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On Effective Field Theories and Emergence: A Response to Luu and Meißner

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Abstract

The paper "On the Topic of Emergence from an Effective Field Theory Perspective" by Luu and Meißner [https: //arxiv.org/abs/1910.13770] criticizes claims of strong emergence in physics and biology, such as those in [Ellis 2016], *inter alia* challenging the idea that there is purpose in living systems. They argue on the basis of the power of Effective Field Theories in calculating low energy phenomena in a bottom-up way. However this line of argument fails to account for cases of strong emergence in condensed matter physics and soft matter physics, where broken symmetries or topological effects are key to what happens. By distinguishing four different types of symmetry breaking, I demonstrate that strong emergence takes place in condensed matter physics, physical chemistry, biology, and at the foundations of physics, where it is needed to explain the direction of the arrow of time. The domain of application of effective field theories of the kind considered by Luu and Meißner is strictly limited, because they do not allow symmetry breaking. They therefore do not apply to condensed matter physics or soft matter physics, and have nothing to say about strong emergence in quantum chemistry, molecular biology, cell biology, or neuroscience.

1 Effective field theories

Emergence in physics can be studied in various ways. Effective Field Theories (EFTs) are one such way, used powerfully in nuclear and particle physics ([Georgi 1993], [Burgess 2007], [Weinberg 2009], [Luu and Meißner 2019]). They are simplified theories that include only those degrees of freedom that are considered relevant for the problem or energy scale at hand. Therefore they are an approximation and are not strictly derived from a more fundamental theory.

This is clear from Hartmann's survey paper [Hartmann 2001], cataloging various forms of EFTs including many that are derived *ad hoc* by using various plausible principles and approximations, rather than being rigorously derived from an underlying fundamental theory. It is also made very clear in [Leggett 1992], quoted in [Drossel 2020], as well as in [Laughlin and Pines 2000] (See §3.2 below). In this sense it is not clear EFTs could be used to defend reductionism at all.[1]

The paper by Luu and Meißner The abstract of "On the Topic of Emergence from an Effective Field Theory Perspective" [Luu and Meißner 2019], henceforth "LM", states,

[1] I thank Barbara Drossel for comments in this regard.

> "*Effective Field Theories have been used successfully to provide a 'bottom-up' description of phenomena whose intrinsic degrees of freedom behave at length scales far different from their effective degrees of freedom. An example is the emergent phenomenon of bound nuclei, whose constituents are neutrons and protons, which in turn are themselves composed of more fundamental particles called quarks and gluons. In going from a fundamental description that utilizes quarks and gluons to an effective field theory description of nuclei, the length scales traversed span at least two orders of magnitude.*"

Thus their paper concentrates on nuclear physics/particle physics context, and cites cases such as the Heisenberg-Euler Theory of photon-photon scattering, Fermi's Theory of Beta Decay, and many nuclear physics/particle physics examples, including an impressive derivation of fine-tunings in the triple-alpha process [Lähde *et al* 2020]. It goes on to in effect claim that EFTs function as a theory of everything in physics,[2] thereby disproving the possibility of strong emergence. I will argue that LM do not in fact provide a solid basis for a generic argument against strong emergence in areas of physics such as solid-state physics and soft matter physics, much less in relation to quantum chemistry and molecular biology. In particular I claim that EFTs have nothing useful to say about consciousness, even though LM include a section in their paper that purports to discuss this issue. My analysis is based on some conceptual distinctions I introduce next.

1.1 Conceptual issues

The conceptual advances in the present paper are twofold. First, I distinguish different aspects of the nature of emergence as follows.

- Emergence **E** of system from its components. For example, the emergence **E** of nuclei out of protons and neutrons, emergence of water or a metal or hemoglobin molecules out of the underlying nuclei and electrons, or of a human body out of its constituent cells. The issue of phase transitions is important here. These occur when a major change in the emergent state takes place, such as the transition of water from a liquid to a gaseous state when boiling occurs.

- Emergence **P** of properties of the emergent system out of its underlying constituents once it has come into existence. How do properties of a nucleus arise out of the nature of its constituent neutrons and protons, and theirs out of the constituent quarks? How do rigidity or electrical conductivity or optical properties of a crystal, or chemical properties of a molecule, arise out of the underlying electrons, protons and neutrons? How do properties of a cell in a human body arise out of properties of its underlying biomolecules? How does behaviour arise out of those cells?

Furthermore, one must distinguish between Synchronic Emergence $\mathbf{E}(\mathbf{s})$ and diachronic emergence $\mathbf{E}(\mathbf{d})$.

