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PAUL NSUBUGA

A discussion for the metaphysics of downward causation

The case for ontological emergence

[Una discusión sobre la metafísica de la causalidad descendente.
El caso de la emergencia ontológica]

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Fax: 948 425 622
E-mail: emarcoa@unav.es

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Paul Nsubuga

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Presentation

Abstract: The past decades have been marked with an increased venture in understanding and employing the notion of emergence. The notion of emergence argues for the appearance of novel properties known as emergent properties, which are irreducible to their basal properties. A hierarchical structure of levels in reality accompanies the notion of emergence where emergent properties occupy higher levels and basal properties lower levels. In this way, the notion of emergence presents itself as an overt rejection of radical reductionism, which posits that everything can be reduced to the basal properties. Hence, the irreducibility of the emergent properties to the basal properties constitutes the former and the latter separate ontological entities. The dispositions of the emergent properties endow them to cause in the basal properties through what is known as downward causation. However, the irreducibility of emergent properties and downward causation on basal properties have been a source of constant apprehension towards the notion of emergence. This thesis presents a rapprochement for an interpretation of ontological emergence and downward causation that synchronises with our classical notions on ontology and causality. Complexity and an ontology of levels based on the constitution rather than the composition of the levels help us explain irreducibility. We have pleaded for the Aristotelian causal pluralism, thus involving the formal and final cause to account for the disquieting problem of downward causation. Hence, we contend that the phenomenon of emergence makes sense within the present scientific and philosophical framework.

Keywords: Ontological emergence, Downward causation, Aristotelian causality.

Resumen: La noción de emergencia se refiere a la aparición de propiedades nuevas en los sistemas, denominadas propiedades emergentes, que son irreductibles a las propiedades elementales. Acompaña a la noción de la emergencia una jerarquía de niveles en la realidad, donde las propiedades emergentes ocupan los niveles superiores y las propiedades elementales ocupan los niveles inferiores. Así, la noción de emergencia se presenta como una noción opuesta al reduccionismo radical que supone que todo sistema natural se puede reducir a sus propiedades elementales. Las disposiciones de las propiedades emergentes las capacitan para poder causar en el nivel de las propiedades elementales con una causalidad que se suele denominar «de arriba a abajo». Sin embargo, la irreductibilidad que caracteriza las propiedades emergentes y la causalidad de arriba a abajo ha provocado un cierto recelo respecto de la noción de la emergencia. En esta tesis hemos presentado una aproximación a la noción de emergencia ontológica y de la causalidad de arriba a abajo que se corresponden con las nociones filosóficas clásicas en los campos de la ontología y la causalidad. La complejidad y la ontología de niveles de la realidad ayudan a explicar la irreductibilidad de las propiedades emergentes. Hemos apelado a la causalidad plural de Aristóteles para explicar la causalidad de arriba a abajo. Así, sostenemos que las nociones de emergencia ontológica y de causalidad de arriba a abajo poseen un sentido preciso dentro del marco científico y filosófico.

Palabras clave: Emergencia ontológica, causalidad de arriba a abajo, causalidad aristotélica.

The quest for answers to some of the most profound questions regarding existence, change, purpose, and destiny has characterised man's philosophical endeavour since its inception. The human being has an insatiable pursuit for knowledge and a disposition to be enthralled by the majesty of reality that unfolds before him. Different schools and doctrines of philosophy have occupied themselves with these profound questions to make sense out of existence, change, purpose and the destiny of all there is. We seek to know how things come to be, how they change, why they change, and their change. The philosophical notion of emergence appears to elucidate some of these fundamental questions on existence, evolution, purpose and destiny. Although emergence provides an insight into some of the essential questions, it does not exhaustively answer them. Nonetheless, the importance of emergence cannot be underrated because, from the Big Bang to the present, everything in our universe has emerged somehow (Campbell, 2015). Given that the universe's evolution presupposes the emergence of entities, this makes the notion of emergence indispensable if we are to obtain a holistic insight into reality.

Emergence is a philosophical notion that seeks to understand how newly unexpected and irreducible entities in reality appear from their basal components. The new entities or properties that emerge from the basal elements are known as emergent properties. We can divide emergence broadly into epistemic and ontological emergence. In the former, although the emergent properties are unexpected, they are reducible to the basal components. However, in the latter, the emergent properties are not reducible to the basal elements, and the irreducibility of the emergent properties constitutes the basis of what is known as downward causation. Downward causation is the causal influence of the emergent properties on their basal components or lower levels.

In the past two decades, emergence has received increased attention both in science and philosophy of science. Sartenaer notes that people are talking about emergence in almost all fields, «from entanglement in quantum mechanics to ecosystem dynamics in ecology» (Sartenaer, 2016, p. 80). As many areas call upon the concept of emergence to understand or explain better phenomena, this should accentuate the said concept's importance. On the other hand, the philosopher ought to be concerned, not so much with the mere application of the notion of emergence but with what emergence really is and how it materialises. Much as we have voluminous literature on the instantiations of ontological emergence and downward causation, there is still a meagre endeavour in understanding the nature of the two. Hence, a metaphysics of emergence and, most significantly, downward causation is a pending and imperative task. Understanding how downward causation ensues allows us to appreciate better ontological emergence. The reason is that downward causation is the *sine qua non* condition for ontological emergence (Tabaczek, 2019). Hence, this relationship between ontological emergence and downward causation constitutes the essence of this thesis as its title reads: «A discussion of the Metaphysics of Downward Causation: The Case for Ontological Emergence.»

This thesis comprises five chapters. As I explain each of these chapters' structure, I will concurrently explain why I have opted for this specific order of chapters. Let us begin with chapter one.

Chapter one provides the introduction and historical perspective on the general concept of emergence, including the types of emergence. This chapter sets the precedence and is the point of departure for the whole thesis. Many questions raised at the inception of emergence, especially on the nature of causality in emergence, remain open, and they deserve the same attention now as they did then. I will identify three eras so far that the notion of emergence has trod. Each of these three eras has peculiar characteristics that have shaped the reception and perception of the idea of emergence. After introducing the different types of emergence, I will narrow myself down to ontological emergence – this thesis's theme.

Chapter two describes how emergent properties appear and some core concepts related to emergence. Having covered the introduction of emergence, we can then look at the fundamental explanations of how emergence ensues, namely, the metaphysics of emergence. Chapter two will review the reductionist world view and then present emergence as a challenge to the reductionist paradigm. The factors contributing to this paradigm shift include the rise of complexity theory and systems of systems theory. This finds a clear manifestation in complex dynamic systems that exhibit new properties that are not reducible to the sum of the parts. I will also look at two mechanisms that can be called upon to account for the instantiation of emergence, including the rise in complexity and Pauli's exclusion principle. We shall also see how the increase in complexity and Pauli's exclusion principle explain emergent properties' irreducibility. The last part of chapter two is dedicated to an appraisal of the core characteristics of emergent properties.

Chapter three discusses the epistemology of emergence, and I expound on the concepts that we frequently employ in the discussion of emergence.

These concepts at times have a different connotation in science and philosophy, yet they are used in emergence discourse. For this reason, we need to establish a 'common discourse' across these different fields of what we mean by the concepts we employ while discussing emergence. A bridge between these various fields is the philosophy of science. The aim is that understanding the concepts central in the discourse on emergence will allow us to grasp emergence better. Here I will also cover some ideas that will prove necessary while discussing downward causation, such as levels of reality and the nature of properties – especially emergent properties. I will begin by looking at some auxiliary concepts like abstraction, theories and models. I call these auxiliary concepts because much as they do not form part of the definition of emergence, they constitute the discourse on emergence. This will be followed by other concepts like properties, levels of reality, and laws that constitute the definition of emergence.

Chapter four focuses on the metaphysics of downward causation and what downward causation consists of. I will begin by discussing a metaphysics of causality, which will later serve the purpose of arguing that the mechanism of downward causation synchronises well with the notion of the classical or conventional causality and its causal relata. This is meant to argue against those who may consider downward causation as a mere illusion or an inconsistent notion (Soto, Sonnenschein and Miquel, 2008). I will also contend that the irreducible higher levels or emergent properties exert a causal influence by virtue of the dispositional powers imbued in them. For this reason, it was paramount first to cover the introduction on emergence, how the properties emerge stressing their irreducibility; and here in chapter four, downward causation bases itself on the irreducibility of the novel emergent properties to cause on the parts. To understand downward causation on the lower levels or parts, we have to call upon the notion of levels in reality we saw in chapter three. I will also add the formal and final causes as another explanatory account for some downward causation manifestations. This will be heralded by a plea for recuperating and reincorporating the formal and final causes in the current philosophical discourse. Chapter four ends with two alternative theories on causality, namely: manipulability and cause as difference-making. These alternative causal theories serve as an annexe to the earlier presented explanatory accounts of downward causation.

Chapter five is a chapter that wraps up the thesis and treats the two main topics of ontological emergence and downward causation. This chapter is a very good representation of the thesis given that I present solid examples of the theoretical presentations in the previous chapters. Chapter five shows how an instantiation of ontological emergence is followed by downward causation resulting from the emergent properties, as we saw in chapter four. Chapter five is, above all, geared to present a discussion of ontological emergence in current science. This reveals the privileged position occupied by the natural sciences in the discussion of emergence and a better grasp of reality. However, the hierarchy in natural sciences also raises serious metaphysical questions, especially on the possibility of reductionism and constructionism. I will present ontological emergence as a form of spontaneous broken symmetry in nature. The advantage of this is that spontaneous symmetry breaking can be modelled mathematically, but it also shares the same characteristics as ontological emergence, such as novelty and irreducibility at the phase shift. I will look at some specific examples of ontological emergence and the corresponding downward causation in thermodynamics, quantum mechanics and superconductivity. Ontological emergence and downward causation will also be presented in bio-properties and neuroscience.

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List of Abbreviations

GUI	Graphical User Interface
ISO	International Standards Organization
LLC	Logic link Control
MAC	Media Access Control
NASA	National Aeronautics and Space Administration
OOP	Object Oriented Programing
pH	Potential of hydrogen ions
WHO	World Health Organization
mph	Miles per hour
AAAI	American Association for Artificial Intelligence
OSI	Open Systems Interconnection
TCP/IP	Transmission Control Protocol/Internet Protocol
MAC	Media Access Control
LLC	Logic Link Control
CDS	Complex Dynamic Systems
FFE	Far from equilibrium Systems
CCFP	Causal Closure of Fundamental Physics

Works of Aristotle

Phy	*Physics*
Met	*Metaphysics*

Works of St. Augustine

De Lib. Arb	*De Libero Arbitrio libri tres* (by St. Augustine)

Works of St. Thomas Aquinas

De prin. nat.	*De principiis naturae*
In Phys.	*In octo libros Physicorum Aristotelis exposition*
De Anima	
Metaphysicorum	
ST	*Summa Theologiae*
SCG	*Summa contra gentiles*
CM	*Commentary on Metaphysics*

Raimundus Lullus (1232-1315/16)

Opera Ea	Opera Ea Qvae Ad Adinventam Ab Ipso Artem Vniversalem, Scientiarvm Artivmqve omnium breui compendio, firmaque memoria apprehendendarum, locupletissimaque vel oratione ex tempore pertractandarum, pertinent

Francisco Suarez (1548-1617)

DM	*Disputationes Metaphysicae*

Galileo Galilei (1564-1642)

Il Saggiatore	*The Assayer*

Chapter Five
DISCUSSION OF ONTOLOGICAL EMERGENCE IN CURRENT SCIENCE

5.1. Introduction

In the last chapters, we have built a case for the notion of emergence in reality. Chapter one covered the historical context and dispositions that led to the blossom of the notion of emergence. In chapter two, we have covered the implied ontological suppositions of emergence and, in part, the metaphysics of emergence. Chapter three was centred on the epistemology of emergence, while chapter four has discussed the metaphysics of downward causation, which is an appraisal for the causal powers of the emergent properties. The irreducibility of the emergent properties and their causal powers distinguish epistemological emergence from ontological emergence.

Experimental science as we know it now plays a very important role in our interpretation of reality. The Big Bang theory tells us that the universe is expanding and that it had a beginning. Evolutionary biology and genetics allow us to explain the differences between the human races inhabiting diverse localities without losing sight of a convergent ancestry. Neuroscience reveals the astounding complexity of our evolved and adapted nervous system. Neuroscience also allows us to understand phenomena like neuroplasticity and numerous applications in psychiatry and psychology. Revolutionary techniques like the aforementioned neuroplasticity are now employed to heal traumas or learn new skills (Kolassa and Elbert, 2007; Forg, 2019). That said, science plays a role much more than harnessing the powers of nature or improving the standard of living. Scientific discoveries allow us to marvel at the very fabric of reality or fathom our understanding of the human person. Hence, experimental science is not fictitious because it deals with reality, and even the theoretical branches of science theorise on reality. For example, cosmology is a science that studies the physical universe whose nature has made our life possible. However, «although it is a physical science, it is of particular importance in terms of its implications for human life» and our interpretation of human life (Smeenk and Ellis, 2017). This means that science is not just theoretical but has a lot to tell us about ontology if we make the right interpretations of what we discover.

Chapter five will discuss selected trends of ontological emergence in some of the current debates in science and the philosophy of science. Areas such as solid-state physics, quantum mechanics, thermodynamics, superconductivity, bio-properties, and neuroscience provide us with evidence of ontological emergence and, consequently, downward causation.[1] At this point, the hierarchical prerequisite of emergence cannot be overemphasized. Emergence in physics tailors us a paradigm for understanding other manifestations of emergence in reality: ontological and epistemic aspects of emergence combined. We have seen that as the hierarchy extends upwards, we begin to see how different sciences take shape: physics, chemistry, biology, neuroscience, psychology, and sociology.

First, we will revisit the notion of «broken symmetry»[2] as proposed by Philip Anderson to serve as a point of departure for ontological emergence in physics. Broken symmetries also constitute the basis for understanding phase transitions, and these are key in arguing for the irreducibility of the higher levels to the lower levels.[3]

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1 The order that I have adopted under 'Ontological emergence in Physics,' namely, Thermodynamics, Quantum mechanics and Superconductivity does not represent necessarily the ontological hierarchy those branches of physics occupy fundamentally. Rather, the order here adopted leans more towards to the chronological order of the acceptance of the formulation of those theories by the scientific fraternity.

2 Anderson simply defined broken symmetry as the «shift from quantitative to qualitative differentiation» (Anderson, 1972, p. 393). The differentiation that results from a shift from quantitative to qualitative is what allows us to demarcate between the micro and macroproperties; or basal level (properties) and emergent level (properties) respectively.

3 Chuang Liu (1999) discusses the emergence of cooperative phenomena which are characterised by «an invariance of phenomenal properties under 'mereological manipulations' of nearly identical parts (or a limited number of species of such parts), operations of random interchange, re-arrangement, addition, or subtraction» (Liu, 1999, p. 93). One of these emergent cooperative phenomena are phase transitions which are characterised by «not being reducible» (Liu, 1999, p. 92). The other 'cooperative phenomenon' is irreversibility which

My argument is that where we see ontological emergence manifested in physics, chemistry, biology, neuroscience and other subsequent levels, we shall have some kind of a 'broken symmetry'[4] instantiated as well. Broken symmetry and phase transitions always point to the irreducibility of the higher (new) entity to the lower entity because of the «scale change causing [a] fundamental change.» (Anderson, 1972, p. 394). The 'scale change' that Anderson talks about is the change from the micro to the macro or lower level to the higher level, respectively. Eventually, the causal powers of the emergent properties will greatly exploit the fact that they are irreducible to the basal properties. This is the case of downward causation in ontological emergence.

5.2. Ontological Emergence in Physics

The Causal Closure of Fundamental Physics (CCFP) is a tenacious rival to the notion of ontological emergence. Robert Bishop defines the CCFP as: «The fundamental context-free laws and particles[5] at a time t_a determine the state s(t_a) and all subsequent states for all $t > t_a$» (Bishop, 2019, chap. 2, p. 1). This is also known as the radical formulation of the CCFP. With such a radical formulation, the result will be that the context-free fundamental principles or laws govern everything. In his book 'Dreams of a Final Theory', Stephen Weinberg considers that these fundamental context-free laws in principle are derived from the study of elementary particles. When we study elementary particles, «we will learn something about the principles that govern

is not far from the philosophical notion of irreducibility. However, phase transitions tend to be applied to an infinite limit. This creates a problem to discuss phase transition in finite systems which happen to be the majority of emergent property scenarios to which we refer ourselves. Mainwood (2006) while discussing emergence in physics, refutes various claims that the 'ineliminability' of the infinite limit in modelling phase transitions produces a great metaphysical significance. He suggests a definition of phase transitions which can be applied to finite systems. This allows us to extend the results of the theories that are applied to the infinite limit to finite systems.

4 I am banking on the combined prudence and pragmatism of the reader to note that 'broken symmetry' is a notion that strictly speaking, is applied to physical systems as we shall see later. When I apply this notion on non-physical emergent property instantiations, it is only in the measure that it serves as an analogy.

5 Particles here is a generic term for strings (from string theory), quantum fields or whatever the most basic feature of physical reality turns out to be.

everything» (Weinberg, 1992, p. 61). The metaphysical assumption of such a conviction is that everything can be reduced to elementary particles.

