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Mind from Matter: the Chemical Connection

Robert Pascal^[a] and Addy Pross^{*[b]}

Dedicated to Professor Helmut Schwarz on the occasion of his 80th birthday

Abstract: One of life's most extraordinary features is its mental dimension, one whose origin and essence remain a deep scientific mystery. Given the modern scientific view that life emerged from non-life, how was 'dead' matter able to take on mental capabilities? In this Review we report on two recent scientific discoveries, which together offer new insights into the possible physical basis of mind and the origin of 'self'. First, recent thinking in microbiology now contends that simplest life manifests highly developed cognitive capabilities, suggesting that such capabilities were initiated early in the evolutionary process, likely within chemistry.

Second, the recent discovery of a new dimension within chemical space of energized dynamic kinetically stable (DKS) chemical systems appears able to explain the emergence of systems with distinct non-physical characteristics, including cognition and 'self'. These two developments, when coupled to a physically based description of the evolutionary process, offer a feasible means of outlining the physical/chemical basis for life's mental state and a means for its emergence. A door toward resolution of the seemingly intractable 'mind from matter' problem may have opened up.

1. Introduction

Life is very strange. Modern science has little doubt that living things are composed of nothing but physical and chemical 'stuff', yet in some incomprehensible way that 'stuff' behaves strikingly different to non-living 'stuff'. Living things are cognizant, aware of themselves and their environment, in continual need of energy and resources for self-maintenance, and through active management of themselves and their environment doggedly pursues an agenda, one broadly associated with survival and reproduction. Moreover, that cognizant character is increasingly understood to underpin all life forms.^[1–3] Even bacteria, exemplifying simplest prokaryotic life, are able to both sense and respond to a strikingly large range of environmental signals. Lyon has gone as far as to claim that bacteria do the equivalent of 'decide,' 'talk,' 'listen,' 'cheat,' 'eavesdrop,' 'lure,' 'vote' as part of life's processes,^[4] while Broach has gone the extra mile in proposing that bacteria are actually able to 'think'.^[5] Thus, regardless of the precise language that might be chosen to express life's cognitive functions, it is now generally accepted that highly developed cognitive capabilities are already present in all life forms, including the very simplest ones.^[4–6]

But that leads to a long-standing and inexplicable physical quandary: how could 'stuff' of any kind be cognitive, let alone have thoughts? If the cosmos is fundamentally physical, how can mental characteristics of any kind exist? More remarkably, how could that mental capability already be present in simplest life? A mental dimension is seemingly incompatible with a physical/material epistemology, an incompatibility that confounded the leading physicists of the 20th century.^[7–10] Max Delbrück, for example, spoke of the "feeling of absurdity evoked by the question 'mind from matter'".^[10] The issue is a far-reaching one as our current understanding of the cosmos

and the natural order that underpins it, are brought into question by the 'mind-body' problem.^[11]

In this Review we describe recent developments in chemical theory and practice which together seek to offer new insights into the mind-matter dichotomy by outlining how a mental capability could arise within certain material forms, as well as offering a physical/chemical mechanism for its emergence. Our conclusion can be stated forthwith: the mental world is physically based and derives from a recently discovered, but, as yet, inadequately recognized state of matter, a kinetic state of matter – dynamic, energized, thermodynamically unstable, yet persistent.^[12,13] Such kinetic states of matter are increasingly understood to constitute an integral part of the physical world in much the same way that the traditional thermodynamic states of matter have been till now.^[13i–m] As will be discussed, all living things, with their unusual emergent properties, exemplify physico-chemical structures in that dynamic kinetic state, and, as was recently reported,^[14] it is the from the reality of such states that a mental dimension is able to emerge.

