature of any explanation should be non-reductive, and (D) the brain must support special information states with a 'Dual Aspect': in addition to ordinary information content, they must possess an additional aspect permitting them to support *subjective* experience. Chalmers's points,

including several others in addition to these four, have served as the anvil, on which all work in the field has since been forged.

Chalmers's main point (2-4) was that the existence and nature of experience *IS* the hard problem. It can be restated as follows: all of us, when we experience anything, carry a '*sense of our own presence*', of which we may be more or less strongly aware at different times. When we recall a story from our life, our memory includes a 'sense of our own presence' at the events we describe e.g. when our name was called out in a roll call in class at school and we replied, 'Present!', our response affirmed our 'sense of our own presence' in class. This factor both affirms the non-triviality of subjective experience, and identifies what is needed to explain it: something that carries a sense of being in 'Time present' (as TS Eliot puts it) (6). That is what is really required.

A largely unrecognized problem is that Chalmers's points (2) have not been sufficiently rigorously implemented. The general attitude on how to represent states of experience in physical terms is exemplified by a tacit point made in the many books by Amit Goswami (7): since classical physics cannot represent conscious experience, quantum physics must be used to do so (*sotto voce*: quantum theory is all that is available). Goswami waxes eloquent on all that can supposedly be achieved using quantum theory, but that approach fails to take into account that standard quantum theory is used to represent matter, so *to use it to try to represent states of experience fails to distinguish between object and subject in any fundamental way*. It trivializes Chalmers's points.

Similarly, quantum theory is basically *reductive* in nature (states of many particles are represented as products) – one reason why physics likes it. Though Chalmers states that a *non-reductive* theory is required to represent experience (2), in practice, no one has proposed an *intrinsically* non-reductive theory to do so. All uses of quantum theory, including the latest Hameroff-Penrose proposals (5), fail to provide the *inherently non-reductive* information states required to properly fulfil Chalmers's requirement: no reason is given for the chosen states to be anything other than states of objective matter!

This paper proposes to remedy these defects in current theory by adopting a radically different approach based on theories of regulation emerging from complexity biology. The supposed seat of conscious experience, the brain, is the ultimate regulator of the body, so its complexity states constitute an obvious place to start a search for possible physical states serving as the basis for experience. Indeed, conscious experience may be considered the highest level of overall control in the brain, which provides many inputs to induce it to take appropriate action, but leaves final decisions in the experiencer's hands. Biologically speaking, this is *precisely* the place to start,

Complexity biology is remarkable for the obscurity of its new concepts: fractality, edge of chaos, and self-organized criticality. Their biological rationale is not given.

'Criticality', the central concept, may be very simply stated, however: organisms prefer their regulatory systems loci of control to be at critical feedback instabilities. Since conscious experience is at the locus of control of the whole organism, *feedback instability becomes the physical condition of choice to consider as a possible basis for experience.*

When Norbert Wiener first proposed his revolutionary new theory of control in Cybernetics (8), he pointed out that all control requires feedback, which entails the possibility of feedback instability, a mathematical 'singularity', with mathematical physics as different from the physics of ordinary matter as is conceivable. Next, we list various properties of feedback instabilities, in preparation for their use to explain fundamental properties of experience in the following section.

METHODS

Instability only happens when the potential well for system restorative forces is not described by the usual Hooke's Law form $y = ax^2$, but rather $y = ax^p$, where $p > 2$ or even $p > 4$, making the well flat at its minimum. Energy levels are not evenly spaced: *system oscillations are neither simple harmonic, nor quantizable*. The usual quantum field theory description of stabilizing oscillations breaks down. (I)

Instead of being oscillations with well-defined frequencies independent of amplitude, as in all quantum systems, frequencies are highly amplitude dependent, and unpredictable. Excitations cannot be separated into a set of fixed frequency oscillators – the idea of harmonic analysis in terms of normal modes does not hold. Instead, the system becomes subject to long range correlations, representing a new kind of ordering principle. (II)