According to the CCFP, we should expect the fundamental principles (laws, initial and boundary conditions) to govern everything and that everything ought to be reducible to these fundamental principles. Hence, it would be possible to specify all the possible state transitions s(t_i) at some time $t_{i,}$ given the fundamental principles. If the reductionist CCFP holds at all levels, then we should expect constructionism to hold at all levels as well.[6] In his celebrated paper «More is Different», Anderson already pointed out how constructionism fails based on broken symmetry.[7]

The argument of broken symmetries leads us to draw two important conclusions. The first is that we cannot exhaust reality with an explanation based on elementary particles since the constructionist argument fails.[8] The second is that if we have to adopt a new epistemic discourse to understand the 'new emergent properties,' then we are not simply dealing with epistemic emergence.[9] We have to call upon ontological emergence at this point. Several phenomena in physics that comply with a description of broken symmetry have been tagged to manifest emergent behaviour: superconductivity, superfluidity, quantum entangled states, ferromagnetism or the Bose-Ein-

6 «... the reductionist hypothesis does not by any means imply a constructionist [hypothesis]» (Anderson, 1972, p. 394). A constructionist hypothesis is of the view that since everything is reducible to the fundamental level, then we can reconstruct the universe from the fundamental level or laws. However, we are not able to reconstruct the universe from its fundamental laws because as complexity increases there is a manifestation of new (emergent) behaviour which is not governed by the fundamental laws precisely. The emergent behaviour manifests instantiations of broken symmetries.

7 «The constructionist hypothesis breaks down when confronted with the twin difficulties of scale and complexity. The behaviour of large and complex aggregates of elementary particles, it turns out, is not to be understood in terms of a simple extrapolation of the properties of a few particles. Instead, at each level of complexity entirely new properties appear... This formulation, called the theory of 'broken symmetry,' may be of help in making more generally clear the breakdown of the constructionist converse of reductionism» (Anderson, 1972, p. 393).

8 This is a constant obstacle and a frustrating enterprise to the theory of everything (TOE).

9 We should be keen when we come across scenarios that require us to change our epistemic or theoretical dispositions and they are marked with an instantiation of novel and irreducible entities. The combination of these two is a manifestation of ontological emergence given that «... ontological emergence as novelty of reference... [has] two conjuncts: a formal, i.e. not interpretative, condition – linkage – and an interpretative condition – ontological novelty, which is a difference in intension, and sometimes also extension» (De Haro, 2019, p. 48). This builds on what we have discussed in chapter three on emergence in theories section 3.3.

stein condensation, among others. We will argue that these aforementioned physical phenomena, taking more interest in the emergence of the arrow of time in thermodynamics, quantum decoherence, quantum entangled states, and superconductivity, are some of the examples of ontological emergence in physics. However, let us first discuss in more detail the argument of broken symmetry in the following section.

5.2.1. *The Argument of Broken Symmetry*

In chapter two, we saw how as complexity increases, it paves the way for new entities or new properties that are ontologically different from their basal properties. Anderson's understanding of broken symmetry is that as complexity increases resulting in the emergence of new levels, «at each stage entirely new laws, concepts and generalisations are necessary, requiring inspiration and creativity to just as great a degree as in the previous one.» (Anderson, 1972, p. 393). When entirely new laws, concepts, and generalisations come into play with the 'new' properties, this then constitutes a description of a 'fundamental change.' As stated earlier in footnote 2 in this chapter, this fundamental change consists of a quantitative shift (of order) to a qualitative shift.

There are other senses in which broken symmetry is employed: for example, in 'translational and rotational broken symmetry.' This is discussed concerning order parameters and topology in mathematics and physics.[10] James Sethna (1992) discusses translational and rotational broken symmetry, which in themselves do not have to necessarily imply a 'fundamental change.' Translational and rotational broken symmetry refer to the loci and bearing to a given axis (spatiotemporal symmetry). However, Anderson (1972) applied

[10] Frank Wilczek (2015) in his book 'A Beautiful Question: Finding Nature's Deep Design' discusses different types of symmetries in physics and he shows how these symmetries are engraved in the very fabric of nature. Apart from showing how symmetries play a pivotal role in beauty and harmony, he goes on to discuss supersymmetry. This is an extension of the Standard Model with the purpose of filling some of the gaps of the Standard model by predicting a partner particle for each of the model particle. Wilczek's discussion of symmetry revolves around 'absolute symmetries' that help us to explain the unity of reality, especially when he talks about 'change without change.' However, broken symmetries on the other hand help us to understand the discontinuities within the global frame of the unity of reality.

broken symmetry implying a 'fundamental change', which is the philosophical interpretation of an ontological change.[11]

Brading, Castellani and Teh (2017) trace the application of the term broken symmetry in modern physics to Pierre Curie (1856-1906). Pierre Curie understood broken symmetry as the coming to be of a 'new phenomenon' in a medium due to the original symmetry group of the medium having been lowered by some cause. Lowering of the symmetry is what is understood as 'broken symmetry' in contemporary physics. The 'broken symmetry' is a new symmetry that we associate with the *emergence* of a 'new phenomenon.' The expression 'broken symmetry' should not lead one to think that the 'new phenomenon' lacks symmetry.[12] Broken symmetry is applied in the measure that the 'new phenomenon' has a lower (hence different or broken) symmetry as compared to the original (basal) entity's symmetry. The opposite of 'broken symmetry' is an «absolute symmetry [which] means [a] total lack of differentiation» (Castellani, 2003, p. 324) or being symmetrical.

Different phases of a system are manifested, each with different characteristic properties. Ice, for example, has a lower symmetry than water (hence broken symmetry), and the two phases have different properties characteristic to each of them (Sethna, 2020). Pierre Curie studied[13] the relationship between the physical properties with interest in the symmetrical properties of physical systems. He looked at the thermal, electric and magnetic

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[11] To understand this fundamental change as an ontological change we have to take into consideration that, «... phase changes embody essentially incompressible information, i.e. there exists no law or algorithm more concise than the process itself that can capture and describe what happened» (Sánchez-Cañizares, 2016, p. 21). This means that the product of the phase transition is not merely explained away appealing to reductionism. If it is not reducible, then it should be addressed in the ontological perspective. Javier Sánchez-Cañizares inspired in Anderson (1972) continues to say that, «every time a new complex structure emerges, a sort of phase-transition is happening anew, which cannot be described with the degrees of freedom corresponding to the former situation. A new conceptualization is needed. A new set of degrees of freedom comes to the fore that turns out to be as fundamental as those of the lower levels.» (Sánchez-Cañizares, 2016, pp. 21-22).

[12] One of the fundamental processes of pattern-formation is symmetry breaking. Broken symmetry is a paradoxical phenomenon because «it starts when a symmetric system starts to behave less symmetrically. In some manner... symmetry gets lost. Curiously, the typical result of a loss of symmetry is pattern, in sense of regular geometric form, because only *seldom is all symmetry lost*.» (Stewart and Golubitsky, 1992, p. 5).

[13] Pierre Curie (1894) wrote an article «Sur la symétrie dans les phénomènes physiques symétrie d'un champ électrique et d'un champ magnétique» – On the Symmetry of the physical phenomena: symmetry of an electric field and magnetic field.

properties of these physical systems. His findings led him to establish that the properties of physical systems were related proportionally to the structure and symmetry of the system. If we were to consider a 2-D schematic representation of ice and water, the ice represented by the atoms forming a hexagonal lattice structure appears to be more symmetrical and regular than the water, whose atoms appear disorganised and irregular. However, rotating the water through an arbitrary angle, it would remain as it were before. In this case, «water as a phase has complete rotational and translational symmetry» (Sethna, 1992, p. 2). The same applies, for example, when a milk drop falls on a floor. Upon impact, it will tend to spread over, but since it retains rotational symmetry, it will rebound. On the other hand, for the 2-D schematic representation of ice to remain as it were before after a rotation through an arbitrary angle, one has to rotate it by multiples of 60º (given its hexagonal structure). Thus ice has a broken rotational and translational symmetry as compared to water.[14]

Sethna (1992) proposes that one way to ascertain the existence of a broken symmetry between two materials is by trying to mix them smoothly. For example, water and oil will not mix. However, oil and alcohol will mix as alcohol and water will mix as well. In physics, broken symmetry is seen as a discontinuity that demarcates between one level and another, between microstates and macrostates; or between different phase spaces. With this phase transition come 'entirely' new properties, new laws, and concepts. The macrostates have a dependency on the microstates but cannot be predicted by or reduced to them. This explanation of broken symmetry brings us close to understanding the phase shift or fundamental change from basal properties (lower level) to the emergent properties (higher level).

The parameters that describe a physical system include its states, the observables and the equation of its motion (where the solution to the equation are the states of the system) (Castellani, 2003). When we have a broken symmetry, it means that we have an «invariance under a specified group of transformations» (Brading, Castellani and Teh, 2017). Similarly, if broken symmetry involves lowering the symmetry of the original group, then the phenome-

[14] We shall employ this rotational symmetry of water later while discussing why we should expect ice to melt into water as predicted by the Boltzmann's theorem and under downward causation in the Rayleigh-Bénard convection cells.

non of the broken symmetry is just the symmetry of one of the subgroups of the original group. This also explains the reduction of the number of degrees of freedom up the hierarchy.

Anderson argued that in a many-body system as $N \rightarrow \infty$, where N is the number of constituents/parts in a system, in such a limit, the behaviour of the system can be defined. However, when the N increases for very large systems, the symmetry of the fundamental (microscopic) level will increasingly become unstable until a critical point beyond which it will be lost. As N increases in large systems, «that matter will undergo mathematically sharp, singular 'phase transitions' to states in which the microscopic symmetries and even the microscopic equations of motion are in a sense violated.»[15] (Anderson, 1972, p. 395). This is the «orthodox characterisation of symmetry breaking» (especially spontaneous symmetry breaking) where «novel properties of systems with infinite degrees of freedom, namely, the existence of multiple equilibrium states» emerge with the $N \rightarrow \infty$ limit (Fraser, 2016, p. 585). This explains why an increase in complexity may give birth to new properties, broken symmetry, or ontological emergence. However, as we covered in chapter two, complexity is much more than increasing the number of particles or members of a system. Nonetheless, the increase in the number of particles of a system is a contributing factor to the increase in complexity. It is also worth emphasizing that we can have broken symmetries in a finite system, as defended by (Mainwood, 2006; Fraser, 2016; Wallace, 2018).

Broken symmetries are divided into two: explicit and spontaneous broken symmetry. The latter will prove important for understanding better ontological emergence (Moon and LaRock, 2021). Hereafter, we will explore these two types of broken symmetries, but let us look at the Heine definition of continuity before we get into them. The continuity function formulation helps us define when we ought to talk about a phase transition or when the novel emergent entity from the broken symmetry can be considered irreducible to its basal entity.

[15] When Anderson employs the term 'violated' here, he does not mean that the equations are violated rather that the equations of the microscopic level no longer apply or can no longer be used to describe the macroscopic level. I am going to maintain this connotation of 'violation' in the forthcoming discussions when I talk about violation of laws at a given level.

Let us consider a real function $f(x)$ that is said to be continuous at $a \in \mathbf{R}$ where **R** is a set of real numbers for any given sequence $\{x_n\}$ and

$$\lim_{n \to \infty} x_n = a$$

It follows that

$$\lim_{n \to \infty} f(x_n) = f(a)$$

We also assume that these conditions hold for continuity of a function $f(x)$ at a point $x=a$:

i. Function $f(x)$ is defined at $x = a$.

ii. Limit $\lim_{n \to a} f(x_n)$ exists.

iii. It holds that $\lim_{n \to a} f(x_n) = f(a)$

Since ontological emergence assumes that the emergent entity is irreducible to the basal properties, or the emergent level phase is likewise irreducible to the basal level or original phase, then we should expect a discontinuity in a function that tends to relate the novel with the original entity. This should be coupled with how De Haro (2019) defines ontological emergence as a non-commutativity of linkage and interpretation. This means that not only is there a discontinuity in the function that describes the domain of the emergent entity (D_t) and the domain of the basal entity (D_b) but also the «range of the interpretation of the top theory (i_t) [emergent theory, T_t,], is not the same as the range of the interpretation of the bottom theory (i_b) [basal theory, T_b], nor is it a subset of it.» (De Haro, 2019, p. 18). This can be formulated as:

$$D_t \not\subseteq D_b$$

and the interpretation maps will be

$$i_t \circ \text{link} \neq i_b$$
$$\text{ran}\ (i_t) \not\subseteq \text{ran}\ (i_b)$$

now taking the emergence base of the entire set of theories as $\{T_b(x)\}$, the bottom theories will have the same interpretation map, i_b, however, the range of i_b varies with, x through $T_{b,}$ giving us

$$i_b\,(T_b(x))$$

if we take x to be bounded from below by 0, a linkage map[16] taking the limit $x \rightarrow 0$ gives us

$$\mathrm{T}_t\!: = \lim_{x\rightarrow 0} T_b(x) \lim_{x\rightarrow 0} T_b(x)$$

In this case, De Haro (2019) concludes that the statement for ontological emergence will be:

$$\mathrm{ran}(i_t) \not\subseteq \mathrm{ran}\,(i_b)\,|_{x=0}$$

If we are going to present cases of ontological emergence banking on symmetry breaking and phase transitions, then we have to incorporate the function of continuity and the property of non-commutativity to seal our definition of ontological emergence.

5.2.1.1. Explicit Broken Symmetry

This is where a term is openly introduced or added into the Hamiltonian-Lagrangian[17] formulation of the system, thus triggering a break in the

16 According to De Haro, a linkage map is an inter-theoretic relation between two theories. We have ontological emergence between theories if the linkage map between them does not allow you to encounter all the elements of one theory in the other or vice versa: «The idea of the linkage map, link, is that it exhibits the bottom theory, T_b, as approximated by the top theory, T_t. The map's being surjective and non-injective embodies the idea of 'coarse-graining to describe a physical situation' (but linkage is not restricted to mere coarse-graining: see below). The linkage map (and so, the broad meaning of 'linkage', as an inter-theoretic relation, used here)» (De Haro, 2019, p. 8).

17 A physical system can be defined by some generalised parameters: the set of all configurations of a system as the configuration space; the dimension of the configuration space as the number of degrees of freedom of the system; and finally the coordinates of the configuration space as generalised coordinates. The Hamiltonian-Lagrangian formulations are mathematical tools that help us describe the dynamics of [a] physical system where the Lagrangian function has dimensions of energy thus describing the dynamics of the system and the Hamiltonian function similarly has dimensions of energy though it is the Legendre transformation of the Lagrangian function. (Jones, 2016).

symmetry of the physical system (Castellani, 2003). The broken symmetry results from the variation in the dynamical equations, but although it could be a small variation, it is not small enough to be neglected (Gross, 1996). An example of explicit broken symmetry is seen, for example, in the Zeeman effect, where a magnetic field is introduced, leading to the splitting of a spectral line into several components. The splitting of the spectral lines results from the magnetic field, causing perturbations in the Hamiltonian of the atoms of the spectral line. David Gross cites the isotopic symmetry of the nuclear force as an example of explicit broken symmetry «due to the small values of the up and down quark masses and the weakness of the electromagnetic force.» (Gross, 1996, p. 14257).

Given that explicit symmetry breaking is a case of 'approximate' symmetry, it will generally lead to an equally approximate conservation of laws. Since explicit broken symmetry gives a slight variation in the dynamical equations, it may be accompanied by some sort of rotational or translational symmetry breaking. An example of this explicit symmetry breaking is experienced in electromagnetic radiation where charges are accelerated, which causes a rotation or translation of the electric field in free space. The rotation results in a broken symmetry of the originally associated electrodynamic structure. The explicit broken symmetry then causes the electric field lines to curl around a receiving or transmission antenna (or radiating terminals) (Sinha and Amaratunga, 2016). On the other hand, linearly oriented transmission lines do not radiate. In this case, although the curl of the field line breaks the symmetry, its effect on the signal output can be neglected.

From our discussions on emergence, an approximate change in value that culminates in an approximate conservation of the laws does not fit the description of ontological emergence. This is neither the radically broken symmetry described by Anderson. Besides, since explicit symmetry breaking is foreseen or provoked openly, it does not articulate the conditions (like unpredictability) to consider it an instantiation for ontological emergence. Hence, I will turn to spontaneous symmetry breaking.

5.2.1.2. Spontaneous Symmetry Breaking

Spontaneous symmetry breaking (SSB) results when a given part of the physical system does not exhibit all the symmetries of the laws that govern the entire system (Steven, 2008). This means that if we have a physical system governed by the Hamiltonian-Lagrangian formulation that obeys symmetry, it will have solutions to the Euler-Lagrange equations derived from variational procedures which do not obey the same (original) symmetry. This can be attributed to the lower energy state and the stability of those states that do not obey the system's symmetry. The difference in states that is also manifested in the different phase space (that of the subgroup of the system from that of the system) constitutes the broken symmetry in reference to that of the group.[18]

Spontaneous symmetry can be invoked to explain phenomena like phase shift of matter in crystals, magnets, superconductors and superfluids, charge and spin density waves, nematic liquid crystals, and particle masses. Spontaneous symmetry breaking leads to «the occurrence [or emergence – my addition] of ordered states which are the phenomena we characterise as the 'broken symmetry.'» (Morrison, 2012, p. 150). In this way, «symmetry breaking is reflected in the behaviour of an order parameter that describes both the nature and magnitude of a broken symmetry» (Morrison, 2012, p. 152). The new phenomenon, a state in which the original symmetry is broken, is characterised by new properties and behaviour where the laws or equations of prior states only apply in a modified version.

We have seen that the reason broken symmetry warrants us to talk about ontological emergence is that at its instantiation, equivalence is broken between the micro and macro level. Without equivalence, we cannot reduce the macro-level to the micro-level, nor can we explain the macro-level in terms of the micro-level. This is where De Haro (2019) definition of ontological emergence becomes relevant again. If there is no equivalence between the macro

[18] «According to the general understanding of SSB, the system described by a Lagrangian with symmetry group ***G*** when in a phase in which ***G*** is broken to a subgroup ***H*** will possess a set of Nambu-Goldstone excitations described by fields that transform under the symmetry group ***G*** like the coordinates of the coset space. In this case ***G/H***» (Morrison, 2012, pp. 153-154). The Nambu-Goldstone are spinless bosons that are characterised by quantum numbers found in models that manifest spontaneous breakdown of a continuous symmetry (Brauner, 2010). Since they transform nonlinearly producing a phase shift, their elicitation can be used to model the field in the broken symmetry directions in a group space (Watanabe, 2020). A great application of the Nambu-Goldstone boson is the understanding of superconductivity. The superconducting transition is an example of spontaneous symmetry breaking and this is a transition that is associated with the Nambu-Goldstone boson and the Higgs boson (Yanagisawa, 2019). A detailed synthesis of the Nambu-Goldstone boson and their generalisation in the Quantum Field Theory (QFT) can be found in the original papers where the theories were developed respectively (Nambu, 1960; Goldstone, 1961; Goldstone, Salam and Weinberg, 1962).

and micro levels, we can talk about a «non-commutativity of linkage and interpretation» between the two levels. A similar theory to broken symmetry is that of the renormalisation group, which explains the jump from microstates to macrostates.[19] We will now reinforce this correlation of broken symmetries and ontological emergence, looking at some applications of broken symmetry that manifest ontological emergence beginning with thermodynamics.