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2. Discussion

2.1 Steps Toward Understanding

The first step in addressing the perennial problem of mind is to acknowledge that matter's mental capability is not a fundamental property of all material forms but can only be found in those material forms we characterize as living. Moreover, it is presumed that the existence of such a capability was 'discovered' by nature through a process of Darwinian natural selection.^[15] That suggests, as with all biological innovations that emerged through the evolutionary process, that life's mental capability came about for the survival advantage it offered its living host. But, as will now be discussed, the fact that an evolutionary process led to the emergence of that mental capability offers a possible means of identifying its origin, as well as its physical basis.

Of course, the evolutionary process gave rise to an endless array of functional innovations, not just mind. Indeed, it is striking to note that nature has proven to be the ultimate technologist, routinely exploiting a wide range of physical and chemical principles in order to facilitate life's ultimate goals of survival and reproduction.^[16] Yet, there is a striking difference between life's mental capability and the many other technological discoveries uncovered by nature. In most cases the physical and chemical principles underpinning those other technological achievements are broadly understood. Thus, for example, the aeronautical principles enabling flight, the principles of electromagnetism enabling bioconductivity,^[17] the chemical principles governing molecular replication,^[18–21] the laws of thermodynamics^[22] facilitating energy transduction, and so on, are well understood, even if the level of human technological capability often remains diminished compared to nature's extraordinary level of technological proficiency.^[16]

With mind, however, the story is strikingly distinct. In mind we have a technological innovation 'discovered' by natural selection that we do not understand, and certainly are unable to mimic. What structural and organizational requirements of matter would enable it to express mental activity, to be able to 'think'? We do not know. Computer-based artificial intelligence, though profoundly useful, does not involve self-aware objects capable of independent thought. For science, the

mental world remains a black box. This large gap in our scientific understanding of mind leads to an awkward conclusion: that a gaping hole within the natural sciences continues to exist, one that is impeding the natural merging of the physical and biological sciences. But, of course, being aware of a problem is the first step toward solving it. The very existence of a mental dimension, coupled to the fact that it came about through an evolutionary process, offers pointers by which this long-standing puzzle might be addressed.

2.2 Reductionism and Understanding

The prime tool for centuries for achieving scientific understanding has been that of reduction, the idea, broadly speaking, that one might better understand the complex by reducing it to its simpler elements. Understanding how a watch operates by identifying its component parts and their manner of interaction, illustrates the approach. However, that approach has been problematic in biology, at least with regard its unique holistic properties.^[23,24] We understand life's molecular components and many of the processes they undertake in exquisite detail, and yet we do not understand how life's global emergent properties, such as cognition, agency, desire, intentionality, mind, and so forth, come about.^[25,26] No surprise then that the current view amongst mainstream physicists and biologists is that biology is not reducible to physics and chemistry, and that a holistic approach for understanding such characteristics should be applied. In cognitive science, for example, one approach to addressing the problem of mind has been to think of it as a software program operating on a hardware neural system. But the insights brought about through such a holistic approach have been limited, to say the least. Heavily funded research programs, such as the Human Brain Project and the Brain Initiative, which performed large-scale computer simulations of the human brain, have not delivered the hoped for breakthrough in our understanding of the mental domain.^[27]

With hindsight the problem with a holistic approach to biology is more readily discernible: given that we are still struggling to understand the holistic character of a single biological cell – effectively a dynamic network of trillions of interacting molecules and molecular aggregates – it should not come as a total surprise that a network of billions of cells, each



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one individually composed of trillions of those molecular entities, might prove to be overwhelmingly complex. Somehow a means of unravelling that extraordinary degree of complexity in living systems needs to be found, with mind being just one particularly challenging aspect of the problem. However, we would claim, despite the earlier mentioned misgivings, that a reductionist approach to the problem can prove effective - if approached somewhat differently, and that's where the significance of the evolutionary process comes to the fore. As will now be discussed, the evolutionary process, by its very nature, opens up reductionist insight into life's central questions.