- Synchronic emergence $\mathbf{E}(\mathbf{s})$ occurs when the emergence processes considered take place effectively instantaneously, that is, the timescale Dt involved in determining the macro variables is much larger that the timescale dt of the underlying dynamics. This is the functional emergence of higher level properties out of lower level properties.

- Diachronic Emergence $\mathbf{E}(\mathbf{d})$ occurs when that is not the case. This is the issue of how did the system come into being over the course of time? Examples are creation

[2] As does Sabine Hossenfelder in [Hossenfelder 2019] and in many emphatic blog posts.

of particles through collisions in a collider, nucleosynthesis of elements in stars or the early universe, growth of a crystal, developmental processes in biology.

Similarly, one must distinguish between Synchronic Emergence $\mathbf{P(s)}$ and diachronic emergence $\mathbf{P(d)}$ (this is the distinction often made in discussions of emergence).

- Synchronic emergence $\mathbf{P(s)}$ occurs when the emergence processes **P** take place effectively instantaneously. This is the emergence of time independent higher level properties out of lower level properties,[3] for example how the strength and thermal capacity of a solid arises from atomic and electronic interactions.
- Diachronic Emergence $\mathbf{P(d)}$ occurs when that is not the case. This is the issue of how the higher level and lower level dynamics mesh, for example how superconductivity and superfluidity arise out of specific crystal structures, water flow arises out of molecular interactions, and brain function arises out of electron flows in neurons.

The issue of whether emergence is strong or weak arises in each of these cases. All these processes are very different in the cases of physics and biology. This paper is concerned with **P** rather than **E**, except in the case of biology (Section 5) where it matters what kinds of entities are present in the world today: **E** strongly influences **P**.

Second, in his famous paper "More is Different" ([Anderson 1972]) and later writings, Phil Anderson emphasized the crucial importance of symmetry breaking in emergence, but did not distinguish between different types of symmetry breaking. I will distinguish five different types of symmetry breaking occurring in the relation of macro dynamics **M** and microdynamics **m**.

- $\mathbf{SSB(m)}$, Spontaneous Symmetry Breaking **SSB** occurring at the micro level **m**;
- $\mathbf{SSB(M)}$, Spontaneous Symmetry Breaking **SSB** occurring due to the emergence processes **E** creating the macro level **M** from the micro level **m**, that is $\mathbf{E}$: $\mathbf{m} \rightarrow \mathbf{M}$;
- $\mathbf{SB(NS)}$, symmetry breaking **SB** in biology that has occurred due to Darwinian processes of natural selection **NS**;
- $\mathbf{SB(C)}$, symmetry breaking **SB** occurring due to the cosmological context **C** of the evolving universe subject to special initial conditions.
- $\mathbf{SB(PD)}$, symmetry breaking due to purposeful design and manufacture, as is the case for all manufactured objects.

Outcomes On the basis of these conceptual distinctions, I demonstrate that

1. The EFTs characterised by LM are unable to describe the emergence processes occurring in condensed matter physics (Section 3.4);
2. Symmetry breaking in condensed matter physics and chemistry is of the form $\mathbf{SSB(M)}$, and leads to strong emergence (Section 3.4);
3. All the macroscopic arrows of time are cases of strong emergence, due to $\mathbf{SB(C)}$ (Section 3.5);
4. Molecular biology, and hence all biology, as well as being based in quantum chemistry and so subject to $\mathbf{SSB(M)}$, is additionally a case of $\mathbf{SB(NS)}$ and hence is strongly emergent for two separate reasons (Section 5.2).

[3] This is the topic of materials science.

1.2 This paper

In the rest of this section, I summarize the idea of an Effective Theory in general in Section 1.3, and the specific version of an EFT put forward by LM in Section 1.4.

I then in the subsequent sections consider the scope of EFTs (Section 2), and their relation to emergence (Section 3), including a demonstration that strong emergence occurs in condensed matter physics (§3.4) and a proof that the existence of the arrow of time is a case of strong emergence (§3.5. I respond as regards Phil Anderson and emergence in Section 4. I comment on emergence and life in Section 5, including a demonstration that biology involves strong emergence (§5.2). I respond as regards testability, strong emergence, and Popper in Section 6. The Conclusion (Section 7) proposes, following Hartmann, that a proper understanding of emergent outcomes in physics requires a blend of theories, models, and EFTs, while understanding biology requires mechanistic explanations.