5.2.2. *Thermodynamics*

The second law of thermodynamics is mainly related to the evolution of entropy within a system. However, it also seems to explain many of our time asymmetric macroworld's experiences. Several macroscopic systems exhibit an entropy gradient in temporal evolutions such that their thermodynamic entropy is lower in the past and higher in the future (Chen, 2020). There is a direction of the succession of events in the macroworld. We are born, we grow old, and we eventually die. «Rewinding a film of such processes displays an unphysical sequence of events: eggs cannot unsmash, and people cannot become younger» (Robertson, 2020, p. 548). It never seems possible to undo the past. This monotonic increase and time arrow governed succession of events is encoded in the second law of thermodynamics which tells us that «the entropy of a closed system is a non-decreasing function of [increasing] time» (Sánchez-Cañizares, 2016, p. 22). Consequently, this depicts «the notion of entropy generation as the marked characteristic of irreversible behaviour» (Lucia, Grisolia and Kuzemsky, 2020, p. 1). The embedded time arrow in the second law of thermodynamics tags it as a time-asymmetric law, and this subsequently suggests that macroscopic entropy is time-asymmetric.

However, we know that the underlying microworld is time-reversal invariant, obeying the Newtonian mechanical laws. This constitutes the quandary that scientists and philosophers have tried to decipher, namely – how the

[19] Renormalisation group (RG) is a model that permits us to investigate changes happening at different scales within a physical system. Ontological emergence can be seen in a system where the macrostructures of the systems are instantiated with different behaviour and accompanied by different properties from those of the microstructure. RG is «relevant for determining the type of cooperative behaviour that characterises the universality of emergent phenomena» (Morrison, 2012, p. 143). However, I am not going to enter into detail with this since the notion of broken symmetry suffices for my explanation of ontological emergence.

time-reversal invariant laws of the microstates underlie the time asymmetric laws of the macrostates. It seems clear that the time asymmetric laws that underlie the macroworld cannot be reduced to the time-reversal invariant laws. This should probably motivate us to consider the possibility of the emergence of the arrow of time in the macroworld. At the same time, our prognostications from the dynamics of the statistical mechanical microworld (as formulated by Boltzmann) make accurate predictions in the macroworld entropy of a system in thermodynamic equilibrium.

In what follows, we will look at Boltzmann's work on the statistical mechanical microworld dynamics and the macroworld entropy. However, this treatment does not answer the discrepancy between the time-reversal invariant microworld and the time asymmetric macroworld. We will follow this to argue that the discrepancy between the time-reversal invariant microworld and the time asymmetric macroworld can be understood as a broken symmetry of time resulting in the emergence of the time arrow embedded in the second law of thermodynamics. With an emergent time arrow, we can equally talk about the emergence of the macroworld entropy mechanisms and the ensuing downward causation on the microworld.

5.2.2.1. Boltzmann Entropy Theorem and Statistical Mechanics

Various attempts have been made to reconcile the time-symmetric dynamics of the microstates with the time asymmetric dynamics of the macrostates. One of the earliest attempts to relate the microscopic time-reversal invariant behaviour with the macroscopic time-asymmetric behaviour is Boltzmann's work on his kinetic equation and the *H*-Theory. [20] Although Boltzmann's work aims at relating the behaviour in the microscopic world with that of the macroscopic world, his attention was not specifically directed to relating the time-symmetric invariant behaviour with the time asymmetric behaviour. Rather, Boltzmann's

[20] «In 1872 Ludwig Boltzmann published his celebrated kinetic equation and the *H*-theorem that gave the statistical foundation of the second law of thermodynamics. The *H*-theorem states that if $f(x; v; \tau)$ is the distribution density of molecules of the ideal gas at the time τ, position x and velocity v, which satisfies the kinetic equation, then entropy defined as $\boldsymbol{S} = -\int dx\, dv\, f(x; v; \tau) \log (f(x; v; \tau))$; is non-diminishing, i.e. that $dS/d\tau \geq 0$. Boltzmann's kinetic equation rests on the molecular chaos hypothesis which assumes that velocities of colliding particles are uncorrelated and independent of position.» (Lesovik *et al.*, 2016, p. 1). The papers where Boltzmann published his equation and *H*- theorem were (Boltzmann, 1872, 1896).

equation and *H*-Theory aimed at relating the number of microstates with the entropy in the macroworld. If we consider a very large system in thermodynamic equilibrium, its entropy *S* will be given by:

$$S = k \ln \Omega$$

Where k is the Boltzmann's constant related to the molecular energy and Ω is the maximum number of microscopic ways in which the macroscopic state corresponding to *S* can be realized.

To appreciate Boltzmann's equation and the *H*-Theory, we must first distinguish the microscopic from the macroscopic world. The former is characterised by the velocities and positions of all the particles of the system, while the latter is characterised by the mean averages of the velocity and other microscopic properties. Under equilibrium, the macrostate variables correspond to the mean of statistical distributions of the microstate variables – and this defines Boltzmann's statistical entropy.[21] Boltzmann attempted to 'equate' thermodynamic properties represented by the macrostate to the microstates by assigning a probability distribution[22] to an ensemble of microstates. The probability distribution would hence correspond to each possible macrostate (Albert, 2000). From a methodological point of view in the philosophy of science, one may ask, «why should an individual behave like an average of many individuals?» (Huggett, 2002). This can be answered by the fact that we use probability theory in statistical mechanics to formulate entropy as a statistical property.[23]

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[21] Entropy as a concept is coined by Rudolf Clausius (1822-1888) as a thermodynamics property that predicts that some spontaneous processes are either impossible or irreversible (Daub, 1972). It has then assumed as many definitions as it has found applications in other natural sciences like chemistry, biology, or Information theory. It could also be defined as the measure of molecular disorder or randomness of a system.

[22] Suppose a macrosystem contains «more than 10^{20} atoms, and that we have very limited information about the microscopic state. We might know that the atoms are in some sort of container, which restricts their positions, and we might know something about the temperature or total energy, which restricts their momenta. We might also have made observations of the uniformity of the density. It is unlikely that we have made more than a thousand measurements, and certainly less than a million. Therefore, the only reasonable description of our knowledge of the microscopic state of a macroscopic system is by probabilities» (Swendsen, 2008, p. 643).

[23] «Boltzmann derived his equation for the time derivative of the distribution of atoms in the six-dimensional space of position and momentum by approximating the number of collisions between atoms. This approximation had the effect of turning the macroscopic dynamics into

This relation between statistical mechanics and entropy (probability distribution of microstates that correspond to a macrostate) may persuade us to consider a thermodynamic property like temperature as having two transitions. The first transition is «going from the individual particle states to ensembles as the physically relevant states» (Bishop, 2019, chap. 4, p. 9). This first transition is a result of the thermodynamic and continuum limits sharing a common feature. Bishop notes that «they mathematically signal a physical transition from individual particle states and observables to ensemble states and observables with distinguished equivalence classes» (Bishop, 2019, chap. 4, p. 10). Then we have the second transition, which comprises the «transition from the ensembles in the statistical mechanics domain to thermodynamics» (Bishop, 2019, chap. 4, p. 10). However, given these transitions in temperature, Bishop sustains that algebraic statistical mechanics tells us that the relationship between the temperature and the motion of the molecules is quite complex; it is emergent (Bishop, 2019).

Boltzmann entropy equation and its relation with statistical mechanics may also provoke some noteworthy questions to the inquisitive mind of a philosopher of science. Can we consider the relation of statistical mechanics with entropy [thermodynamics] as simply the average motion or energy of the molecules of a fluid, thus defining «macroscopic variables in terms of a mechanical ontology?» (Serafino, 2003, p. 7). In other words, which kind of reduction are we talking about when we reduce thermodynamics to statistical mechanics? The fact is that under thermodynamic equilibrium, Boltzmann's theory allows us to explain thermodynamic properties such as temperature in a statistical mechanical formulation. This is because we can talk about continuity[24] to a certain degree from the microworld to the macroworld allowing

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a Markov process, for which the development of the system depended only on the current state, and not on its history. Because Markov processes show irreversible behaviour, Boltzmann's equation did also. In particular, Boltzmann showed that a particular quantity which he called *H* could not increase with time.» (Swendsen, 2008, pp. 643-644).

24 First Boltzmann distinguished between the microstates and macrostates. Hence, «whereas the microstate $X(t)$ of a system is given by the complete specification of its microscopic degrees of freedom, its microstate $M(t)$ is specified by (approximate) values of «observables» that characterize the system on macroscopic scales (typical examples are volume, pressure, temperature, magnetization, and so on). The macroscopic state of a system is completely determined by its microscopic configuration, that is $M(t) = M(X(t))$, but one and the same macrostate can be realized by a large (in general infinite) number of different microstates, all of which 'look macroscopically the same'» (Lazarovici and Reichert, 2020, p. 345).

us to map the probability densities of the ensembles of the microstates to the macrostates.

The limitation of Boltzmann's theory in the face of non-equilibrium or far from equilibrium thermodynamics cannot go unmentioned.[25] With non-equilibrium thermodynamics, Boltzmann theory cannot be relied on unless we call upon coarse-graining and renormalisation techniques (Sánchez-Cañizares, 2016; Montefusco, Peletier and Öttinger, 2020; Šafránek, Aguirre and Deutsch, 2020; Teza and Stella, 2020). Coarse graining[26] does not achieve this reconciliation without any trade-offs. It has been discussed elsewhere the trade-offs incurred and the limitation of its degree of transferability (Ridderbos, 2002; Guenza, 2015; Robertson, 2020). Coarse graining «describes the knowledge achievable about the system by a macroscopic observer with limited measurement capabilities» (Šafránek, Aguirre and Deutsch, 2020, p. 1). We can add that *the process of coarse-graining modifies the entropy of the system since the entropy will emerge as dependent on the coarse-grained result*. However, the number of microstates that would be averaged out would increase with the coarseness of the reduced coarse-grained unit.

It is clear that there is a broken symmetry of time between the time-reversal invariant microworld and the time asymmetric macroworld. This also means we need a theory for the time-reversal invariant microworld that will be different for the time asymmetric macroworld. The non-commutative linkage and interpretation between bottom theory (or laws) and top theory (or laws), respectively (as De Haro (2019) suggests), constitute grounds to talk about ontological emergence. In what follows, we are going to make a case for the ontological emergence of the time arrow in the second law of thermodynamics.

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[25] «Understanding Thermodynamics just from a statistical point of view misses the critical point signalled by non-equilibrium Physics. Since fundamental microscopic laws refer to microstates, they do not favour any particular macrostate. They are blind regarding the latter. But they are also blind regarding the arrow of time, which seems to have [a] different status from the rest of spatial dimensions featuring the Universe» (Sánchez-Cañizares, 2016, p. 22).

[26] «In a coarse-graining procedure a number of atoms in a molecule are grouped together defining a new 'fictitious' coarse-grained unit that is centred at the position of the centre of mass of this subsystem. In doing this simple process, the dimensionality of the configurational space is reduced, smoothing the probability distribution and the related free energy surface. The new statistical coarse graining unit effectively represents a number of microstates that have been averaged out during coarse-graining» (Guenza, 2015, p. 2177).

5.2.2.2. Emergence of the Time Arrow in the Second Law of Thermodynamics

We have seen that Boltzmann's formulation of entropy and its relationship with statistical mechanics did not require any postulates of any time-asymmetric elements. Partly, this is because, according to Eddy Chen, Boltzmann sought to answer the question, «if a system is not at maximum entropy, why should its entropy tend to be larger at a later time?» (Chen, 2020, p. 2). The tendency to attain a higher entropy is explained by the fact that the states of a larger entropy occupy a much larger volume in the system's phase space than lower entropy states. This is derived from Boltzmann's equation that we have seen above ($S = k \ln \Omega$). We have also seen that the second law of thermodynamics tells us that the entropy of a closed system is a non-decreasing function of time. However, the second law of thermodynamics is not one of the laws that underlie the fundamental theory, but we have seen that the fundamental laws are time-reversal invariant. Hence, where does the second law of thermodynamics 'inherit' the time asymmetry? The question of why entropy increases with time underscores the arrow of time embedded in the second law of thermodynamics.

We also have to note that even if the fundamental laws were time asymmetric, that would not invalidate the question of the origin of the time asymmetry in the second law of thermodynamics. Here, Callender (2016) cites that the weak interaction between quarks and leptons violates time symmetry, but this violation does not seem responsible for the time asymmetry in thermodynamics.[27] If we try to use statistical mechanics and Boltzmann's theorem to predict back in time, we encounter what is known as Loschmidt's paradox or the reversibility objection. Josef Loschmidt's criticism was the impossibility of deducing an irreversible process using time-symmetric dynamics (Wu, 1975; Müller, 2019) because statistical mechanics is blind to the arrow of time. This explains why our expectations from time-reversal invariant statistical mechanics for retroactive predictions contradict our observations from thermodynamics.

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[27] While discussing asymmetry between matter and antimatter Quinn and Witherell (1998) explore in detail the charge parity (CP) reversal violation in the weak interactions. Bernabeu (2020) also discusses other broken symmetries in fundamental laws of physics but also highlights how some properties like the mass of some particles have their origin in broken symmetries. Going back to Callender (2016), these violations at the fundamental level do not seem to explain the time asymmetry of the second law of thermodynamics.

In a bid to solve the discrepancy between statistical mechanics and thermodynamics, there has been a proposal of a cosmological hypothesis postulating that entropy was much lower in the very distant past (Callender, 2016). Albert (2000) calls this the 'Past Hypothesis' (PH).[28] This restricts earlier states from having had a higher entropy than the present states because the universe began in an extremely small occupation of its available phase space. The PH acts as a boundary condition for statistical mechanics, thus, hovering over the reversibility objection. There are some objections to the PH, like we cannot verify it independently. To this objection, North (2011) argues that the cosmological data[29] points to the fact that after the Big Bang at the beginning of time, the universe was in thermal equilibrium and existed in extremely low entropy due to gravity.[30]

The proposal of some hypothesis that claims that in the distant past, the universe existed in low entropy is an example of explicit symmetry breaking. This is because the proposed hypothesis constitutes boundary conditions introduced in the system equations to observe later how the system stands or evolves. When we explicitly introduce the PH and realise that it provides a substantial explanation for the origin of the time arrow in thermodynamics, then it is not far-fetched to assume that the origin of time asymmetry in thermodynamics is due to SSB. I would posit for SSB that the time asymmetry thermodynamics cannot be reduced nor deduced from time-reversal invariant laws of statistical mechanics and that the PH is a phenomenon that emerges spontaneously. We have seen that there are reasons to suggest that the conditions that constitute the PH transpired. Understanding the reversible microworld and the irreversible macroworld can only be achieved by incorporating

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28 Lazarovici and Reichert (2020) discuss other proposals that aim at explaining the arrow of time without making reference to the PH like these authors: (Carroll and Chen, 2004; Barbour, Koslowski and Mercati, 2016).

29 Using the Bekenstein-Hawking formula of entropy of a particle at a black hole, Penrose determines the entropy of a particle at the singularity of the Big Bang as if the universe were a giant black hole. This entropy turns out to be 10^{43}. Considering an estimated 10^{80} particles in the universe, the entropy will be $10^{43} \times 10^{80} = 10^{123}$. Hence, given that entropy is on a logarithmic scale and taking the ratio of the total phase-space volume available to that of the original phase-space volume, Penrose (2016) calculated that the odds against the special initial low entropy states coming about by chance are less than $1{:}10^{10\wedge(123)}$. Hence the odds of an initial low entropy happening by chance is staggeringly small.

30 Wallace (2011) also submits a remarkable defence against those who downplay the mathematical rigour of the PH like (Earman, 2006; Frigg, 2009).

the emergence of a «time-asymmetric ingredient» in the latter (Uffink and Valente, 2015, p. 432). Hence, from the microworld dynamics to the second law of thermodynamics, we encounter a broken symmetry manifested in the emergence of the arrow of time.[31]

If we hold that the time asymmetric has its origin in the emergence of the time arrow from the microworld dynamics, then it should be logical to sustain that the macroworld of thermodynamics is emergent on the microworld of statistical mechanics. Hereafter, we will look at some manifestations of ontological emergence in thermodynamics with some examples of downward causation to explore further this emergence.

5.2.2.3. Downward Causation of the Rayleigh-Bénard Convection Cells

In the previous subsection, we have stressed the emergence of the arrow of time manifested in the macroscopic time asymmetrical thermodynamic properties. We have also held that at the microscopic level, we have the time-reversal invariant symmetric properties. Here, we shall show that the Rayleigh-Bénard convection, a thermodynamic and fluid dynamic phenomenon satisfies this description of downward causation. To appreciate the example of downward causation in the Rayleigh-Bénard cells, we have to maintain a division of the microscopic and macroscopic levels within our thermodynamic system. As we saw in the previous chapter, I will defend a kind of downward causation manifested as constraints or boundary conditions that the macro-level exerts on the micro-level.