2.3 Evolution and Complexity

The evolutionary process from its inception has been fundamentally one of complexification - from simple and chemical to complex and biological.^[12,13n] That would suggest that following the evolutionary process back toward its (presumed) simple origins, could be expected to help identify the source of life's emergent properties. Just as it is easier to identify the principles of flight by studying its technological beginnings, say, in a kite, a glider, or the equivalent of the Wright Brothers 1903 model, than by studying a highly complex Boeing 747 airplane, so the outcome of a long period of evolutionary progress should be more readily explicable if one is able to trace that process back in time to its beginnings. In other words, despite the common view that biology is not reducible to physics and chemistry, the fact that physics and chemistry evolved into biology, suggests that biology *should* be reducible to physics and chemistry. The underlying idea is clear: go simple! Reductionist logic is *inherent within the process itself*.

But there's a catch of course. For that approach to work, a prerequisite would be that the evolutionary process be understood, and it still isn't, at least not in physical/chemical terms. In fact, it has been that lack of understanding of the evolutionary process that has been responsible for our inability to apply reductionist methodology to biology's central problems. Despite the revolutionary insights that have derived from Darwinism, evolutionary theory continues to be a highly contentious issue.^[25,26,28] At least one source of the difficulty is readily identified. Much of the confusion has derived from the conceptual separation of the evolutionary process into two phases, a so-called physical/chemical phase whereby inanimate matter was transformed into simplest life - the so-called origin of life phase - followed by the so-called biological phase, in which simplest life evolved into complex life, or as Darwin put it, into "endless forms most beautiful and most wonderful". But, given that it is generally acknowledged (implicitly, by Darwin himself in a letter to J.D. Hooker)^[29] that the two phases are likely part of a continuous process, it should come as no surprise that an evolutionary theory that attempts to deal with just one phase or the other, runs into difficulty. A biological theory of evolution that addresses just the second, biological phase of the process can, at best, be incomplete. A successful evolutionary theory would need to address both chemical *and* biological phases as a

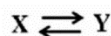
unity, to be able to both explain how 'dead' stuff came to life, as well as how life, once it emerged, complexified and diversified into those "endless forms". But that also means that evolutionary theory cannot get away from having to incorporate physico-chemical thinking into its conceptual framework. After all, the process necessarily started within chemistry.

And that's where the utility of the dynamic kinetic stability (DKS) concept comes in.^[12-14] Given the increasingly acknowledged view that the evolutionary process was continuous, from inanimate right through to complex life,^[12-14,18] it means that a physical/chemical theory, rather than a biological theory, would be required to cover the entire process. It would be inappropriate for the physico-chemical part of the process to be explained by a biological theory, though, of course, it would be quite acceptable for both phases to be explained in physico-chemical terms. As Weinberg noted, explanatory arrows always point down.^[30] Accordingly, let us now describe the DKS concept and how it could be utilized to describe the entire evolutionary process, both the initial chemical phase as well as the later biological phase. Such a theory will then be shown to offer fresh insights into life's striking global characteristics, in particular its mental dimension.

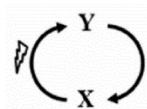
2.4 Dynamic Kinetic Stability (DKS)

Chemistry is a relatively mature science with many of its central principles - the nature of the chemical bond, the second law of thermodynamics, transition state theory and reaction kinetics - having been formulated around a century ago. So, it might come as a surprise that the existence of a kinetically stable dynamic state of matter only came into clearer view a little over a decade ago with the discovery of dissipative self-assembly processes. Its essence in simplest terms is that a chemical system might well be stable in *time* terms - persistent - though unstable in *energy* terms.^[13m] Stated more formally, two chemical entities, X and Y, might achieve a stable steady-state mixture by two quite different means. First, in the traditional way, expressed in Scheme 1a, the two entities, X and Y, undergo reversible interchange by traditional chemical means until the thermodynamic minimum, the equilibrium state, is reached, after which no further concentration changes in X and Y take place under the given conditions.