Many authors have recognized that living organisms seem to possess abnormally low entropy (9). Analysis of *correlations at critical instabilities* offers a rigorous reason for this to hold: correlations endow a system with a form of order i.e. *negative entropy*. (III)

More importantly, since the system possesses long range coherence, its excited states cannot be separated into, *or **reduced** to*, mutually independent states, as in normal mode analysis. Such a system is therefore *non-reductive*. Chalmers's important point, (C) above, is satisfied, now by the physics itself, not merely supposedly, in the philosophy. (IV)

Next, consider the nature of the feedback leading to the instability. Critical feedback occurs when a particular loop, possibly part of a complex system of loops, attains a feedback gain, **g**, of precisely **g = 1**. But when information travels round a (possibly multi-channel) loop with **g = 1**, the information returning to a given point is *unchanged*, it constitutes a faithful reproduction of the information that started. In a profound sense, the loop represents a *self-observing system*. (V)

Comments: **a.** A more labored, but better proof may be obtained by considering changes in the physics as **g** approaches the value **1** from below. **b.** The above example is not at all the same as that of a video-camera looking in a mirror, or a lady doing her make-up, or like looking at oneself between two mirrors, with an infinite set of images receding into the distance, or slowly bending out of sight, due to the tiny angle between the planes of the mirrors. It constitutes a completely new and original definition, not previously proposed.

Since a flow of information brings a system with intelligent understanding, 'knowledge', a system that is 'self-observing' due to a loop of circulating information, becomes a potential candidate for a 'system with *self-knowledge*'. (VI)

This idea that a system at a critical instability forms a 'self-observing system' may seem naïve, but, for the following reason, it is highly non-trivial: it provides an explanation, complementary to (I) and (III) above, for why such systems are non-quantizable. In quantum theory, the quantum theory of observation states that a process of observation annihilates quanta. *A 'self-observing system' would annihilate all system quanta by means of the process of self-observation*. That is the *dynamic* reason why no quanta are found in such systems, and they are not quantizable (VII)

Now consider the nature of excitations at critical instabilities: they are not simple harmonic oscillations but complex, correlated mixtures known as *critical fluctuations*. Their physics is responsible for all the properties of critical points. They cannot be represented in a Hilbert Space, as is normally the case in quantum theory, for states in Hilbert Spaces are, in principle, separable into individual states that may subsequently become superimposed. This luxury is not the case for critical fluctuations, which are *irreducible mixtures*, inherently non-reductive members of a different kind of mathematical 'space', called a 'Banach Space'. (VIII)

Now consider information properties of such states: (a) they are mixtures, meaning that they automatically have non-zero information; they are not like quantum information vectors, each with *zero intrinsic meaning*, like letters of the alphabet. More importantly (b) they carry the critical, **g = 1**, 'self-observing' information loop as an irreducible aspect of their information properties. We therefore propose to represent them as a vector bundle <===== with an added information loop: **O**. In other words: <===== + **O** ➜ <=====**O**. (IX)

Criticality states are located at 'The Edge of Chaos' meaning that they are adjacent to a region containing many bifurcations. (X)

RESULTS

Now let us apply the above properties of systems at critical feedback instabilities to derive different aspects of conscious experience. Instability physics is completely

different from stability, so many new possibilities may emerge. First, consider how information structure (IX) applies to experience.

The information structure of the critical fluctuations (IX) carries information content in the vector mixture bundle <=====, and also the information loop **O**, representing a process of self-observation potentially yielding self-knowledge (VI). In the 1980's, the usual dictionary definitions of consciousness was 'possessing self-knowledge', so this seems promising.