First, let us consider fluid dynamics where a fluid is in thermal equilibrium. When the system is further moved away from thermal equilibrium by increasing control parameters such as temperature and fluid velocity, the old equilibria will increasingly become unstable. When the critical points of the control parameters are attained, the equilibria will be broken, «and new branches of local equilibria with new order emerge» (Morrison, 2012, p. 149). This is why we saw that broken symmetry does not necessarily mean there is no symmetry at all, but rather a new order, pattern or symmetry has emerged.

[31] «The existence of a global strictly increasing entropy function on every nontrivial network thermodynamic system trajectory establishes the existence of a completely ordered time set that has a topological structure involving a closed set homeomorphic to the real line, which establishes the emergence of the direction of time flow.» (Haddad, 2017, p.34).

The new phase will have its unique order that is different from that of the old equilibrium. This is a similar though general explanation that heralds the broken symmetry that instantiates the Rayleigh-Bénard convection cells.

Henri Bénard (1874-1939) was a French physicist who set up the experiment for the convection cells in 1900 (Wesfreid, 2006). For a more detailed presentation on Rayleigh-Bénard cells, one may refer to (Tyvand, 2002; Bishop, 2008). I have only extracted the gist that portrays ontological emergence and downward causation leaving out the fluid mechanics equations Bishop (2008) presents and the cylindrical analyses of the cells that Tyvand (2002) makes.

The experiment consists of a liquid in a container with the liquid's vertical height relatively small compared to the container's diameter. This setup establishes two parallel horizontal planes – the top and bottom layer of the liquid. The liquid is allowed to reach thermal equilibrium with the environment, such that even after a small perturbation from the environment, it will still attain thermal equilibrium easily. After this, the bottom layer of the liquid is heated slowly while the upper layer is maintained at a fixed temperature. This will result in thermal conduction that will establish a uniform gradient of temperature (ΔT) between the top and bottom layer of the liquid. The bottom layer will undergo thermal expansion, becoming less dense than the layer above. The action of gravity creates instability that results in a buoyancy force that tends to lift the liquid from the bottom layer. However, the upper layer will act as an external force against the buoyancy force. The system is relatively stable in this state due to boundary conditions and constraints of the whole system that maintain the stability of the liquid in this homogenous conductive state. The system's constraints at this point prevent the infinite number of convections patterns that could have taken place. However, when ΔT attains a critical value ΔT_c, the system will become globally sensitive to small perturbations in the fluid density. The stable homogenous conductive state of the fluid molecules and the spatial symmetry is broken, resulting in the self-organization of the micro-fluid molecules into large macrostructures known as the Bénard cells.

Once the spatial symmetry of the micro-fluid molecules and the stable homogeneity is broken, the Bénard cells emerge as a macro level that will now configure and constrain the possibilities of the micro-fluid molecules. The system composed of Bénard cells does not possess the original rotational symmetry of the fluid in the micro molecule homogeneity. The downward causation of the macro-level of the Bénard cells consists of «the collective effects of steady, large-scale, shear fluid motion suppressing local deviation» (Bishop, 2012, p. 7). The micro-fluid molecules constitute the macro Bénard cell, but after the broken symmetry in the homogeneity of fluid to form Bénard cells, the properties of the system are determined by the macrolevel of the Bénard cells. By constraining the system's behaviour, the collective action of the macromolecules (Bénard cells) exerts downward causation on their constituting micro-fluid molecules (Flack, 2017). Downward causation results from the long-range correlation of the Bénard cells whereby «an individual fluid molecule can only execute motions allowed to it by all other fluid molecules and the dynamics.» (Bishop, 2012, p. 7).

We have seen how the second law of thermodynamics with its description of entropy accounts for several macroscopic world irreversible phenomena. With these last Rayleigh-Bénard cells, we have seen a case of downward causation of the macrolevel on the micro-level within thermodynamics and fluid mechanics. However, as we noted above, thermodynamics does not constitute the fundamental description of reality. In the next section, we look at a more fundamental branch of physics, namely Quantum mechanics. Similarly, we shall present some instantiations of broken symmetry that manifest ontological emergence and consequently downward causation.

5.2.3. *Quantum Mechanics*

Quantum mechanics (QM) could be one of the «most successful theory ever formulated» because despite being subjected to rigorous tests, «for almost a century, none of its foundations has been called to question.» (Farmelo, 2019). However, with all the success attributed to the QM theory, for decades, a comprehensive interpretation of the theory is still wanting. This is partly because QM 'seems' to violate some classical physics fundamental principles that seem to have been engraved in our 'common sense.' Jan Faye contends that any metaphysical interpretation of QM aims to account for these violations (Faye, 2019). Maudlin (2019) presents an extensive treatise on the philosophical concerns on QM in his book 'Philosophy of Physics: Quantum Theory.'

In classical physics, the system's state can be specified by a set of parameters from which the list of properties of the system can be established (Jeffrey, 2020). For systems with very many particles or degrees of freedom, classical statistical mechanics is invoked, assigning a probability distribution over the system's state space (Wayne, 2018). Similarly, in the case of a fluctuation that may result from the perturbations of the environment, the system state is determined by the probability density in the particle phase space (Doskoch and Man'ko, 2019). The probability distribution of the physical quantities of the system will then tell us the probability for the system to be in a specific state. Hence, the dynamics of the system can specify how the properties of the system change in terms of a given law of evolution of the state. In this way, the classical states can be mapped to physical quantities to describe the state of the system.

On the contrary, there are no quantum states that assign definite values to all physical quantities. The particle state in QM may be determined «either by the wave function (state vector in the Hilbert space) or by the density operator» (Doskoch and Man'ko, 2019, p. 130). The Born rule comes in handy as it postulates the connection between QM in Hilbert's space formalism and the probabilistic predictions of the outcome (Brumer and Gong, 2006). The Born rule[32] can be stated as:

Suppose an observable $\hat{O}$ which has eigenstates $\{|O_i\rangle\}$ and spectrum $\{O_i\}$,

The observable will be measured on systems that are described by the state vector $|\psi\rangle$

If the wave function is normalised, the probability of yielding a value O_i will be given by

$$|\langle O_i|\Psi\rangle|^2$$

The alternative formulation of the probability of observing a system in position x that is in a state Ψ can be described by the coordinate range of:

$$x \text{ to } x + dx$$

giving us:

$$|\langle x|\Psi\rangle|^2\, dx.$$

[32] This was formulated in (Born, 1926, 1927) in German. However, Born (1927) has been translated to English by D. H. Delphenich. Nonetheless, there are various English works (Mehra, 1988; Neumaier, 2019) where the Born rule has been elaborated in English including his Noble lecture (Born, 1964) which presents a qualitative description of the Born rule. This is helpful for those that are not familiar with the mathematics of QM. Another helpful resource is that of Tang (2005) that covers fundamentals of QM.

Consequently, another expression of the Born rule where we may experience a change of state can be stated as follow:

$$P(\Psi,\Phi) = | P(\Psi,\Phi) |^2$$

Where P is a well-defined probability distribution, P(Ψ, Φ) is the transition probability from a state Ψ to a state Φ or the probability of a quantum jump[33] from Ψ to Φ.

Hence, the particle state in QM will be characterised by assigning its expected values to a physical quantity.

Although «no consensus on essential questions has been reached» on the interpretation of QM, we can still identify some major trends (Schlosshauer, Kofler and Zeilinger, 2013, p. 222). Generally, all interpretations of QM will have some kind of formalism comprising equations that generate predictions given the initial and boundary conditions. According to the Copenhagen interpretation of QM, the state of the QM system is the result of a combination of the observer's interaction with the system and what he observes. Some authors may argue that this does not seem to be an objective interpretation of reality from the QM theory.[34][35] However, I would rather not agree with

[33] A quantum jump is another phenomenon that could present us with emergent properties. Brändas (2015) seems to propose an epistemic emergent approach to the quantum jump by portraying it as a complex symmetric representation. On the other hand, the quantum jump may also be seen as an ontologically emergent phenomenon. Zurek (2007) holds that the origin of the quantum jump resides in the breaking of the unitary symmetry of the Hilbert's space implied by the quantum superposition principle. The preferred outcome states that emerge from this broken symmetry provide us a framework for the wave-packet collapse which designates terminal points of quantum jumps and defines the measured observable by specifying its eigenstates. Progress has been made to measure quantum jumps experimentally using a superconductor artificial three level atom (Minev *et al.*, 2019). Although the quantum jump trajectories can be predicted, the quantum jump remains complex in that at each stage of the quantum jump there is a probability that the jump trajectory may continue or is cancelled (Petrakou, 2020). Though it may not be that straight forward to agree on whether it is epistemic or ontological emergence, a quantum jump seems to point to an instantiation of emergence.

[34] «Copenhagen interpretation tells us nothing about the underlying physics of the system. It provides just the essential mathematical formalism in order to make extremely accurate predictions, to compute the probabilities of different outcomes. The state vector represents our knowledge of the system, not its physics.» (Lazarou, 2009, pp. 2-3).

[35] «Perhaps the common characteristic [feature] between the different proponents of the Copenhagen Interpretation is precisely that facing certain ontological problems they retreat and stop any attempt to analyse the situation in fully realistic terms.» (Gambini and Pullin, 2016, p. 2).

authors who only reduce the QM theory to a mathematical interpretation or formulation that has no connection to reality. This would ground QM theory only to an epistemic and subjective interpretation.

On the other hand, it is no doubt that many scientists and philosophers of science will agree that «everything seems to work perfectly and the experimental results [of QM] verify the theoretical predictions [of the same]» (Michopoulos, 2020, p. 1). Like we have argued before under Theories section 3.3.4, our theoretic or epistemic conclusions can lead us to an 'ontology' more fundamental than mere formulations, laws, or principles. Peter J. Lewis prefers to approach the question of QM and ontological emergence cautiously because «the interpretation of the theory is so contested that drawing any metaphysical conclusions from it is risky at best.» (Lewis, 2017, p. 53).

Many authors[36] (Teller, 1986; Hawthorne and Silberstein, 1995; Wallace and Timpson, 2010; Lancaster and Pexton, 2015; Richard, 2016) have suggested that QM provides us with more than compelling evidence for ontological emergence. The most important aspect of this argument is that QM systems can be interpreted in a new way that fits the general classical definition of emergence. Ontological emergence in quantum systems means that «quantum mechanical systems have ontologically new properties and downward causation where macro systems have effects on their micro components» (Gambini, Lewowicz, & Pullin, 2015, p. 5). An example of this emergence frequently cited is the role of consciousness and decision making[37] with the collapse of the wave function as a form of downward causation. However, although consciousness is sufficient for reducing the wave function, it is very likely not a necessary condition. We will look elsewhere for the evidence of ontological emergence in QM: from the emergence of the classical world and the emergence of the molecular structure.

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[36] Some scientists will use the terminology of relation of holism on the parts as referred to downward causation of the higher level on the lower levels like Teller (1986).

[37] «... the fact that probabilities are not fundamental [to the wave function], and do not emerge until we get to the very high level of agents, arguably removes what might be thought of as excessive constraints at the physical level for the emergence of conscious decision-making.» (Bacciagaluppi, 2020, p. 305). Earlier on Bacciagaluppi discusses the role of downward causation when we consider «the emergence of the quantitative probabilistic aspects of quantum mechanics (i.e. the Born rule), especially in the much-discussed decision-theoretic approach by Deutsch-Wallace» (p. 303).

5.2.3.1. Decoherence

Ontological emergence is said to manifest in QM at the transition from QM to classical mechanics under decoherence. Quantum decoherence[38] can be described as the loss of coherence of the quantum state. Coherence is understood by the existence of a definite phase relation between the different possible states of the system. Theoretically, if a quantum system were to be isolated ideally, it could maintain coherence indefinitely, but the challenge would be that it could neither be manipulated nor investigated.[39] In the mere act of measurement or manipulation, the coherence of the system would be shared by this interaction, thus resulting in quantum decoherence. Just as energy is lost to the environment, decoherence resulting from the quantum system sharing its coherence with the environment (or manipulation process) can be seen as losing information from the system to the environment.[40] The appearance of the classical mechanical properties is a result of «the unavoidable and generally irreversible disappearance of certain phase relations from the [local] states of systems by interaction with their environment according to the Schrödinger equation.» (Joos, 2009, p. 155). This gives us grounds to make a case for the ontological emergence of the macro or classical environ-

[38] «Equivalently, decoherence describes irreversibly *increasing* entanglement as a consequence of a unitary global dynamics. Phase relations between certain states of a system are preserved globally (because of the assumed unitarity), but are no longer locally accessible, thus leading to apparent non-unitarity or, in other words – to an apparent violation of the quantum superposition principle. This non-unitarity can be described as a disappearance of non-diagonal (in a certain basis) elements of the density matrix characterizing the local system. The two most important consequences of decoherence are suppression of interference and the selection of a set of preferred (dynamically stable) states» (Joos, 2009, p. 155). Others authors who have also treated the question of decoherence in commendable detail include: (Zurek, 1991, 2003; Humphreys, 1996; Silberstein and McGeever, 1999; Kronz and Tiehen, 2002; Gambini, Lewowicz and Pullin, 2015; Sánchez-Cañizares, 2016, 2019).

[39] «The key idea promoted by decoherence is the insight that realistic quantum systems are never isolated but are immersed in the surrounding environment and interact continuously with it... In short, decoherence brings about a local suppression of interference between preferred states selected by the interaction with the environment.» (Schlosshauer, 2004, p. 1268).

[40] «The degradation of quantum information due to the coupling of the system containing the quantum information to the environment is called decoherence... Early researchers used the word decoherence to refer to operations which destroyed quantum coherences and transferred information to the environment in a very specific manner. With the development of quantum computation many authors loosened the use of this word to refer to any system-environment couplings, not just those which destroy coherence in a specific basis or involve specific transfer of information from the system to the environment.» (Bacon, 2001, p. 13).

ment from the quantum environment since the process of emergence, in this case, is irreversible and certain phase relations disappear. [41][42] Kiefer and Joos (1999) describe the classical world as the 'larger system', which should also be understood as the macrosystem or higher level.

We have seen that downward causation considers the causal effects of the macroworld on the microworld. This would still hold in QM as well.[43] In this regard, George Ellis (2018) argues that «top-down action occurs in physics in general, and in quantum physics – the bottom level of the hierarchy of emergence» (Ellis, 2018, p. 11661).[44] A lot of the downward causation of the macroworld on QM has been described by the measurement process. Drossel and Ellis (2018) discuss a specific instance of downward causation of the macroworld on QM «looking at top-down contextual effects within realistic measurement contexts» (Drossel and Ellis, 2018, p. 1). They present an integrated approach that focuses on the context-dependence of the measurement process, positing that «measurement is truly a stochastic, non-unitary process that can be labelled as a 'projection to an eigenstate' of an observable A – a

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41 Kiefer and Joos (1999) stress the same point of the irreversibility of the emergence of the classical properties on the quantum world. Their argument is that for the emergence of the classical world from the quantum world, coherence is not lost (in the strict sense) in the quantum world but delocalised – a non-equivalence of phase space: «The coherence is only delocalised into the larger system. As is well known, any interpretation of a superposition as an ensemble of components can be disproved experimentally by creating interference effects... Nevertheless, one often finds explicit or implicit statements to the effect that the above processes [decoherence processes] are equivalent to the collapse of the wave function (or even solve the measurement problem). Such statements are certainly unfounded. What can safely be said, is that coherence between the subspaces of the Hilbert space spanned by n can no longer be observed at the considered system, if the process described by is truly irreversible.» (Kiefer and Joos, 1999, p. 109). Where n denotes the states of the measured system which are discriminated.

42 Also Maximilian Schlosshauer using the uncontrollable degrees of freedom explains the irreversibility of decoherence: «... due to the many uncontrollable degrees of freedom of the environment, the dynamically created entanglement between system and environment is usually irreversible for all practical purposes; indeed, this effective irreversibility is a hallmark of decoherence.» (Schlosshauer, 2019, p. 3).

43 «A general construction based on pre- and post-selected ensembles is suggested, wherein the N-body correlation can be genuinely perceived as a global property, as long as one is limited to performing measurements which we term 'strictly local' ...under certain boundary conditions, higher-order correlations within quantum mechanical systems can determine lower-order ones, but not vice versa. Surprisingly, the lower-order correlations provide no information whatsoever regarding the higher-order correlations. This supports a top-down structure in many-body quantum mechanics.» (Aharonov, Cohen and Tollaksen, 2018, p. 11730).

44 In the next section, we shall see a case of ontological emergence within QM where superconductivity will be presented as an emergent quantum macro phenomenon.

wave function collapse» (Drossel and Ellis, 2018, p. 1). Without inserting any ad-hoc term into the Schrödinger equation, they posit a wave function collapse process. The outcome of the measurement process is the eigenvalue of the eigenstate to which the symmetry is broken. The measurement process breaks symmetry because it reduces the state space to the subspace generated by other independent observables by selecting one definite outcome in the measurement process (Ziaeepour, 2018).[45] Ziaeepour argues that the final outcome of either a measurement process or decoherence manifested with the collapse of the wave function is a phenomenon that can be compared to a phase transition due to SSB.

From QM laws, we cannot predict how the transition from QM to classical mechanics will be.[46] In a way, this brings us back to the question of causal closure. If we take QM to be one of the descriptions of the fundamental level, *why is it that the transition from QM to classical mechanics is not sufficiently explained or predicted by the QM theory?* Another question that comes to mind is, for example: given that QM theory describes the behaviour of the elementary particles, why is it that the macroworld behaves differently and is being governed by Newton's laws of motion, Navier-Stokes, and Maxwell's equations? The transition from the quantum world to the classical world is evidence of «a genuine ontological change between the quantum and non-quantum domains marked by the qualitative differences in states and observables» (Bishop, 2019, chap. 6, p. 9). This comes with the undeniable evidence of how classical behaviour or collective macrolevel[47] behaviour like the aforementioned New-

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45 Here, it is also important to stress again that the selection of the outcome of measurement is not just an epistemic operation. Pusey, Barrett and Rudolph, (2012) in their formulation of the PBR theory (named after them) defend that any model in which a quantum state is only a representation of information about the underlying physical state of the system, and a model in which the systems prepared independently have independent physical systems, will outrightly make predictions that contradict those of quantum theory. Hence, «the wavefunction must represent some aspects of the real physical situation of individual systems» (Maudlin, 2019, p. 89). Another entry that presents quite a commendable job on the reality of the quantum state is Leifer (2014).