However, as shown in Scheme 1b, if appropriate material and energy resources were to be continually provided to the system, then X could be transformed into some product material Y in an *energized dynamic kinetically stable (DKS) state*. Furthermore, Y, in that energized state, could undergo further reactions, also maintained through that material and energy supply, to form what is effectively an autonomous chemical system. That entire DKS state could then revert back to X through a series of cyclic irreversible energy-releasing dissipative processes.^[13o] Significantly, material Y and its associated reacting species, all of which constitute elements of that DKS state, could express quite different properties to those obtained in a traditional thermodynamic process, thereby opening up a new dimension in chemical



(a) thermodynamically stable state



(b) dynamic kinetically stable state

Scheme 1. Simple pictorial representation of X,Y interconversion from within (a) a thermodynamically stable state, and (b) from within an energy-fueled dynamic kinetically stable state.

possibility. Indeed, a potentially infinite set of dynamic kinetic states for X,Y interconversion exist, as each individual state would depend on the X and Y interconversion rates, which are not pre-determined, but are dependent on the rates of material and energy supply. The existence of such DKS stable chemical systems as a general class of stable kinetic systems was reported a little over a decade ago by van Esch, Eelkema, and colleagues^[31] and has been intensively investigated following that early pioneering study.^[32–35]

But the importance of the DKS concept in the context of the life phenomenon is that it describes not just certain chemical systems, but the entire class of living things.^[12,13] By definition, each and every living entity, as well as many of the chemical systems from which those entities are composed, are now understood to be in that DKS state. All living things are energy-fueled dynamic systems undergoing continual molecular turnover, much like water in a water fountain that is constantly being physically turned over. However, the fact that the DKS framework encompasses both chemical *and* biological systems, offers a possible theoretical description for the entire evolutionary process from chemical to biological, and able to do so in physical/chemical terms. Indeed, through the DKS concept it becomes possible to formulate a persistence principle,^[13i,j,m] an analog to the second law of thermodynamics, but one able to act as a directing principle in nature, in some cases where the second law is less able to do so.

2.5 Persistence

Grand, in his 2000 text, *Creation*, made the extravagant claim that the most important law of nature could be expressed as: *things that persist, persist, things that don't, don't*.^[36] Though that fundamental idea has received scant attention in the literature, its central idea can be reformulated more explicitly into a directing principle in nature: *from less persistent to more persistent*, one we have termed the persistence principle.^[13i,j,m] The principle's rationale in the first instance is based on logic, as Grand's tautological formulation makes clear. But at a deeper level it rests on the reality that persistence is an expression of stability, but stability within a *time* dimension, not an *energy* dimension.^[13i,m] Thus, any physical system could be either time-stable and/or energy-stable. Within a second law context the two stability kinds turn out to be complementary – a system at equilibrium is both time-stable and energy-stable; it exists in a maximum entropy/

minimum energy state and remains unchanged over time.^[22] However, there exist physical and chemical systems that are time-stable, though *not* energy-stable, and all DKS systems are in that time-stable, energy-unstable category.^[13]

An important insight afforded by the persistence principle is that it allows the direction of the evolutionary process to be characterized in physico-chemical terms. The kinetics governing DKS systems indicate that when two DKS systems that replicate irreversibly compete for the same energy and material resources, the more stable DKS system drives the less stable one into extinction.^[19,20] In other words, replicative DKS systems are driven toward increasing DKS. Accordingly, that places the evolutionary process for replicative DKS systems (that includes all living things) within a physico-chemical framework. It suggests that the evolutionary process does have a direction – toward systems of greater DKS. Natural selection, of itself, is not a directing force. Natural selection only selects, and it selects for greater stability, but stability of the DKS kind.

But an additional insight from the DKS description comes about: with the establishment of a coherent physico-chemical basis for describing living forms, a means of addressing life's global characteristics becomes possible. The question of how cognition and a mental dimension were able to emerge from an inanimate physico-chemical system can now be considered.