We therefore **hypothesize** that: *The loop may be attributed a function, 'registering the state's own existence', analogous to humans 'being aware of their own presence' during experience.*

The <u>hypothetical</u> nature of this statement is important to understand. The idea that these states may represent experience is not deductive, but <u>inductive</u>. It represents an entirely new departure in scientific thought. The reasoning offered in this section serves to justify this hypothesis

The role of the loop can also be understood by considering the approach to pure consciousness in meditation, described in detail by Shear and others. In self-transcending meditation systems, the content of the mind is allowed to die away, until one is left in a state of pure self-awareness. This can be represented by the sequence:

$$\text{<=====}\mathbf{O} \qquad \text{<====}\mathbf{O} \qquad \text{<===}\mathbf{O} \text{ <==}\mathbf{O} \quad \text{<=}\mathbf{O} \quad \text{<}\mathbf{O}$$

The zero vector at end right has zero information content, but the information loop is still present, indicating the system is in a state of pure self-observation, or self-knowledge. But this is precisely how pure consciousness is traditionally described: sensory, affective, mental and intellectual aspects of awareness have died away, and all that remains is a pure 'sense of one's own presence'. This is exactly what the information loop, **O**, was intended to represent. In other words, the analysis of pure consciousness as experienced in meditation, illustrates how the vector bundle <=====, combined with an information loop **O**, represents an information state carrying information, <u>together with</u> a 'sense of the experiencing subject's own presence'. According to Shear, the universal, trans-cultural experience of such states is not of unconsciousness, or sleep, but of heightened awareness, 'Pure Consciousness', in which awareness of 'Self' alone remains.

To summarize, information states of excitations at critical feedback instabilities, <=====**O**, possess precisely the aspects required to represent experience. Chalmers' deeply insightful requirement of 'Dual Aspect Information States of Consciousness' is satisfied in a highly non-trivial way – the 'Dual Aspect' for subjectivity is precisely represented by the information loop!

A further implication of the analysis of <**O** as the aspect of <=====**O** remaining in the state of pure consciousness, is that the information loop <**O** is responsible for the inner experience of the passage of time, first attributed to the mind's inner sense by the

great German philosopher, Immanuel Kant. This is plausible, because at the singularity the loop is essentially infinitesimal. The information rotates around it effectively at infinite frequency generating a continuity of experience of time passing. To contemporary neuroscience, this experience presents a paradox, for scanning of cortices takes place at regular intervals, yet inner experience is one of a continuous flow of time passing. This conflict is resolved by the model attributing the subjective sense of time to the loop $<\mathbf{O}$, rather than to changes in the external information content represented by $<=====$.

Finally, the theory of meditation from the ancient tradition of Yoga states that experience has two aspects, one involved in experience, and the other a witness, uninvolved in it. The Mundaka Upanishad likens experience to two birds in a tree: the first pecks the fruit, while the second looks on – the roles of $<=====$ and $<\mathbf{O}$. The role of meditation is said to be to strengthen the witness $<\mathbf{O}$, until that dominates experience and the sense of Being is no longer overshadowed by activity (10). Clearly, in the model, the role of meditation is to grow the experience of $<\mathbf{O}$, and diminish experience of $<=====$. It allows neuroplasticity to convert $<=====\mathbf{O}$ into $<=\mathbf{O}$. The proposal for representing experience by criticality states thus yields an accurate model of the long-term effects of regular meditation.

Point VII, that a $\mathbf{g} = \mathbf{1}$ loop annihilates quanta, i.e. reduces wave packets, means that the proposal includes *a new form of objective reduction of wave packets*, similar to, but different from the OR proposed by Penrose: similar in that mathematical singularities are identified as the root cause, but different in that the singularities are caused by feedback singularities rather than quantum gravity ones. Critical feedback systems reduce all wave-packets, even external ones fed into the system. When the system registers information in excited states, the same non-linearity reduces external wave-packets, yielding a model for the OR of the wave packet by consciousness.

Intelligence: a vitally important aspect of subjective awareness is its apparently integral ability to take decisions and make choices. It is difficult to imagine being aware without the accompanying sense of likes and dislikes, and the inclinations to choose the former and reject the latter. How can the experiencing subject make such choices? The present model suggests a way. A critical system is at the 'Edge of Chaos' (X), so brief incursions into the chaos region are possible to make selected trajectories pass on the chosen side of a given bifurcation point. Choice thus becomes possible, providing a plausible basis for the universally experienced connection between 'self-awareness' and the 'ability to make decisions' that characterizes conscious experience.