46 «Yet there is nothing in the laws and properties of QM domain simpliciter determining the sequence of transitions that must take place to get to the macroscopic world of experience... Hence the emergence of the macroscopic world of our experiences is an example of contextual emergence.» (Bishop, 2019, chap. 6, p.6).

47 Collective macro behaviour is the general idea of SSB in QM that Van Wezel and Van den Brink (2007) present. Their argument is that as the collection of QM particle grows larger, the system as a whole will increasingly become unstable against small perturbations. When the instability

ton's laws of motion, Navier-Stokes and Maxwell's equations properties has a causal influence on the quantum level constituents.

5.2.3.2. Molecular structure as an emergent property

QM fails to explain some chemical properties (in particular molecular structure) within the strict demands of classical reduction. Since «QM calculations put [or arrive at] molecular geometries in by hand,» we say that the molecular structure is an emergent property on QM (Robin, 2010, p. 190). From QM, neither can we predict the molecular structure nor reduce it to the quantum mechanical properties of the component atoms. We are going to consider two related approaches to arrive at the emergence of the molecular structure from QM. I find the argument of molecular structure decisive in ontological emergence since chemical properties derived from the molecular structure have accompanied the discussions of emergence from its inception.[48] The first is Findlay's approach using the Born-Oppenheimer approximation, and the second is Robert Bishop's approach based on quantum entanglement. For these two manifestations of the emergence of molecular structure from QM, it is good for us to understand the idea of quantum entanglement.

For a definition[49] of entanglement, let us borrow the very words of Schrödinger:

> «When two systems, of which we know the states by their respective representatives, enter into temporary physical interaction due to known forces between them, and when after a time of mutual influence the systems sepa-

increases, an infinitesimal perturbation will be sufficient enough to cause the collective system to break the underlying symmetry of the Hamiltonian. Breaking the Hamiltonian of the quantum state could mean the system ending up in the classical state.

48 «In the early years of emergence, Stuart Mill proposed the difference between resultant and emergent effects or forces basing on the chemical or molecular structure and bonding of chemical compounds. As quantum mechanics emerged, some of these bonding dynamics in chemical compounds were able to be explained in terms of the interaction of the atoms and dipole moments thereof. This seems to have shattered the hopes of ontological emergence in molecular structure as with the explanations from quantum mechanics, it was after all just a case of epistemic emergence at most.» (Bishop and Ellis, 2020, p. 501). However, we see that the more QM theory has advanced, the more it has opened afresh the debate on ontological emergence.

49 Wilczek (2016) and Lewis (2017) also provide a commendable step by step and detailed treatise on entanglement but Schrödinger's (1935) words in his seminal paper will suffice for our consideration.

rate again, then they can no longer be described in the same way as before, viz. by endowing each of them with a representative of its own. I would not call that *one* but rather *the* characteristic trait of quantum mechanics, the one that enforces its entire departure from classical lines of thought. By the interaction, the two representatives [the quantum states] have become entangled.» (Schrödinger, 1935, p. 555).

It is also good to stress the ontological nature of entanglement as a «*physical phenomenon in which the quantum states* of multiple subsystems cannot be described independently of each other, even though the subsystems are spatially separated.» (Guo, 2019, p. 1). Jeffrey (2020) compares the physical nature of entanglement to the energy associated with the peculiar quantum correlations between separated quantum systems. Entanglement is thus a «counterintuitive idea that particles can have an intrinsic [physical] connection that endures no matter the distance between them» (Ornes, 2019, p. 22413). If entanglement is understood simply as a mathematical formulation and not a *physical phenomenon*, then the arguments that follow hereafter are futile to be accorded any consideration.

According to the Born-Oppenheimer approximation, the nuclei in a molecule are considered to be stationary while the electrons are considered free to move.[50] Chemists can reduce the energy of a system, thus enabling them to arrive at the minimum energy and eventually establish the molecular structure given the relative positions of the nuclei (Scerri, 2012). Electronic energy is related to nuclear geometry. We could either solve the electronic Schrödinger's equation or use the Born-Oppenheimer approximation to establish the nuclear geometry. Although these two would lead to a slight difference in the calculated energy of the molecule, the Born-Oppenheimer approximation reveals the symmetrical properties of the molecule, which the electronic Schrödinger's equation does not reveal.

Physics tells us that the electrostatic force is a highly determinant factor for the overall molecular structure among the four fundamental forces. In the-

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50 «The nuclei within a molecule are thousands of times more massive than the electrons, and so they can be regarded as approximately at rest when the electronic motions are considered. The trick is to solve a Schrödinger equation just for the electrons, in which a fixed nuclear geometry appears as a parameter. In principle, the electronic Schrödinger equation could be solved for many different arrangements of the nuclei to see how the electronic energy depends on nuclear geometry» (Robin, 2010, p. 186).

ory, the molecular structure should also depend on the quantum mechanics of the charged particles with their electrostatic forces (Robin, 2010).[51] The reason why the Coulomb Schrödinger equations do not give us the symmetry of the molecule is that they describe «mere assemblages of electrons and nuclei rather than molecules, which are structured entities» (Robin, 2010, p. 186). As a result of quantum entanglement of the electrons and the nuclei, the entangled state represents the 'assemblage descriptions.' On the other hand, the Born-Oppenheimer approximation leads us to the symmetrical properties of a molecule, leading us to determine its structure. This is because the would-be exact solution to the full Schrödinger equation «is simply replaced by a less symmetrical structure that is compatible with the asymmetrical charge distribution» (Robin, 2010, p. 186). The molecular structure stems from a symmetry breaking of the more symmetrical joint system of the electrons and the nuclei. Hence, by replacing the symmetrical structure with an asymmetrical charge distribution, the Oppenheimer 'approximation' acts as an 'error correction' that unveils the molecule's symmetry and corresponding molecular structure.

Robin argues that unless we apply the Born-Oppenheimer approximation by fixing the positions of the nuclei, we cannot arrive at the molecular structure, let alone distinguish between two isomers that have the same molecular number. The molecular structure is a feature that we cannot arrive at from a solution of the Schrödinger equation given «that we have had no choice but to put the molecular structure in by hand» (Woolley, 1998, p. 11). We have to consider the nuclei's position as fixed parameters and not as variables in themselves. Woolley adds that the fact that we cannot derive molecular structure from QM «... is not a problem of not having a big enough computer [but] we need a new idea» (Woolley, 1998, p. 11). This 'new idea' alludes not only to a change of the epistemic paradigm but the very ontological description manifested in the molecular structure. This is why the molecular structure is ontologically emergent on QM.

[51] Our conception of «atoms and molecules as given; they are interpreted as collections of specified numbers of electrons and nuclei and there is a corresponding Hamiltonian operator to use with the Schrödinger equation. A fundamental account of this Hamiltonian recognises that electrons and nuclei carry electric charge and must be described by electrodynamics. If one chooses to present electrodynamics with the Coulomb gauge condition imposed, so that the vector potential is purely transverse, the energy carried by the longitudinal electric field (due to the charges) is just the Coulomb interaction» (Woolley, 1998, p. 10).

Like I hinted at earlier, there is another argument to support the emergence of molecular structure from QM based on entanglement. We have seen that due to the entanglement that occurs when quantum systems interact with other systems, we can say that ideally an isolated molecule does not exist. A molecule will at least couple up with the radiation field of the environment to produce a coupled entity known as a dressed state (molecule and coupled field). Bishop (2019) notes that with screening, we can reduce the coupling of the molecule with the fields (gravitational or electromagnetic), although a complete decoupling is not possible in theory.

As a result of quantum entanglement, we can never achieve an isolated molecule. Even in the hypothetical case of an isolated molecule from the environment, the electrons would be entangled with the nuclei. If we consider a molecule like ammonia hypothetically isolated, it would not have a nuclear frame at the quantum level. The lack of a «well defined nuclear frame means no molecular structure since there is no fixed position for nuclei relative to electrons» (Bishop, 2019, chap. 4, p. 14). This means that there is no molecular structure from the quantum level unless entanglements are broken to establish the relative position of the nuclei to electrons.

If we work with the context-free quantum Hamiltonian[52], we can only know the number of nucleons and electrons, and possibly their Coulomb's forces. This does not give us the spatial arrangement since the electrons and nuclei are entangled. Hence, if it does not tell us about the spatial arrangement, neither can we tell the molecular structure. (Bishop, 2019). It follows that if we cannot predict the molecular structure from the quantum level, there is a deeper issue at hand regarding downward causation. The chemical behaviour of the molecule depends greatly on its molecular structure. In the case of isomers with the same molecular formula, we see this, but they will have different chemical properties and orientations because of their different molecular structure. A good example here is carbon with its isomers of graphite and diamond. Hence, from the quantum level, we cannot predict the behaviour of a molecule.[53] Since the molecular structure determines the chem-

[52] This means without fixing any position of the nucleons or electrons.

[53] The fact that we cannot predict the molecular structure from QM also tells us that QM is neither a complete closed causal theory. Steven Weinberg claims that «today, even though we cannot predict everything that chemists may observe, we believe that atoms behave the way they do in chemical reactions because the physical principles that govern the electrons and electric

ical characteristics of the molecule by constraining the components of the molecule, it exercises downward causation on the lower levels of the molecule.

Many reductionists will argue that life properties can be reduced to chemistry, then to physics eventually. So far, we have seen that from physics to chemistry, we encounter 'instances' of broken symmetry manifested in the emergence of the chemical properties from physics. Later, we will look at how bio-properties emerge from the physical layer and that, equally, they cannot be reduced to chemistry, let alone physics. This is an endeavour that argues for the ontological emergence and the resulting downward causation on the lower constituents by the higher levels. However, right now, let us look at yet another phenomenon in QM that instantiates macro quantum emergent properties and consequent downward causation known as superconductivity.

5.2.4. *Superconductivity*

Superconductivity is a physical property of some materials where their electrical resistance drops to zero below a given critical temperature T_c and the magnetic flux fields cease to hinder the current flow in the material (Drozdov *et al.*, 2015). The phase space of the three parameters come into play to define the superconducting phase, namely: temperature, magnetic density and current density (Kunchur, 2019). The phenomenon was first discovered by the Dutch physicist Heike Kamerlingh Onnes (1856-1926) in 1911 when he cooled mercury to the temperature of liquid Helium at 4 kelvin (Vacca, 2005). A phase transition occurs when the temperature of a superconducting material is reduced below the critical temperature T_c (which some prefer to call Curie Temperature, attributing it to Pierre Curie). The critical temperature at which the phase transition to superconductivity occurs varies from material to material (Bednorz, Takashige and Müller, 1986).

As the temperature is cooled, the magnetic flux is expelled from the material leading to perfect demagnetisation in the superconducting phase. The

forces inside atoms leave no freedom for the atoms to behave in any other way» (Weinberg, 1992, pp. 9-10). However, we know that if we cannot predict the molecular structure from QM, then we are still far from a complete closed causal theory or even a theory of everything. Besides, «more than 20 years have passed since Weinberg wrote his book, but the dream is still as elusive today as it was back then.» (Hossenfelder, 2015, p. 46).

ejection of the magnetic field flux from the conductor's interior is known as the Meissner effect. The magnetic field flux diminishes from the surface inwards, indexed by a penetration depth λ_L (Bardeen, Cooper and Schrieffer, 1957). John Bardeen, Leon Cooper, and John Schrieffer, in their 1957 paper, came up with a microscopic superconductivity theory (BCS theory – which is formed from the initials of their names).[54] This was after *failed and insufficient attempts to understand superconductivity from both conventional physics and the elementary quantum theory of solid-state*, *which aim to understand* the behaviour of electrons separately from that of ions in the crystalline lattice phase.[55]

Two stages lead to the formation of the superconducting phase: forming the Cooper pairs and the condensate. These two stages result in the flow of electrons without resistance in the material leading to the superconductivity state. Without resistance, a current flowing through a superconductor would flow indefinitely without loss of power.

In what follows, we will look at the formation of the Cooper pairs and the condensate under the mechanism of superconductivity. We will later show how the superconducting phase is emergent on the normal conducting phase of the material while looking at the «Emergence of the superconducting phase.» Lastly, we will close off this section with the Josephson effect. The Josephson effect further provides us with evidence to consider the Cooper pair as an emergent particle and also strengthens the previous claim of the superconducting phase emerging from the normal conducting phase.

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54 There is another theory of superconductivity that was developed independently by Nikolay Bogolyubov and John George Valatin which comprises of transformations that find solutions to the BCS theory in a homogeneous system (Nikolay, 1958).

55 Apart from the concerns of entanglement of the electrons when we look for an explanation from elementary QM, a familiarity with the BCS theory tells us how quantum theory of solid state and conventional physics were not able to address this problem. We can use Ohm's law for the relationship between current and Lenz's laws in a magnetic field in normal conductors. However, for superconductors, we have to resort to the London equations. Fritz London (1948) in his paper, 'On the Problem of the Molecular Theory of Superconductivity' suggested that the London equations were a result of the coherence in the quantum state. The London equations which were developed with his brother Heinz London relate the superconducting current and the magnetic field around them. Brian Pippard (1953) after carrying out penetration experiments proposed modifying the London equations with the coherence length. The real breakthrough to the current BCS theory came with John Bardeen (1955) in his paper 'Theory of the Meissner Effect in Superconductors' where he argued that the proposed modification of Pippard would occur naturally in theory with an energy gap. This was confirmed by Leon Cooper (1956) with the calculation of the attractive force that bounds the states of electrons. Schmalian (2010) has a more comprehensive treatise on the history of the theory of superconductivity.

5.2.4.1. Mechanism of Superconductivity

In a normal conductor, the electrons that occupy the outermost shell are loosely bound to the nucleus which makes it easier for them to move freely within the lattice. These mobile electrons are responsible for the current flow once an electromotive force is applied across the conductor. The flow of these electrons can be described by Drude's model[56] of electrical conduction, where the behaviour of electrons is treated with classical mechanics (Suzuki and Suzuki, 2020). When the electrons flow within the conductor, they are met with resistance as they collide with impurities and the lattice vibrations. These collisions lead to power loss through the dissipation of heat. From Ohm's law, we know that the current flowing is inversely proportional to the resistance of the conductor. As the temperature increases, the lattice vibrations increase, meaning more collisions and more resistance to the flowing electrons. Hence, we should expect that as the temperature is reduced, the resistance ought to reduce proportionately. However, as we have seen above, Onnes observed that the resistance fell to zero abruptly below the critical temperature, yielding to the material's superconductivity phase. The fall of resistance to zero seemed to contradict the expected proportionate reduction of temperature and resistance. The aforementioned BCS theory explains how the sudden fall of resistance to zero emerges, thus creating the superconducting phase of the material. Although the BCS theory explains superconductivity at low temperatures, it fails to explain superconductivity at 'high temperatures', for example, at 80 kelvin. At such 'high temperatures' and those above, we have to seek solace to explain superconductivity in other electron coupling mechanisms (Bednorz, Takashige and Müller, 1986).

The BCS theory explains that given the lattice atoms lose the outermost less bound electrons to the nucleus, this leaves the atoms with an overall positive charge. When any of the mobile electrons traverse through the lattice, it will cause a slight attraction to the cations. This attraction will cause a local distortion in the lattice leading to a slight concentration of cations around the electron. When another second electron travels through the lattice (probably in a direction opposite to the first electron), it will be attracted to the concen-

[56] The original work by Paul Drude were published in German (Drude, 1900a, 1900b). There are other models that explain the motion of free electrons like the Sommerfeld model.

tration of cations since it is negatively charged. We would expect these two electrons (the first and the second) to repel each other since they carry the same charge. However, this is not the case: first, several positively charged atoms are involved in the lattice distortion and second, the attraction by the cation is stronger than the repulsion force between the electrons. The two electrons are hence attracted to each other via the electron-lattice-electron interaction. The lattice distortion, also known as lattice deformation, has vibrations quantized in terms of phonons. Hence, a phonon locks the two electrons to form a Cooper pair.[57]

After the Cooper pairs form, they will overlap to form a large network of particles they share in the same binding energy, which is the condensate. We will elaborate more on the condensate in the next section of the emergence of the superconducting phase. The condensate is what characterises the superconducting phase since just one Cooper pair does not constitute current flow.

However, we also have to consider other factors that play a role in determining the transitional temperature, like the magnetic field and pressure. In general, applying a magnetic field on a superconductor will suppress superconducting properties. This results from «a simple thermodynamic competition of the superconducting and magnetic free energies» (Asaba *et al.*, 2018, p. 1). The applied magnetic field will destroy the electron pair that is established in the superconducting state. However, a reverse possibility exists when an applied magnetic field could improve the superconductivity by enhancing the transitional temperature. This reverse possibility materialises under specific conditions:

> «... the superconducting transition temperature (T_c) is expected to be enhanced by magnetic fields in the finite momentum pairing system with strong Rashba-type spin-orbit coupling, non-centrosymmetric superconductors, in topological superconductors, and notably in the unconventional Ising superconductors based on atomically layered transition metal dichalcogenides (TMD)» (Asaba *et al.*, 2018, p. 1).

57 «The usual analysis in the BCS theory relies on a momentum-space picture, dealing with interactions between plane-wave electron states. In particular, it is often stated that the Cooper pair consists of a pair of electrons with opposite wavevectors **k** and **-k**, which interact via the exchange of a virtual phonon.» (Kadin, 2007, p. 285).