2.6 Emergence of Cognition and Mind

Let us begin with two unambiguous statements. First, cognition and mind are emergent properties of living forms, and second, living forms are composed solely of material 'stuff'. Those two statements in themselves appear to lead ineluctably to the conclusion that cognition and mind are material characteristics, at least for certain material forms, and therefore, that in some fundamental manner, cognition and mind necessarily have their roots in chemistry. The question then becomes: what kind of chemical system could show cognitive ability, at least in rudimentary form? We would suggest that excitation of an initially inert chemical system into the DKS state could have been a first step in enabling the beginnings of mental activity. Let us describe how.

The DKS state, whether chemical or biological, is by its nature totally dependent on its environment. Without a continuing supply of material and energy resources external to the system, the system collapses immediately, and in that regard, the relationship of a DKS system to its environment is quite distinct

to that of an inanimate system to its environment. Indeed, that state of total dependence can be thought of as inducing the beginnings of ‘awareness’, an awareness by the DKS system of its environment. But now to the key point: once that awareness is continually enhanced (through replication and evolution, as discussed below), the concept of ‘self’ begins to emerge. On the one hand the DKS system is materially distinct and separate from its environment, yet due to its total dependence on its environment, it is necessarily aware of that environment. Thus, it is within that duality that the origin of ‘self’ can be found – self-awareness that derives from external awareness.^[14] Moreover, notice in that description we are proposing the physical means by which a mental dimension could emerge. Awareness is not a physical attribute, but rather a mental one. Though mental attributes derive from physical circumstances, they are inherently non-physical, meaning they cannot be detected and measured by physical means. Thus, the dependence of an ‘inside’ (the DKS system) on its ‘outside’ (the system’s environment) effectively leads to the establishment of a mental domain, a non-physical relationship between a physical system and its supporting environment.

Of course, the presumed mental facet of a simple DKS chemical system is clearly limited, one would say of no practical physical/chemical significance. For true cognitive function to emerge and for life to exist, a further requirement is essential: a replicative capability. As will now be discussed, a replicative capability for that chemical DKS system was a crucial element in the evolutionary process, not just for the emergence of life’s unique physical characteristics, but also for the possible emergence of its mental ones. Thus, one might say that the DKS state is the seed from which the mental state could sprout, while the evolutionary process is the mechanism by which that mental dimension could emerge and develop thereby giving rise to its distinct and unique functional capabilities.

A further comment on the role of replication. The existence of replicating systems in chemistry is well-established and no longer controversial.^[18,37] If, however, a DKS system was in some manner able to acquire a replicative capability, the resultant evolutionary process would be quite different to that followed by ‘regular’ replicating systems. Replicating molecules, for example, have now been studied for over half a century and no general evolutionary process toward life-like systems has been observed in such cases; they simply follow the usual thermodynamic directive. In contrast, kinetic theory predicts that a system that is replicative *and* in the DKS state would undertake a distinct evolutionary process - from *less* persistent DKS replicators to *more* persistent ones, from less stable relatively simple replicators to more stable, more complex ones.^[12,13] And, significantly, just as a replicative DKS system would be expected to evolve along a physical axis toward enhanced physical capability, so its rudimentary mental capability, initially of no biological significance, would be expected to evolve toward enhanced mental capabilities. In both cases the evolutionary process would take place for functional reasons – to enhance the systems stability/persistence. Remarkably, Darwin, in his landmark thesis 160 years ago, based on evolutionary logic alone, already

acknowledged the existence of a mental dimension from life’s outset, and, as testament to his genius, lead him to hypothesize that the entire evolutionary process took place along both physical *and* mental axes.^[14,38] 160 years on we are re-discovering Darwin’s revolutionary insights.