IMPLICATIONS FOR COGNITIVE SCIENCE

States of experience are cognitive states, so if dual aspect vector mixture bundles, <=====**O**, represent states of experience, they must also be *cognitive states*, and form *the basis for a new approach to cognitive science*. But what kind of cognition does this form of cognitive science support? Certainly not the digital, reducible, form in video recorders and films based on digital encoding, for as we have seen the physics of the states is non-reductive.

The long-range correlations offer a means to estimate the quantity of information encoded into the vector mixture states, for correlations create order, which translates into negative entropy, a standard measure of information content. We therefore propose (III, above) that criticality states support a new kind of information: system-wide correlational, negentropy information.

This has several significant consequences:

1. The dynamic, fluid nature of correlations in such systems, means that their correlational information cannot be equivalently presented by fixed classical entities, like digits. It constitutes a 'subtle form of information' with no digital equivalent. *It cannot validly be digitized*.

2. Furthermore, any information processing undergone by such information must be unrelated to digital processing, and cannot be represented digitally. This property which Penrose spent ten years or so trying to establish through meta-mathematics seems to fall out of the hypothesized structure, simply by virtue of the definition of the class of systems (instabilities), the kind of excitations (inherently non-separable mixtures), and the class of information that they can support (coherence information, carried by internal system correlations). Penrose's thesis in 'The Emperor's New Mind'

(1), and its sequel (11), is completely supported, no laborious hundred page proof

seems to be required.

3. Consciousness is associated with high levels of correlation, as first, Domash (12), and second, Penrose (1), have conjectured. Objections overruled them: quantum correlations do not exist at the temperatures required to support life. Our proposal resolves this conflict: *correlations are not quantum mechanical, but long-range criticality correlations*.

These points lay the groundwork for considering criticality excitations as cognitive states. The states are not digitizable, and their information is not reductive, rather it is correlational, non-reductive, system spanning, and *holistic*. But to what could *holistic information* refer? Here again, Immanuel Kant provides the key (13) in his concept of the 'transcendental unity of apperception': the nature of apperception is to 'grasp the whole', and to see things in terms of *Gestalts*, as later generations of German cognitive scientists put it. Viewed as cognitive states, *criticality forms the basis for a biophysical theory of*

Gestalt Cognition that can be realized in nervous systems because *neuronal networks can support critical instabilities*.

IMPLICATIONS FOR NEUROSCIENCE

Neuroscience has long been dominated by McCullough's conjecture, that neuronal states of firing and not firing are equivalent to digital states one and zero respectively, implying that they only use digital information. Now, however, the questions are, first, how can neuronal networks support instability states, and, second, why should they do so? The answers are straightforward.

1. There is a well-known isomorphism between neural nets and spin glasses, meaning that neural nets are capable of phase transition behaviours, and accompanying critical point phenomena of arbitrary complexity, such as tricritical points (14), and higher order critical points (15,16).

But why should these be necessary? Therein lies answer

2. Kauffman (17) found that genetic networks only function effectively at 'The Edge of Chaos', meaning that they contain critical instabilities. But there is no limit to the complexity of critical instabilities that genetic networks may contain. Ayurveda's Tridosha system of overall organism regulation (18) suggests that a 1-to-3-furcation coordinates overall system function, requiring a tricritical point. Various 1-to-5-furcations, as in fingers and toes, or Ayurveda's five subdoshas, require higher order critical points.

In order to control organism function precisely, its regulatory systems must be capable of modeling such mathematical singularities accurately. *Their control systems must support higher order critical points*. The neural net-spin glass isomorphism uniquely qualifies neuronal networks to do so. Hence, even an organism as simple as *C. Elegans* contains a network of neurons. Why? Because it can model and regulate its genetic network with all its complex critical instabilities! That is the fundamental reason why *neuronal networks were selected to regulate genetic networks*.