Here, the applied magnetic field H presents itself as a boundary condition for the phase transition, and hence H determines the transitional temperature and the superconducting properties. The behaviour of superconductors under an applied magnetic field typifies the superconductors either as type I or type II (Biswas *et al.*, 2019).[58] The former has a lower transition critical magnetic field H_c beyond which a phase shift occurs from superconducting to normal phase, while the latter will have a much higher order of magnitude $H_{c.}$ (Ireson, 2012). Since type II superconductors have a high H_c, they find applications in high magnetic fields like particle accelerators and biomedical instrumentalisation.

An increase in pressure has a collateral effect of increasing the transitional temperature, thus enhancing superconducting properties (Bednorz, Takashige and Müller, 1986; Drozdov *et al.*, 2015; Cheng *et al.*, 2019). An increase in pressure does not change the lattice crystal structure or chemical composition of the material. However, since pressure is a continuously tunable thermodynamic parameter, it allows us to understand the charge conduction mechanism and phase transition without introducing entropy in the system (Arumugam *et al.*, 2017). However, pressure «alters the lattice constants through bond lengths and angles, which inevitably affect the electronic and magnetic correlations» (Ijaduola, Shipra and Sefat, 2019, p. 1). Hence, since increasing the pressure will increase the T_c, pressure also constitutes the initial or boundary conditions of the phase shift.

On the other hand, the difference between low and high temperature superconductors can also be explained by the complexity[59] of «transition-metal alloy compounds» that constitute the superconductor (Bednorz, Takashige

58 We cannot have emergence of a superconductor from type I to type II since either type I or type II superconduction is determined by the make-up of the material. However, we use the strength of the applied magnetic field H_c to distinguish between type I and type II. Since H_c is independent of the material in question, it is a boundary condition for type I and type II superconductors. At very high H_c, type II will remain in the superconducting phase while type I will lose superconducting properties at relatively low H_c.

59 «... all of the known high T_c materials have complicated structures, and it pushes the limits of supercomputing to calculate accurately these numbers. Efforts to date suggest that electron-phonon coupling in these materials might be strong enough to account for T_c as high as 40 K, but it seems to be difficult to reach 90 K or above without some enhancement of the coupling strengths from those calculated within the local-density approximation (LDA). However, a complete calculation of T_c from first principles, even within the LDA, has not yet been possible for any high-temperature superconductor» (Cohen, 1994, p. 34).

and Müller, 1986, p. 189). The relationship between the complexity of the superconductor and the T_c has in recent studies been correlated with doping to achieve high transitional temperatures. Thus doping may improve the superconducting properties, which tells us that a new crystal structure comes with new conducting properties.

Experimental studies also support the theoretical description of behaviour change from the micro to macro level in superconductors. X-ray crystallographic studies reveal that when a superconducting material is cooled below its T_c, the material's electronic properties undergo a phase shift, leading to the superconductivity properties. However, there is no change in the crystalline structure. Hence, «superconductivity is not associated with any marked change in the behaviour of the atoms on the crystal lattice» (Ford, 2004, p. 83). It results as a cooperative activity of the entire condensate – the whole or the macro level. This means superconductivity is a macro effect that emerges on the level of individual electrons once the condensate is established. In the next section, we will rely on the fact that superconductivity is a macro phenomenon to build a case for the emergence of the superconducting phase.

5.2.4.2. Emergence of the Superconducting Phase

First, as we have seen under the mechanism of superconductivity, two stages precede the superconducting phase: the formation of the Cooper pairs and the condensate. Individual protons, neutrons and electrons are fermion particles. This means that no two of these particles can simultaneously be in the same state since they obey Pauli's exclusion principle. However, although the Cooper pair is formed by two individual electrons that are fermions, it has different properties from those of the individual electrons or their sum. When a phonon locks together the two electrons[60] to constitute a Cooper pair, the result is a new particle – a boson. The boson obeys the Bose-Einstein statistics but not Pauli's exclusion principle. This means that all the Cooper pairs can fall into the lowest energy level, making them reside in the same state because they are bosons and not fermions anymore. The Cooper pair has slightly lower energy such that it leaves an energy gap above it of the order of 0.001ev

[60] Here am concentrating on the emergence of the Cooper pair but Franklin and Knox (2018) also argue for the phonon as an emergent entity.

that inhibits collision interactions that lead to resistivity. Given the different properties that characterise the Cooper pair, which is a boson now, we can say it has properties that are emergent on the properties of the individual electrons that are fermions.

The second instantiation of emergence in the superconducting phase is the formed condensate. Given that the bosons do not obey Pauli's exclusion principle, this permits the Cooper pairs to fall into the same energy level allowing them to overlap and entangle to form a large network of interactions. The collective network of the electrons in the lattice prevents any collisions. To collide with the lattice, the whole network of Cooper pairs would have to collide, which is unlikely. This is because one cannot take any energy from the system that is already in the ground state and the bosons of the condensate are already in the ground state, thus all occupying the same state at the same time. As we have seen, the article where the theory of superconductivity was explained was entitled 'Microscopic Theory of Superconductivity.' Probably, 'microscopic' here alludes to the fact that the BCS theory rests on the electron Cooper pairs to explain the superconductivity phenomenon. However, superconductivity is not a microscopic but rather a macroscopic phenomenon. We cannot talk about current conductivity at a micro-level with only an electron or a pair of electrons like the Cooper pair of the BCS theory.

Unlike in the normal conductor, as we have seen, electrons are not scattered but paired up in the superconductor, and they «condense into a new state» (Halperin, 2010, p. 5). This 'condensed state' is formed by the many pairs of electrons that overlap strongly, thus constituting a highly collective condensate. This implies that «the pairs [of electrons] cannot scatter one by one because they are all forced to belong to a single wave function» (Halperin, 2010, p. 5). Under the 'condensed state', which is the superconductivity phase, the energy required to break one pair of electrons will affect the energy of the entire condensate. The pairing of electrons forming the entire condensate increases the energy barrier such that collisions and oscillations of the atoms are not strong enough to break the chain of paired electrons. The collective flow of the Cooper pairs, all sharing in the same bonding energy constitutes the condensate that manifests the superconductivity phase. Under this phase, the electrons flow without resistance from either collisions or atomic oscillations. The condensate here is a macro-level (higher level) description of the superconductor relative to the micro-level of scattered electrons. This is why we should consider the superconducting phase as a macro-level emergent phase on the micro-level of scattered electrons. We also have to note that the superconducting phase is irreducible to the normal conducting phase on two fronts. First, we need different theories to explain and understand the micro-level of the individual electrons in contrast to the macro-level of the condensate. Secondly, the macro-level superconducting phase is not renormalisable[61] and cannot be treated with perturbation theories.

5.2.4.3. Josephson Effect

Another macroscopic quantum phenomenon that exhibits emergent properties on the microscopic quantum properties is the Josephson effect. The Josephson effect was predicted by B. D. Josephson (Josephson, 1962, 1964a, 1964b) through the equations he developed. According to the Josephson effect, the Cooper pairs in a process known as Josephson tunnelling move from one superconductor to the other across a weak insulating layer at the junction. This results in a current that flows continuously without any applied voltage across what is known as a Josephson junction (JJ). When there is an applied voltage, the current oscillates very rapidly that the net current flowing will be zero. However, «in [the] presence of a voltage drop, the current should oscillate at a frequency related to the drop in voltage.» (Tafuri, 2020, p. 1241).

The JJ is a device made of two or more superconductors that are coupled by a weak link at the junction, and it may take various forms: an insulator (S-I-S), a non-superconducting metal (S-N-S), a physical constriction (microbridge) that reduces the superconducting properties at the junction (S-s-S), or the point contacts (Leggett, 2015). The Josephson effect is an example of the macroscopic quantum emergent phenomenon and shows the irreducible emergent properties of the Cooper pair compared to its constituting individual electrons. To appreciate the emergent characteristics of the Josephson effect, we need to reassess the main obstacles that Josephson had to overcome to calculate the superconducting current.

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61 I have already mentioned something on the renormalisation group. On the other hand, a renormalisable theory is one that is a relevant deformation of some conformal theory. Campbell-Smith and Mavromatos (1998) derive the renormalisation group flow equation for the phonon-electron coupling. However, on computing this equation, it is shown that it cannot be renormalised.

The idea of the Cooper pair tunnelling was discouraged first by John Bardeen of the BCS theory. He suggested that, at the most, the pairing of the electrons would not continue through the barrier as decoherence would occur (Hirschfeld, 2009). Knowing how the Cooper pair is formed from the BCS theory, it was logical to think as Bardeen thought. The transition from the first superconductor to the barrier provides the conditions to expect decoherence. Alfred Brian Pippard presented the second obstacle to the possibility of calculating the tunnelling current across the barrier. To take on the task of calculating the tunnelling current across a barrier, Josephson had been inspired by the work of «Cohen, Falicov, and Philips, who had discovered a way of calculating the tunnelling current, to the case of junctions with superconducting electrodes»[62] (Tafuri, 2020, p. 1241). The current at the superconducting electrodes experienced a phase difference. Hence, Josephson had expected that the tunnelling current would result from a broken symmetry that a phase difference in the current would manifest.[63] However, the possibility of a 'broken symmetry,' let alone a phase difference, was played low by Pippard, his academic research supervisor then and later adviser of his doctoral thesis.[64]

This macroscopic quantum phenomenon is defined by a wave function that describes the whole ensemble of superconducting electrons:

$$\Psi(r,\tau)$$

62 These three published their work under the article (Cohen, Falicov and Phillips, 1962).

63 «I was fascinated by the idea of broken symmetry and wondered whether there could be any way of observing it experimentally. The existence of the original symmetry implies that the absolute phase angle Φ would be unobservable, but the possibility of observing phase differences between the F functions in two separate superconductors was not ruled out. However, consideration of the number-phase uncertainty relation suggested that the phase difference could be observed only if the two superconductors were able to exchange electrons. When I learnt of observations suggesting that a supercurrent could flow through a sufficiently thin normal region between two superconductors, I realized that such a supercurrent should be a function of $\Delta\Phi$. I could see in principle how to calculate the supercurrent» (Josephson, 1974, p. 838). Josephson also notes in this same article the inspiration he received from Phil Anderson through his lectures on 'Broken symmetries.'

64 Here my interest is to highlight the broken symmetry and relate it with emergence. However, although as it has finally been established that we have a broken symmetry manifested in a phase difference in the current across the two superconductors (Josephson, 1974), Pippard also played an important role as Josephson made his research. It was Pippard that introduced Josephson to Giaevar's tunnelling experiments and his theory which helped him arrive at calculating the tunnelling current (Hirschfeld, 2009).

Hence, if the wave function describing the first and second superconductor are

$$\Psi_1 \text{ where } \Psi_1 = |\Psi| e^{i\Phi_1}$$

And

$$\Psi_2 \text{ where } \Psi_2 = |\Psi| e^{i\Phi_2}$$

the sine of the phase difference will give the Josephson current

$$\Phi_1 - \Phi_2$$

Hirschfeld (2009) and (Fursikov, Gunzburger, and Peterson, 2009) show how we can derive the Josephson critical current. From the Ginzburg-Landau equation of superconductivity and the superconducting coherence length, we can get the current density. According to the Ginzburg-Landau equation, the expression of the current density will take two forms: the current leaking into the barrier from the first superconductor and the current leaking into the barrier from the second superconductor. The emergent current that will flow across the barrier is expressed by

$$I = I_c \sin \Delta\Phi,$$

Where I_c is the Josephson critical current
and

$$\Delta\Phi = \Phi_1 - \Phi_2$$

In the article (Josephson, 1974), which was originally the Nobel lecture Josephson delivered on the 12th of December 1973 for his Nobel prize, he acknowledged how the Cooper pair does not undergo decoherence across the barrier as expected from the BCS theory predictions. He also mentions the broken symmetry[65] of the superconducting current across the JJ. From here, we can appreciate more how the Cooper pair as an emergent particle cannot be reduced to the summation of the properties of its constituent electrons.

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65 «I should like to conclude by saying how fascinating it has been for me to watch over the years the many developments in laboratories over the world, which followed from asking one simple question, namely what is the physical significance of broken symmetry in superconductors?» (Josephson, 1974, p. 163).

Similarly, the tunnelling current through the JJ is an emergent current from the two currents that would be flowing through the first and the second superconductors. This emergent supercurrent is characterised by a broken symmetry manifested in the phase difference between wave functions on the bulk of each superconductor.

* * *

Under this section on 'Ontological emergence in Physics,' we have seen some instantiations of emergence in physics and the corresponding downward causation. Within physics itself, we can talk about ontological emergence if we can successfully show the irreducibility of the macrolevel to the microlevel of a system and the downward causation of the former on the latter. We have also seen that the molecular structure on which depend many chemical properties is not reducible to physics. In the next section, we look at another level that can neither be reduced to physics nor chemistry – bio-properties.

5.3. Ontological Emergence in Bio-properties

Chapter three (section 3.5.4.2) listed some of the properties that constitute bio-properties, and we stated that they could not be reduced to physical properties. However, what we did not cover was showing how emergent they are, in this case, ontologically emergent. Here we are going to argue for the ontological emergence of bio-properties. Under the emergence of bio-properties, we do not anticipate covering the question of the origin of life or related theories. However, in the discourse that constitutes the question of the origin of life, the emergence of bio-properties has a special place.[66] The origin

[66] One of the arguments in the discourse of the origin of life is that life is not a product of chance. Roger White, (2007) discusses why the origin of life is not a chancy incident. The scientific data inclines to a purposeful origin of life and there are many authors that discuss teleology in biology (Rignano, 1931; Agar, 1938; Idalovichi, 1992; Agutter and Wheatley, 1999; Pross and Pascal, 2013; Trnka, 2015; Flannery, 2020). Teleology constitutes a corner-stone explanation of biological mechanisms in evolutionary biology and natural selection which these authors treat. Teleology in biology distinguishes living systems from inanimate matter and we could perfectly build a case for this broken symmetry though I am not pursuing this argument further. However, if there is a purposeful origin of life and a *telos* in living systems, this helps us answer some of the questions that arise when we talk about the place of function, formal cause or final cause

of life aims at understanding the leap from no life to life (abiogenesis), contextualising it in the environment it happened. On the other hand, under the ontological emergence of bio-properties, we will occupy ourselves with the irreducibility of the bio-properties to their basal (physical and chemical) components and the downward causation of the bio-properties. From abiogenesis, the emergence of bio-properties presupposes that bio-properties do not constitute the fundamental level of reality.

There have been attempts to get physics and biology to enter into dialogue on the question of life. Schrödinger (1977)[67] attempted to answer the question, «what is it about living systems that seems to put them at odds with the known laws of physics... apparently enabling organisms to suspend the second law of thermodynamics?» (Ball, 2018) (Ball paraphrasing and summarising Schrödinger's book).[68]

Polanyi (1968) discusses life's irreducible structure using the mechanistic old age comparison of machines with living systems. Machines operate under the control of two distinct principles: the design, which is the higher level of the machine, harnesses the lower level consisting of the physical-chemical level. The design of the machine is in itself a boundary condition to the machine. Living systems are open because of their self-organisation, thanks to genetic information coupled with environmental conditions to generate mechanisms within the living organism.[69] Living systems can modify or create their boundary conditions, while inorganic matter cannot.[70] The final cause

in living systems. It is with notions of formal and final causality that we are able to explain the manifestation some bio-properties, especially in man such as consciousness and liberty, as also the notion of the human soul. This will be part of the subject that I discuss under downward causation and bio-properties.

67 This book was first published in 1944 but for my research I have consulted the 1977 12th edition which comes extended with a treatise on «Mind and Matter».

68 Stuart Kauffman, however, is of the view that Schrödinger (1977) [though he uses his 1944 edition] in his book *What is Life* is not asking what life is but rather: «What is the source of order in organisms and how do organisms remain ordered in the face of the second law of thermodynamics?» (Kauffman, 2020). According to Kauffman, Schrödinger does not answer these questions because they cannot be answered from physics.

69 «Growth of a blueprint [genetic information of the living organism] into the complex machinery that it describes seems to require a system of causes not specifiable in terms of physics and chemistry such causes being additional both to the boundary conditions of DNA and to the morphological structure brought about by DNA.» (Polanyi, 1968, p. 1310).

70 Someone may argue that with the advance of artificial intelligence and now machine learning, an algorithm can teach itself and learn from its previous experience, or even create other algo-

directs this modification while the formal cause is in charge of defining the identity of what is or is to become. The final cause (purpose and function) and formal cause in living organisms work in unison to achieve self-organisation, evolution, and the ability to define boundary conditions. Likewise, in living organisms, we have the bottom-up and downward causation at play simultaneously (Noble, 2006).

Imari Walker argues that «... life cannot be explained by our current laws of physics» but disagrees with life being beyond physics (Walker, 2019, p. 37). Instead suggests «that an explanation [of life] might demand new physics» (Walker, 2019, p. 38). It would be interesting to know what this «new physics» consists of, but I think that this is the same as saying that the explanation of life does not belong to the realm of physics (at least physics as we know it). If that is so, then we can argue for the irreducibility of bio-properties to physics given that the laws of physics, although they may be applied to bio-properties, are not sufficient to explain life and that there exists a difference of category between the inanimate and animate properties. Stuart Kauffman argues for this ontological difference with the help of the concept of the «Adjacent Possible.» One may argue that although we cannot reduce bio-properties to physics, we may have to discover an intermediate science between physics and biology. Whether this intermediate science is chemistry, biochemistry, biophysics...; it will still be met with a difference of category on either side of the hierarchy between physics and biology.[71]

If bio-properties are irreducible to physics, they should have some downward causal influence on the physical. First, we will discuss the irreducibility of bio-properties to physics using the non-ergodicity of the biosphere, and later the «Adjacent Possible» will help us appreciate downward causation in bio-properties.