The general physical insight that derives from the above description of the life phenomenon is that there is not one, but *two* general paths that nature has uncovered for achieving persistent forms. The first is the well-established thermodynamic path toward systems of greater thermodynamic stability, the one underpinning effectively all physical and chemical activity. But there is also a second path, a dynamic kinetic path, one leading toward greater dynamic kinetic stability, one that also leads toward increasingly persistent forms – kinetically persistent forms.^[13i,j,m] Life, as a physico-chemical phenomenon, manifests an evolutionary process along that second path. In fact, given life’s extended existence on earth of some 3.5-4 billion years – a significant fraction of the universe’s existence – one can only conclude that the kinetically-directed path toward kinetic persistence has proven to be highly effective in its ability to induce the formation of persistent forms. In sum, nature’s goal in the emergence of life, in line with the persistence principle, can be succinctly summarized as that of seeking persistent forms, and it does so at various hierarchical levels – at the cellular, organismal, and population levels. It all comes back to Grand’s insightful logical deduction: *things that persist, persist, things that don’t, don’t*.^[36]

We therefore are led to conclude that the emergence of mind and its subsequent exploitation by nature were physico-chemically feasible once a replicative chemical DKS system was able to emerge. The mental dimension was not a late evolutionary discovery associated with the appearance of neurons and brains, but is inherent in the DKS state’s ontological nature, and therefore fundamental to the evolutionary process. Indeed, a new perspective on Chalmers’ hard question on consciousness^[39] may now be coming into view. Living things, given their inherent chemical character based on dependence and self, cannot exist without mind. Mind is as fundamental to life as its material structure, with life’s mental dimension derived directly from its material nature. Mind and matter are each distinct aspects of life’s ontological nature with the two aspects umbilically linked. In life, neither can exist without the other in agreement with the Varela-Maturana autopoiesis view.^[2] In nature’s drive toward greater persistence, nature exploits both physical *and* non-physical dimensions because within the life material phenomenon, both dimensions exist.

3. Conclusion

Once it is recognized that life’s mental dimension is a necessary and inseparable aspect of life, the question how mind emerged from matter becomes just another way of asking how living emerged from non-living. Paradoxically, 160 years after Darwin, we are still struggling to understand the evolu-

tionary process with current evolutionary theory seemingly in the throes of a Kuhnian paradigm shift away from the modern synthesis's narrow gene-centered focus.^[25,28] Biology understandably focuses on the biological phase of the process – from simple life to complex life. But our analysis suggests that the answer cannot lie solely in the biological plane. Life is first and foremost a physico-chemical phenomenon. Accordingly, an understanding of the process by which inanimate became simple life, the so-called chemical phase of the process, would be critical, not just in resolving the origin of life question, but for an understanding of the entire evolutionary process. One might even venture to say that biology's existence is more of a physico-chemical problem than it is a biological problem, that evolutionary theory needs to be formulated in physico-chemical terms, if it is to provide a fundamental understanding of what life is, what drives the evolutionary process, and the basis for life's striking global characteristics. Through a physico-chemical approach to the life phenomenon, we have sought to describe the physical basis for life's mental facet, its chemical origin, and how life's physical and mental states are intimately intertwined. Once the principles underpinning life's mental dimension have been revealed, the road, in principle, to the synthesis of a cognitive chemical system would appear to be open. Thus, contrary to the widespread view that the reductionist methodology is not applicable to biological understanding,^[11,23] our analysis leads us to an opposing view, that the beginnings of an answer to life's deepest question – what is mind and how it was able to emerge from matter – can be uncovered through a reductionist approach.

A century ago, Lotka informed us that thermodynamics can only tell us what cannot happen. It cannot tell us what does happen.^[40] Through a reductionist approach, kinetic theory is beginning to do just that. Life is a dynamic energy-fueled replicative network striving for ever increasing persistence, exploiting both physical and mental (non-physical) dimensions, because both dimensions exist. Indeed, therein lies our central postulate: within certain regions of chemical space, physical and mental aspects not only exist, but cannot exist independently of each other. All living things, from simplest to highly complex, lie within that space. The challenge of synthesizing chemical systems able to express rudimentary mental capabilities now appears open before us.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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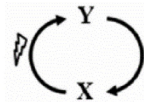
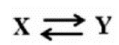
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REVIEW



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Mind from Matter: the Chemical Connection