EXPERIMENTAL VERIFICATION

Experimental support for some of the above proposals seems to exist. Freeman (19) and his collaborators (20) give evidence that, in the EEG, wave packets representing thoughts satisfy *self-organized criticality*, the fundamental principle of complexity biology supporting criticality. This seems to indicate that *states of mental experience satisfy criticality*, supporting our proposal, though further work is needed to verify this. The criticality approach provides a theory justifying Freeman's suggestion.

The idea that experience information is registered as correlations also has strong circumstantial evidence: it provides a theory (to be published separately) for Sheldrake's

'Seventh Sense Communication', recounted in his books, 'Dogs that Know when their Masters are Coming Home' (21), and 'The Sense of Being Stared At' (22). Sheldrake calls direct information transfer between mentally attuned minds a 'seventh sense' (21). Such information transfer can be modelled as a form of 'quantum teleportation' (23) of information between coherent states in different minds – i.e. it becomes available when information is registered in correlations. Seventh Sense Communication therefore provides direct evidence for correlational encoding of information.

Finally, the idea that minds register 'holistic information' as gestalts is illustrated by Sheldrake's story of 'Nkosi the African Grey parrot. 'Nkosi can accurately call out the names of images viewed by her mistress in another room (21). Only gestalt image encoding can provide a plausible explanation for such seventh sense visual information transfer. Furthermore the encoding used by them must be the same. Significantly, since birds are descended from dinosaurs, while primates and mammals are descended from reptiles, the story implies that *the gestalt image encoding was established before the two diverged*. The encoding system is very ancient. (Another reason for encoding images as gestalts is that criticality physics exhibits scale invariance, so the encoded images are scale free and can be recognized independently of distance – very necessary for an animal needing to distinguish friend and foe, family from predator.)

DISCUSSION

Many if not most of the fundamental properties of experience have been derived from the properties of critical instabilities in complexity biology. Instability physics is totally different from the physics of stability. That previously unexplained properties of biological systems should be explainable in terms of critical instabilities occurring in complexity biology is not surprising. That they should explain so many demonstrated and hypothesized properties of conscious experience is remarkable – even compelling.

To clarify the key point that information structures of criticality states must include information loops, consider the following analogy, the generality of which provides a 'proof by illustration'. A fluid system at its 'critical Reynolds number' shows a similar instability in its system of flow vectors, which are no longer exactly stable, but carry the possibility of a tiny vortex forming at each point in the fluid, the presence of which causes instability. To denote a flow vector at such an instability, we add an *unmanifest loop* to it, indicating its *potential* to form a vortex loop.

All such fluid systems can be regarded as information systems, in which the fluid flow carries information. By analogy, at critical feedback instabilities, flows round feedback loops causing the instabilities should be included in descriptions of each system state. *Information vector mixtures denoting criticality states should therefore include attached information loops*. QED

Now consider the implications of the theory for philosophies of mind such as Cartesian duality or embodiment. Clearly, critical fluctuations at feedback instabilities considered as Dual Aspect Information States of Experience, are completely distinct from states of matter. Descartes rightly observed that mind as experienced by human beings is in complete contrast to matter. Criticality based models of states of mind preserve Descartes' distinction between Mind and Matter:

- ☐ Matter forms stable systems represented by excitations of systems of simple harmonic oscillators that are simply quantizable e.g. ordinary quantum fields.
- ☐ Excitations of 'Mind', information states of experience, are represented by excitations of anharmonic oscillators with potential well exponents > 2 or even 4.

In the approach proposed here, phenomena in *complexity biology* are explicitly used to model the mind-body connection. The machinery of conscious experience is linked to structures considered the most complex in biology, probably in the entire natural world. This seems natural: biology's most sophisticated patterns of organization are used to model its most complex (epi)phenomena. The proposed model thus effectively confines 'mind' to the world of biology, as it should.

That the structure to which mind is proposed to couple is integral to all systems of biological regulation is also appropriate: regulation requires feedback, and all feedback contains the possibility of critical feedback instability. Indeed, Norbert Wiener (8) identified feedback instability as the most significant innovation in physical theory added by his account of regulation and control. But apparently no one has previously considered their information properties, let alone how they may relate to experience, as proposed here.