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rithms to execute any emergent function. This still is not self-organization as in the case of a living organism and for the algorithm to arrive at such self-mastery it needed a human design or software design for it to fulfil what is required of it. For non-living and inorganic entities, the goal has to be introduced from outside unlike in living organisms. Systems biology helps us to appreciate the difference between the self-organisation of living organisms and non-living entities (Noble, 2006; Saetzler, Sonnenschein and Soto, 2011). Denis Noble emphasises that its actually the self-organisation of living organisms that «distinguishes a functioning organism from a bunch of molecules.» (Noble, 2006, p. 76).

71 «The phenomenon of «life» which seems to be clear and obvious, distinguishes biology from all other sciences. The characterisation and definition of life require that the biologist creates categories apart from the categories of natural science» (Idalovichi, 1992, p. 85).

5.3.1. *Non-ergodic Biosphere*

Giuseppe Longo and Maël Montévil (2011) contend that the transition from physics to biology is characterised by a change of the mathematical tools of analysis from those used in physics. The transition from physics to biology is a permanent change (ontological) and should not be analysed simply as a transient over a phase change point. Longo and Montévil posit for a broken symmetry from physics to biology since the «symmetry breakings radically change when enlarging the mathematical locus of criticality from one point to a non-zero interval.» (Longo and Montévil, 2011, p. 341).

Stuart Kauffman makes a bold case for bio-properties' irreducibility and maintains an ontological phase transition from physics to biology. He situates his argument of the irreducibility of bio-properties to physics in the broad context that argues for the evolution of the biosphere. In his book 'A World beyond Physics' (2019), Kauffman describes the non-ergodic universe above the level of atoms (Kauffman, 2019, pp. 2-4). An ergodic system is one whose particles or constituents visit all the possible states over some time. Statistical mechanics tells us that, for example, gas particles in a closed container will attain equilibrium after some time, in which time the particles will probably have visited all the possible states. Kauffman postulates that roughly the universe has created all the possible atoms, and hence it can be considered as ergodic. However, when we come to the building blocks of the macromolecules that are attributed to bio-properties – especially proteins, the bio-properties are non-ergodic. Let us review this now – the non-ergodic biosphere.

A primary sequence of a protein comprises 20 different amino acids linked up by peptide bonds (Lopez and Mohiuddin, 2020).[72] However, a typical human protein is a linear sequence of about 300 amino acids, although some proteins may be thousands of amino acids long. Supposing we take only 200 amino acids, how many possible proteins can we get from them? Taking in mind that a protein's primary sequence consists of 20 amino acids, that means we have at least 20 combinations for each of the 200 amino acids. That would bring us to a total number of possible proteins from 200 amino acids as 20^{200}. This is equivalent to 10^{260} proteins. Kauffman claims «this is a hyper-astro-

[72] This entry (Lopez and Mohiuddin, 2020) covers the basic biochemistry of amino acids and proteins with a profound and accessible depth.

nomical number» (Kauffman, 2019, p. 3). Our next question would be to ask ourselves could the universe have created this number of proteins since the Big Bang? The answer is no. There are about 10^{80} atoms in the known universe.[73] From QM, the shortest time for anything to happen in the universe is given by Plank's time which is at 10^{-43} seconds. Now, if we assume that the 10^{80} particles of the universe were only making proteins in parallel at Plank's time, it would take 10^{39} times 13.7 billion years to make all the possible proteins from the 200 amino acids. Hence it follows that the universe in its 13.7 billion years could only have made a small fraction of 1 over 10^{39} of the possible proteins.

If proteins are taken to be some of the macromolecules[74] of life, the evolution of life cannot be understood from the point of ergodic systems in equilibrium or explained by the simplest laws of physics. Although this is an astronomical figure (the possible number of proteins) that indeed tells us of a categorical difference between physics and bio-properties, one may argue that maybe at most, it is epistemic emergence. However, since we do not know the sample space of the probability of the process of evolution of life, we cannot make a probability statement. We claim that the biosphere, life, or even economics are emergent properties because not only can we not tell what will happen, but we do not even know what can happen.[75] However, I think we can appreciate better Kauffman's case of ontological emergence of bio-properties in the non-ergodic biosphere if we bring in combined evidence from the fields of information theory, non-equilibrium statistical mechanics and complex dynamical systems.

The continuous Markovian[76] jump processes in a system are guaranteed by the ergodicity ensemble equivalence of the system, whereas non-ergodic systems

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73 (Gott III *et al.*, 2005; Helmenstine, 2019) provide how the number of atoms is arrived at in the observable universe.

74 Life is not built around proteins only. Lipids like we saw in chapter three under life properties are important for the formation of the cell membrane separating life from no life.

75 «... the evolution of life marks the end of a physics world view of law-entailed dynamics. Our considerations depend upon discussing the variability of the very «contexts of life»: the interactions between organisms, biological niches and ecosystems. These are ever changing, intrinsically indeterminate and even unprestatable [co-creating]: we do not know ahead of time the «niches» which constitute the boundary conditions on selection. More generally, by the mathematical unprestatability of the «phase space» (space of possibilities), no laws of motion can be formulated for evolution. We call this radical emergence, from no life to life.» (Longo, Montévil and Kauffman, 2012, p. 1379).

76 A Markovian system is one that is capable of achieving different states and can pass from one state to another in each time step according to fixed probabilities specified in the transition matrix or diagram.

are characterised by an emergent ergodicity breaking (Vroylandt and Verley, 2019). The emergence of the broken ergodicity introduces a non-equivalence of the dynamical ensembles of the system (Bao, Hänggi and Zhuo, 2005). Pino, Tabanera and Serna (2019) use the Rosenzweig-Porter model, a random matrix with three phases (ergodic, extended non-ergodic and localised) to study the transition between these phases where the non-ergodic phases are characterised with non-analytical behaviour. However, the ergodicity phase breaking transition can be treated with hyper-scaling[77] to achieve an approximate equivalence between the phase transitions (Matin *et al.*, 2020). A phase transition equivalent to a broken symmetry occurs as we move from an ergodic to a non-ergodic system. This is because «non-ergodicity explicitly violates the fourth SK axiom»[78] (Thurner and Hanel, 2012, p. 105). Similarly, if we experience the same transition from the ergodic lifeless inorganic matter to the non-ergodic bio-properties, we should be discussing ontological emergence.

5.3.2. *The Adjacent Possible*

In 1971, Kauffman suggested a theory for explaining replication which is at the heart of bio-properties like reproduction and self-organisation:

> «Replication is the property of a complex dynamic system, not a single molecule. More fundamentally, self-replication is an autocatalytic process in which a set of molecules catalyses the formation of a nearly identical second set. No molecule need catalyse its own formation» (Kauffman, 1971, p. 90)

This theory is now known as 'autocatalytic sets' and has matured in other Kauffman's publications (Kauffman, 1986, 1993, 1995, 2019) as a proposal to understand the origin of life. The idea is that an autocatalytic set is a

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77 Hyper-scaling is a tool that is used to improve and appropriately map two systems against each other where one has an immensely higher quantity of content to map to the content of the other system.

78 Non-ergodic systems obey the first three Shannon-Khinchin (SK) axioms but violate the fourth SK. The SK axioms are four equations that characterise the generalised standard Boltzmann-Gibbs (BG) entropy applicable in thermodynamics, quantum mechanics and information theory (Ilić and Stanković, 2014). However, a violation of the fourth SK axiom is equivalent to a 'broken symmetry' given that the phase space volume collapse. Ergodic systems on the other hand will register an absolute equivalence.

«self-sustaining chemical reaction network in which all the molecules mutually catalyse each other's formation from a basic food source» (Hordijk, 2019, p. 224). To understand life as it is now, we need to consider self-reproduction, variation and evolution according to Darwin's law (Dodson, 1976). However, Kauffman holds that although one could predict autocatalytic sets for the origin of life from physics or complex dynamic systems, natural selection and heritable variations remain beyond the realm of physics, and they cannot be reduced to physics (Kauffman, 2008). He adds that agency which is also very pertinent to understanding the biosphere and human life, can neither be deduced from physics nor reduced to it. When we add consciousness and free will to the equation, we realise that human culture is ceaselessly creative in ways that can neither be deduced nor reduced to physics. Free will in human beings places us at the apex of creation as it imbues us with infinite ways to actualise ourselves.

Bio-properties like function[79] and agency[80] are irreducible to physics and alien to physics, yet they play a central role in the evolution of the biosphere and bio-properties in particular. The biosphere creates its own possibilities of becoming, which are diverse and ample (Kauffman, 2019). This can be said of the economy, the society, and other emergent properties we have covered in chapter three, as Kauffman describes (Kauffman, 2019, pp. 129-139). 'The adjacent possible' is a notion that Kauffman (2000) introduces in evolutionary biology and Complex Dynamic Systems to explain the 'radical' emergence of the biosphere from physics. The adjacent possible is a set of available possibilities for an evolving entity at a specific time in its evolutionary process. Hence, the adjacent possible is what can possibly arise next, given what is actual now

[79] «[The connotation of] functions in the biological sense, does not exist in physics... Thus, if functions are a legitimate part of biology, then biology cannot be reduced to physics» (Kauffman, 2019, pp. 13-14). Probably, the 'physiological function' in biology that only looks at what a biological part (cell, organ, organ system...) does may be equivalent to function in physics. However, if we want to capture function with a connotation of *telos* and purpose as seen in biology, then this is a concept that does not exist in physics.

[80] Meincke (2018) discusses agency in biology versus the claim that we can find some artificial agency in lifeless beings like nano robots. Agency as we know it from the classics finds its true place in living organisms and bio-properties, and this clearly distinguishes them from non-living organisms. Agency as «the ability of living entities to alter their environment (and themselves) with purpose to suit an agenda.» Hence is an emergent property, agency arises from, but is not wholly (and perhaps not at all) accounted for by, the properties of more 'fundamental' constituents (Ball, 2020). Ball argues that agency is at the heart of understanding free will in humans.

(Björneborn, 2020). This is how bio-properties and the biosphere evolve, and they cannot be predicted from the laws of physics.

The new possibilities that emerge are further constrained by the actual properties, which then will determine the future. Bio-properties are self-propagating, self-constructing, and self-organisation properties of a non-equilibrium process that culminates in an indefinite diversity and complexity (Green, 2017). Hence, evolutionary biology cannot be predicted from the laws of physics. Even the explanation of the origin of life using autocatalytic sets is a form of adjacent possibilities, given we cannot tell at which point ensues the spontaneous emergence of biomolecules within an autocatalytic set. All this points to the fact that we encounter ontological emergence from no life to life.

The bio-properties attributed either to the whole organism, organ system, or cell will have a downward causal influence by constraining the parts that constitute them. Like we have maintained in the previous chapter, the irreducibility of the emergent properties to their basal properties is the basis of downward causation. Hence, in the event of emergent bio-properties like what we have covered under this section, we should expect their downward causation on the lower parts.

The emergence of bio-properties we have considered here apply broadly to living organisms. However, some properties can only be ascribed to man (or properties of the human soul) in the strict sense like rationality, free will and the ability to love. These are some of the properties which situate man in the most privileged position among living organisms. In the next section, we will look at some of these exceptional properties attributed to man under the Mind-brain problem complemented with neuroscience to appreciate yet another instantiation of ontological emergence.

5.4. Ontological emergence in Neuroscience

The Mind-Body problem has always centred on how the mind (an immaterial entity) interacts with the body (a material entity). The question of whether there is an interaction or not has been channelled to constitute the discourse of mental causation (Robb and Heil, 2019). In chapter three, we already stated our assumptions and premises on which we ground our approach to mental properties: they are real, irreducible entities that manifest at a higher level than physical properties.

In the last decades, there has been tremendous progress in understanding how the human brain works in neuroscience. Neuroscientists with a bias to physicalism and reductionism are in a race against time to explain all human phenomena as an extension or function of the neural activity.[81] On the other hand, since the non-physical mind occupies a higher level than the physical level, this means that from neuroscience, we cannot prove the existence of the mind or human soul (Clayton, 2004). One cannot explain the mind completely from the material. The mind has to be explained from the immaterial: will, intellect, love, election, free will, and so on (properties attributable to the soul).[82] Hence, neither neuroscience nor any other experimental science that occupies itself with a material subject matter can exclusively lead us to the existence of the mind.

When we talk about the mind in the current philosophical or scientific discourse, there is a need to take into consideration the evolution of what we understand by the term 'mind.' The properties we attribute to the mind are *some* of the properties that have always been attributed to the human soul.[83] Metaphysics gives us reasons we should not expect to arrive at a concrete notion of soul or mind from a science with a material subject matter. However, the fact that sciences that occupy themselves with a material subject matter cannot give us concrete evidence for the existence of the mind does not mean that they cannot even point to the possibility of its existence. Under properties section 3.5, we saw that causal influence is undeniable evidence for the existence of the causal relata. Under levels of reality, we have sustained that «mental properties are higher-level, dispositional properties» (Heil and Robb,

81 «Using the research methods at its disposal, biology can «evade» utilising definitions which belong to the domain of consciousness, soul or spirit. But this is no longer possible when one searches for a comprehensive definition for the phenomenon called 'life'.» (Idalovichi, 1992, p. 85).

82 Reimers (2011) discusses the human soul as the metaphysical basis for the transcendence of the human person. The human person transcends the physical order since he or she is directed toward truth, beauty, and goodness. This reveals the human person as a spiritual being as well as a material being. However, to arrive to the spiritual dimension, we have to depart from transcendent categories.

83 Here, it is good to take into consideration how the notion of the human soul has suffered reductions. Generally the classics (Aristotelian tradition) maintained the soul as the form of the body. Thomas Aquinas promoted the soul as the form of the body with the immaterial soul also known as the intellect or the mind (ST 1a, q.75.2). The reductive explanatory account of the human person begins with Descartes who has promoted a dichotomy consisting of the mind-brain split that sciences of the mind have inherited (Fuller, 2014).

2003, p. 183). Hence, one way to point us to the existence of the mind or even the human soul is by substantiating its causal powers on the physical level.

If we pay attention to the advances in neuroscience, we see some manifestations that point us to the downward causation of the mind on the body. Neuroscience shows us how a higher-level property may exert a causal influence on the brain or body.[84] Under this section, we will make a case for mental properties corresponding to mental states, where the mental states can, in turn, be correlated to but not reduced to quantifiable neural activity. We will end by highlighting the downward causal influence of mental properties on the body.

5.4.1. *The Psycho-physiological Correlation*

Since mental properties are non-spatial properties,[85] there exists no phase space equivalence to the physical or basal properties. This poses a dilemma to understand the interaction of these two different domain properties. The 'alternative theories of downward causation' that we have looked at in the previous chapter may help us resolve the two domains' interaction. If the higher-level mental properties are to have any causal influence on the lower-level physical properties, that causal influence should be reflected either as a cause of a difference or a manipulation of the lower level in some way. The first task would be to devise some kind of mapping of the neural activity as initiated by the presumed mental properties or states.

My hypothesis[86] first supposes that the brain constitutes part of the physical level, the body. We can further divide the physical level into the sensory end

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[84] «It is generally taken for granted that our thoughts, feelings and intentions can influence our behaviour and have an effect on the material world. Nothing is more obvious to us than the fact that by conscious decisions we can control our actions and either bring about things or prevent them from happening. But then we have learned from the neurosciences that conscious decisions and subjective sensations play causal roles only as neural activities in our brains.» (Pernu, 2011, p. 483).

[85] Deacon (2012) argues that the proposed theories of everything in physical sciences have an unacceptable omission since they only look at entities that have physical quantities like mass, momentum, charge and location. However, the properties that constitute who we are cannot not be limited to only those with physical quantities. Things like feelings, meaning, consciousness or purpose that also constitute who we are not physical nor spatial, and this is where the mental properties fall.

[86] I drive this hypothesis from studies that show how mental activities like learning construct neural activity and networks which are responsible for some behaviour (Oby *et al.*, 2019). Mental causation is not magical that it initiates behaviour directly. It will initiate neural activity and that

(end-physical)[87] properties and neural properties (brain/neural activity). Downward causation of mental properties means that we have ruled out any possible neural activity identified or registered on the brain that originates from the sensory receptors or any end-physical property. Hence, we need a way through which we can measure or identify neural activity and correlate it either to a physical cause (bottom-up causation) or mental causation (downward causation).

Rolls and Treves (2011) discuss the results obtained from quantitative information-theoretic analyses of neural encoding in the primate visual, olfactory, taste, hippocampal,[88] and orbitofrontal cortex. The information of the neural activity correlated to stimuli is encoded by the firing rates of the neurons that form a robust code that can be read in as fast as 20ms. The code is sparsely distributed, but it can be read by taking a synaptically weighted sum of the neuron inputs. Understanding this code is what allows us to grasp how the cortex represents and processes information. With these analyses, we can correlate neural activity or neural states to mental states through the potentials that correspond to a given neural state. I am going to show how these advanced neuroscience techniques allow us to talk about ontological emergence and downward causation of the mental properties that we have seen now to be instantiated mental states.

5.4.2. *Correlation of Neural activity to the Mental States*

The psycho-physiological correlation opens us to the possibility of mapping mental and physiological activity on neural activity. Of course, the chal-

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neural activity behaviour. However, we also know of how manipulation of the sensory receptors can activate neural activity, or the presence of some chemical may lead to a neural state and eventually to a determined mental state (euphoria, laughing gas...).

87 The sensory end-physical properties could be the properties of the termination of the motor neurons to muscles, glands, organs, or the sensory receptors of any kind.

88 Anand and Dhikav (2012) while discussing the hippocampus, point out that the limbic system is considered to be a «primitive brain,» that lies deep within the brain. It is associated to stimuli like hunger, motivation, sex drive, mood, pain, pleasure, appetite, and memory etc. The hippocampus constitutes the posterior part of the limbic lobe and frontal part is amygdala. Also the emotional response is organised in hippocampus and is expressed in the cingulate gyrus via mammillary bodies. Fumagalli and Priori (2012) likewise mention the role of the hippocampus in moral behaviour – «moral brain.» Here I want to highlight that we can correlate the neural activity in the hippocampus to stimuli that coordinates emotion, mood and pain. The importance of this mapping is harnessed in the argument of a subsection after where I will be looking at emotional pain and its causal influence on the brain.

lenge remains in curbing any chances of multiple realizability that trigger neural activity, but this is possible to curtail, leaving us with the genuine causal relata. There are various methods used to detect neural activity, which include: «Electroencephalography (EEG), Magnetoencephalography (MEG), functional magnetic resonance imaging (fMRI), optoencephalography (OEG) and Intersectional Short Pulse (ISP)» (Wang *et al.*, 2019, p. 13468).[89] Hence, if we can detect neural activity ruling out the responsibility of any physical causes, then we are left with the alternative of mental causation. Given the psycho-physiological correlation developed from multiple studies, ruling out the intervention of a specific physical cause of the registered neural activity is possible (Allefeld, Atmanspacher, and Wackermann, 2009).

Registering neural activity correlated to mental causation would allow us to talk of the downward causation of the mental on the physical. On the other hand, if mental properties were able to cause on the body, then the mental properties would not be reducible to the physical properties ontologically. Ontologically emergent mental properties suppose that they are unpredictable and irreducible to the physical properties. Hence, the way to verify any higher-level properties on the physical properties (neural activity in the case of brain properties) would be by downward causation of the higher-level properties on the lower-level properties.

Robert Bishop (2019) proposes that we can arrive at the emergence of mental states[90] using the Hodgkin-Huxley equations. The Hodgkin-Huxley

[89] Wang *et al.*, (2019) propose another recent and more advanced non-invasive technique for neural activity based on the microwave scattering principle. It rests on the dynamic properties of dielectric at the brain functional site and its advantage is the ability to detect neural activity at a greater depth. We can be sure that studies where it will be used in neuroscience will be more accurate and with less side effects than the current methods of detection of brain activity.

[90] I have to make a distinction from the way the term 'mental states' is applied in Behaviourism and the way I use it here to refer to mental properties. Behaviourism is a materialist theory because it connects the observable human behaviour with the mind and the behaviourist view of the human mind is that the mental states can be reduced to behavioural dispositions (Fieser, 2008). Hence behaviourism assumes that all behaviour is triggered by stimuli in the environment or is a reflex. Harald Fieser continues to say that the extreme versions of behaviourism reject the spiritual aspect of the mind and restrict mental states to the physical confines of behavioural dispositions. However, Sho Araiba in a recent article presents some lenient diversifications of behaviourism that constitute the current philosophical discourse which take into account the role of the agent in behaviour: This means that behaviour is not purely materialistic since «emergent behaviourism and theoretical behaviourism incorporate the agent in the form of a hypothetical construct such as memory, attention and intentional behaviourism which permit a person to me-

model comprises non-linear ordinary differential equations[91] with a corresponding electronic circuitry set up, explaining the flow of current through ion-selective channels in the neural membrane (Beeman, 2013). Alan Hodgkin and Andrew Huxley, in a joint article in 1952, proposed an explanation of the ionic mechanisms that trigger the generation and propagation of action potentials. They carried their experiments on a giant squid axon (Hodgkin and Huxley, 1952; Schwiening, 2012). Thanks to the Hodgkin-Huxley equations, scientists have been able to «analyse models of neurons from a control perspective and to show how recently developed analytical tools help to address important biological questions» (Drion *et al.*, 2015, p. 1923). The Hodgkin-Huxley model has also been used to study «a fully connected structural neural network to simulate the neural activity and energy consumption of the network by neural energy coding theory» (Zhu, Wang and Zhu, 2018, p. 1).

The Hodgkin-Huxley model consists of electric conductance transmembrane currents combined with gates of potassium and sodium ions. Robert Bishop demarcates the Hodgkin-Huxley model into the micro and macro level. The smaller-scale ion gates constitute the macro-molecular quantum level that would be entangled with the electrons and nuclei. This means that the molecular structure necessary for the pores to either open or close would be contextually emergent (Bishop, 2019). Emergence arises from the fact that given the entangled state of the smaller-scale ion gates with the electrons and nuclei, we cannot predict the opening of the pores, nor can the opening of the pores be reduced to the entangled state of the smaller-scale ion gate. This argument may help to explain the emergence of mental states, but its reverse construction does no explain how physical properties trigger neural activity. In my view, it would need more explanation or clarification on how to explain the physical causes of neural activity.

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diate [in] time and environments.» (Araiba, 2020, p. 170). On the other hand, I employ mental states as understood by functionalism. Graham George (2019) notes that functionalism understands mental states as entities that play causal-functional roles in animals or systems in which they occur. Paul Churchland specifies the causal relata at stake when he writes: «The essential or defining feature of any type of mental states is the set of causal relations it bears to... bodily behaviour» (Churchland, 1984, p. 36).

[91] Johnson and Chartier (2017) provide a step-by-step derivation of these four differential equations and they go on to explain the firing and propagation of the ionic flow of the action potential. For the scope of my research I leave out these interesting details.

There are other authors (Allefeld, Atmanspacher and Wackermann, [2009]; Atmanspacher, [2012] and Atmanspacher and Graben, [2018]) who also describe the emergence of mental states from neural states using the Hodgkin-Huxley equations. To understand this first, Graben (2016) shows how the fluctuations of ion gates are stochastic with the Hodgkin-Huxley equations. This means we have an emergence of stochastic dynamics at the ion gates. Since the emergence of this stochastic dynamic process corresponds to the higher level (which in this case are the mental states)[92] leading to the activation of the neural activity, it can be said how mental states emerge from neural states. Beim Graben (2016) and Atmanspacher and Graben (2018) use functional algebra of the decorrelation of phase space in time to show the emergence of mental states from neurodynamics. However, similar to Bishop's explanation above, this explanation of downward causation of mental states does not seem to explain how physical properties cause mental states (bottom-up causation). It may have to be modified to accommodate bottom-up causation.

Authors writing on the philosophy of the mind that are more inclined to neuroscience than metaphysics often interchange these terms: mental properties and mental states (Fieser, 2008; Ascoli, 2013; Tamir *et al.*, 2016; Polák and Marvan, 2018; Thornton, Weaverdyck and Tamir, 2019). Consciousness[93] and intentionality are perhaps the most widely discussed mental properties (Pernu, 2017). Consciousness as a mental property has also been defined as a mental state, and it is easy to imagine it this way since in itself, consciousness is

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[92] We have to note that the emergence of the stochastic dynamics does not necessarily have to originate from mental properties. However, like other instantiations of registered neural activity that we have considered, the assumption of Beim Graben (2016), together with that of Atmanspacher and Graben (2018) is to rule out any possible origin the stochastic processes from a physical cause. Hence, they appropriate the mental properties as the cause of the stochastic dynamics.

[93] Whereas some authors (Penrose, 1994, 2016; Metzinger, 2000) have mainly concentrated on the neural correlates and consciousness on the psycho-physiological problem, I will not pursue this line of argument. An attractive and strong argument on consciousness as an ontologically emergent property is equally made by Jacques (2019). The postulates of Information Integrated Theory (IIT) and the Maximally Irreducible Conceptual Structure (MICS) permit us to derive for any given system whether it has consciousness, how much, and which particular experience(s) define(s) the system or state (Oizumi, Albantakis and Tononi, 2014; Tononi *et al.*, 2016). Given that IIT sustains that every experience is unique and irreducible, Ignacio Jacques appeals to the causal powers which are manifested in the irreducible singular experience to argue for the causal power of consciousness as the cause of the next state. On the same point, (Sánchez-Cañizares, 2021) argues for formal causation in IIT.

a state of the subject's awareness (Rosenthal, 1986, 1991, 2009; Rosenthal and Weisberg, 2008; van Gulick, 2018). However, Rosenthal extends the application of mental states to other mental properties «such as thoughts, perceptions, and feelings» (Rosenthal, 2009, p. 157). Defining mental properties as mental states is not far stretched because if mental properties are real entities, although they are not spatial, they are instantiated in time (at least for their very first time). Hence, we can refer to an entity that is instantiated together with the duration of its instantiation as a state.

Scientists tell us that the «different kinds of mental states (e.g., fear, disgust, love, memory, planning, concentration, etc.) correspond to different psychological faculties that have correlated activity on the brain» Oosterwijk *et al.*, (2012, p. 2110). This approach of mental states being correlated to large scale distributed neural networks is supported by growing evidence and diverges from what scientists have always believed, namely, that the correlation of the mental states on the brain happens at domain-specific regions. However, without going into the detail of the nature of the corresponding neural network that correlates a mental state, we know that mental states correlate to the neural activity on the brain, which can be measured using the aforementioned methods. Here I have to make a very important observation: *correlating neural activity to mental states after ruling out the presence of a known physical cause to initiate the neural activity presents some limitations*. The first is that by ruling out a physical cause to talk about mental causation does not mean that we discard completely any intervention whatsoever of a physical cause. In our discussion in chapter four on causality, we saw that we cannot talk about matter without form and this why we cannot discard completely any intervention of a physical cause in mental causation.

However, falling back on the roles of causal relata that we looked at, still in chapter four, we can identify a cause and the effect within various causal relata. The whole notion of causal relata and their roles is to help us spot the cause or the effect. We can distinguish mental causation from physical causation despite the hylomorphic relation between the formal and material cause. The other limitation is that we cannot quantify the formal causation or mental causation. However, some of the effects of formal causation or mental causation can be observed, that is to say, after ruling out any other possible causes of those effects. In this case, the correlation of the mental states to neural activity is indirect, and it remains a very reduced representation of the interaction of the mind-body relationship, and neither can it in any way prove the existence of the mind.

However, limited as it is, the correlation of mental states on neural activity offers a substantiation on how the higher-level mental states causally influence the lower-level physical properties. It comes with other challenges, such as the signal processing of the neural activity and possible blurring effects of multiple realizability of the results. Hereafter we will look at how mental states exercise their causal influence on the body/brain. I will also comment briefly on the challenges of measuring and correlating neural activity with mental causation.

5.4.3. *Downward Causation of Mental States*

We have seen the possibility of mapping mental states (emotions, body feelings and thoughts...) to neural states. Another interesting field of research that shows this correlation is that of correlating election and decision making with neural activity (Gold and Shadlen, 2007; Xiaojing, 2008; Broche-Pérez, Jiménez and Omar-Martínez, 2016; Lee and Seo, 2016; Taghia *et al.*, 2018; Kriener, Chaudhuri and Fiete, 2020).[94] We will look at a specific body feeling that is emotional pain, and we will show how emotional pain has a downward causal influence on the body.

There is even overwhelming scientific evidence on how emotional/psychological pain, which necessarily does not have a physical origin (instantiation), activates the same brain regions as physical pain does (Leventhal and Everhart, 1979; Bussone and Grazzi, 2013; Biro, 2014; Pickering and Gibson, 2015; Weits, 2015; Athey and Overholser, 2016; Meesters, Vancleef and Peters, 2019). David Biro notes that,

> «Medicine regards pain as a signal of *physical injury* to the body despite evidence contradicting the linkage and despite the exclusion of vast numbers of sufferers who experience psyc*hological pai*n. By broadening our concept of pain and making it more inclusive, we would not only better accommodate

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[94] Studies on decision making and neural activity show the two kinds of bottom-up and downward causation. There are embedded (at times referred to as 'hidden') neural circuits that influence decision making. This would be the case of bottom-up causation. Physiological states like hunger or thirst can influence the decisions one takes but *they may not impel one under normal circumstances*. However, we also have scenarios where decision making instantiates neural activity, eventually leading to action or behaviour. Gold and Shadlen (2007) evaluate how basic elements of decision making are implemented on the brain.

the basic science of pain but also would recognize what is already appreciated by the layperson – that pain from diverse sources, physical and psychological, share an underlying felt structure» (Biro, 2010, p. 685).

Of course, here caution has to be taken as physical pain may also lead to psychological pain as studies from phantom limb pain show (Whyte and Niven, 2001; Padovani *et al.*, 2015); and other physical ailments that may lead to psychological pain and trauma. It is not only pain that can be mapped to brain regions but passions: happiness, hate, anger, disgust, etc. (Aron *et al.*, 2005; Reynaud *et al.*, 2010; Fischetti, 2011b, 2011a; Song *et al.*, 2015; Fisher *et al.*, 2016). There is also a need to bear in mind the limitation of the methods used to quantify and correlate the neural activity.[95] There has been considerable research into explaining the origin and nature of psychological pain. The fMRI studies show that the anterior cingulate cortex (ACC) is more active during psychological pain and correlated positively with self-reported distress (Eisenberger, Lieberman and Williams, 2003; Panksepp, 2003; MacDonald and Leary, 2005; Apkarian, 2008; Kross *et al.*, 2011). These studies seem to suggest

[95] Since the majority of studies referred here have been realised after the 1990s, they have been made with the fMRI which is a more advanced technology for measuring neural activity as compared to other previous technologies like the Positron Emission Tomography (PET) and Near Infrared Spectroscopy (NIRS). However, although the fMRI provides us with advanced technology and better results than its older brothers, it is good to welcome the results from the fMRI with a keen eye and prudence. This is because the fMRI which is a magnetic field based instrument does not measure directly the brain activity which is basically electrical impulses and the chemical like neurotransmitters (Glover, 2011). Unlike instruments that would measure the electrical activity of the brain like the EEG, MEG and Intracranial Neurophysiology; the fMRI measures the consequences of the neural activity represented by the haemodynamic response (a process that ensures rapid delivery of blood to active neuronal tissues) (Glover, 2011). Neural activity is systematically associated with changes in the relative concentration of oxygen in local blood supply. This is because active brain cells will tend to consume more oxygen for the metabolism that takes place in them. The oxygenated blood that is carried to the active brain cells has different magnetic susceptibility relative to the deoxygenated blood. This results from haemoglobin being diamagnetic when oxygenated but paramagnetic when deoxygenated. Hence, the fMRI comes in handy to measure the brain activity since it is able to inference the changes in the ratio of oxygenated or deoxygenated blood, thus measuring the Blood-Oxygen-Level Dependent (BOLD) response (Glover, 2011). However, the challenge is that the haemodynamic response is probably most tightly coupled to synaptic events rather than action potentials. This means certain types of activity will be invisible to the fMRI (Logothetis, 2008). This produces systematic biases like favouring input (and local processing) to output neural activity. Unfortunately, the extent to which coupling of the brain activity and the haemodynamic response depends on is unknown (or an unknowable variability) which also limits the extent to which we can interpret the BOLD signal (Stokes, 2015).

that during psychological pain, the ACC responds by increasing the activity of the vagus nerve (this is the nerve that starts in the brain stem connecting to the neck, chest, and abdomen). When the vagus nerve is overstimulated, it causes the pains and other physical effects associated with physiological pain (Emery and Coan, 2010).

These attempts to explain the physiology of psychological pain only provide a partial explanation limiting themselves to the path from when the ACC is activated to the registration of the physical pain. There is also a need to understand the roles of the ACC subdivisions (ventral and dorsal ACC) that are activated in social pain. This is because the activated regions vary depending on the social threat, exclusion, rejection, loss or negative evaluation (Rotge *et al.*, 2015). However, Emery & Coan (2010) propose a missing link to these scientific attempts to understand and explain psychological pain in finding a «pathway from mind to body.» This should inevitably take us to consider mental causation. The fact that we have neural activity in the absence of physical stimulation but in the presence of psychological pain, the causal relata responsible for the neural activity leans towards psychological pain. [96]

5.5. Concluding Remarks

This chapter shows that irreducible novelty that emerges within a system can be modelled or understood as some form of Spontaneous symmetry breaking. Ontological emergence in a way can be compared to a phase transition. Although SSB is usually modelled with mathematical formulations, these equations are a faithful representation of the dynamics of physical phenomena. Based on SSB characteristics like novelty, irreducibility, and phase transitions that purportedly manifest in ontological emergence, we have delineated a correlation that seems to suggest a simultaneous instantiation of SSB and ontological emergence. The higher levels cannot be deduced from the lower

[96] «... we can spatially and temporally follow the processes of brain activation and simply consult this imaging data in trying to find out whether mental phenomena have concrete effects. If the effects appear on the screen, the mental has an undeniable effect on the brain and on the subsequent behaviour of the subject. If the effects fail to appear, we have to admit that the mental is nothing but a subjective puff with no real physical and objective effect on the brain and is consequently void of behavioural impact.» (Pernu, 2011, p. 483).

levels, nor can they be reduced to them. They are ontologically different, which capacitates the higher levels to cause on the lower levels. The discontinuities that manifest from lower level to higher level demonstrate once again the limits of reducing causal explanation to the material and efficient causes. If these discontinuities exist in nature, yet reality is one, then the unity of reality should be explained by causes that are boundless to any of the stratified levels of reality.

However, the limitation of the correlation between SSB and ontological emergence is also exposed in the face of the emergence of mental properties that escape the encapsulation by the physical domain. This complicates the already intricate mind-brain problem and the question of downward causation of the mental properties (mental causation). Engaging a genuinely comprehensive discussion on mental causation requires a thorough metaphysics of causality that advocates for re-incorporating the formal and final causes in the philosophical and scientific discourse. We have seen that the final cause acts by attraction and directing. The formal cause defines the identity of the entity. Out of the many available and possible degrees of freedom, the formal cause selects some it actualises, thus defining the entity. This is a process that is accompanied by the final cause definitely. The formal and final causes do not necessarily have to come into contact to cause – after all, causation is not a physical concept; it is metaphysical. It may be true that some specific areas of experimental science may be focused on the material and efficient causes, but that should not close out completely the possibility of the intervention of the formal and the final cause. In other words, experimental science neither exhausts the explanation nor the interpretation of reality. For this reason, physical scientists and those who occupy themselves with ‘seemingly’ purely materialistic phenomena ought to adopt a pluralistic causality that embraces the formal and final causes as well.

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