Subjectivity is deeply connected to intelligence and control. That feedback instabilities and their (non)quantum properties should offer the key to understanding experience is satisfying. Stability is characteristic of 'matter', to which instability seems, in contrast, an irrelevant complication.

Convinced materialists may, possibly rightfully, claim that they have no need of 'Mind' to understand a purely material universe, as they understand the world of perception. However, instability states seem to play a special role in supporting 'experience' in precisely the ways defined by Chalmers (2,3). The simple and straightforward emergence of many properties of mind and subjective experience previously only hypothesized brings confidence in the proposal.

CONCLUSIONS

A hitherto unsuspected, new form of information, 'experience information' has been defined by considering information properties of excitations of a system at

criticality – critical fluctuations. Many reasons have been given for equating it with information used in cognition by experiencing subjects. Chiefly, the information loop(s), integral to its information vector mixtures, can model the 'sense of one's own presence' intrinsic to subjective experience. Whether or not this is really the case for actual states of experience should be subject to further theoretical and experimental investigation. However, Freeman's discovery that self-organized criticality is present in EEG wave packets associated with mental cognition seems to confirm it. His approach may play a guiding role in helping form useful hypotheses for further research.

The theoretical work presented here provides prima facie reasoning for how all this happens: information states built out of criticality excitations carry at least one $\mathbf{g = 1}$ information loop associated with feedback instability. Interpretation of such loops as perfect self-observing systems, suggests a physiological basis for the sense of self, the continuous sense of time passing, and thus the sense of being present in every situation; and so for the kind of sense of 'self' which is integral to human experience. The proposed models may therefore account for the sense of subjectivity accompanying human experience.

The occurrence of the $\mathbf{g = 1}$ loops at loci of control adopted by complex biosystems under self-organized criticality seems intuitively correct. It leads to another serendipitous property of the proposed model: systems of the required complexity are found exclusively in biosystems, and not in the world of ordinary matter, explaining experience's restriction to the world of biology.

The use of critical feedback instabilities from biological complexity to model 'experience' seems to show definite promise, and merits further work. It does not fully explain the presence of the experiencing subject, however. That must still be taken as a fundamental aspect in the universe, beyond explanation, as Chalmers (2,3) took pains to emphasize.

In summary, the proposed theory seems to fit well in the following ways.

1. Complexity seems the right place in biology to find a solution to the problems of experience and subjective intelligence, as the most complex phenomena in biology.

2. 'Experience' and 'mind' occur at the apex of the regularity hierarchy where self-organized criticality operates, so criticality is the condition of choice to analyse.

3. In control theory, Wiener's feedback singularity is the place where any radically new and different property of a physical system should be located.

4. Singularity presents an appropriate physical condition, instability, with correspondingly different physics from stability, the condition for matter. This confirms criticality as the condition of choice to try to locate mind and experience.

5. Furthermore, criticality is commonly found in animal cortices, and is capable of supporting critical phenomena of great complexity. The model fits with contemporary neuroscience.

6. The model presents a physics of experience distinct from the physics of matter preserving the intuitive distinction between 'mind' and 'matter'.

7. The model proposes a class of information structures with a feedback loop integral to their structure and shows that it appropriately models the sense of 'self' common to experience.

8. Criticality's occurrence at the 'Edge of Chaos' allows choices to be made, thus linking the 'sense of self' to active intelligence, as is commonly experienced.

9. The non-linear mathematics of the singularity corresponds to the essential non-linearity implied by the experiencing subject's awareness of 'self'. The essence of subjectivity would seem to be 'non-linearity', a condition that should be added to Chalmers's list of the properties of experience.

10. A system that is essentially non-linear cannot be represented by linear models. The mathematically singular feedback loop at critical instabilities is appropriate to do so.

11. Mathematical singularities at critical feedback instabilities at the apex of complexity-based biological regulatory systems are therefore appropriate conditions to model subjective experience from the perspective of their mathematics, information theory, control theory, physics, complexity biology and neuroscience.

ACKNOWLEDGEMENTS

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