I argue that the ability of EFT approaches to lead to understanding of topics such as a quantum chemistry and molecular biology is strictly limited, and that the kind of EFT advocated by LM is of limited use even within physics. However I agree with LM that all emergent levels are equally valid (§7.2). Every level we can deal with in an experimentally based scientific way represents an Effective Theory as defined in [Castellani 2002], though not in general an EFT.

A first Appendix A comments that the Renormalisation Group (RG) is an approach similar to the EFT approach; indeed some claim they are closely intertwined. A second Appendix B comments on the issue of multiple realisability of higher level states by lower level states, that is a key aspect of strong emergence.

1.3 What is the broad idea?

In explaining EFTs, LM state

> "*The examples of emergent phenomena above [how quarks and gluons form protons and neutrons, and Borromean states] have little to no resemblance to their lower level constituents, which in this case are quarks and gluons. And since their description at the lower level via traditional calculations is essentially all but impossible, physicists instead turn to the powerful tool of effective field theory, where instead of using the lower level constituents to frame the problem, they instead work directly with the emergent phenomena as the relevant degrees of freedom.*"

Stephan Hartmann states [Hartmann 2001]

> " *EFTs account for the physics at a given energy scale by relying only on those entities which are relevant at that scale. ... Using these effective degrees of freedom makes computations tractable and provides some intuitive understanding of what is physically going on at the energy scale under consideration. The resulting descriptions are very accurate. This indicates that the effects of the physics at higher energies do not really make a difference at lower scales in these cases: the physics at high energies is 'decoupled' from the physics at low energies. Its effects are contained in a few parameters of the low energy theory. The formalism of EFTs makes all this more precise. Besides, there is a systematic and controlled way to derive low energy EFTs from a more fundamental high energy theory."*

Elena Castellani gives this definition [Castellani 2002]:

> "*An effective theory (ET) is a theory which 'effectively' captures what is physically relevant in a given domain, where 'theory' is a set of fundamental equations (or simply some Lagrangian) for describing some entities, their behaviour and interactions... More precisely, an ET is an appropriate description of the important (relevant) physics in a given region of the parameter space of the physical world. ... An EFT is the most appropriate and convenient way of describing (in the framework of QFT) the relevant physics in a limited energy domain. It is therefore an intrinsically approximate and context-dependent description.*"

LM propose that the power of EFTs proves strong emergence is not possible, because they "*provide a 'bottom-up' description of phenomena whose intrinsic degrees of freedom behave at length scales far different from their effective degrees of freedom*" .

This is true in the nuclear physics/particle physics context, but the enterprise can go wrong when one moves from particle physics to condensed matter physics. There are strongly emergent cases in that domain where EFTs indeed exist, but cannot be deduced in a purely bottom up way, as I discuss below. And there is one key case of strong emergence (the arrow of time) where there is no EFT that can do the job.

In the rest of this Section, I summarise the kind of EFT proposed by LM (Section 1.4).

1.4 Effective field theories: their nature according to LM

How does an EFT work in practice? LM develop their characterisation by identifying five key elements in constructing an EFT. They are,

> **EFT1**: ***Identification of effective, or active degrees of freedom***: ''*Here the emergent phenomena (e.g. protons, pions, nuclei, breathing modes in large nuclei, etc. . .) dictate the active (relevant) degrees of freedom, despite the fact that such phenomena can be expressed as collections of more fundamental degrees of freedom (i.e. constituents).*"

This is exactly right, and is why EFTs cannot be derived in a purely bottom up way, as emphasized strongly in the case of superconductivity in [Laughlin 1999] and in general in [Leggett 1992]. I discuss this in Sections 3.2, 3.3 , and 3.4.

> **EFT2**: ***Separation of length scales***: "The separation of length (or:a energy) scales is implicit in all EFTs. By their very definition, emergent phenomena occur at length scales that are larger than their constituents' intrinsic scales. Such separation in length scales, or equivalently energy scales, allows one to express an EFT as an expansion in the ratio of scales."

This first part is right, this is the emergence of hierarchy in physical systems The second part – the usefulness of a power series expansion – is a major assumption which while very powerful may or may not work in various other contexts, say in deriving the Second Law of Thermodynamics from quantum field theory, much less in relating physics to biochemistry and molecular biology. It works well in nuclear physics/particle physics cases, as the authors demonstrate. I discuss this in Section 2.

> **EFT3:** ***Identification of symmetries:*** "*Symmetries play a fundamental role in the construction of any EFT of some emergent process. The symmetries that the emergent phenomenon respects are identical to the symmetries of its constituents and their interactions.*"

This is the reason the EFT approach mentioned here simply does not apply to most of solid state physics, where broken symmetries are the key feature leading to emergence [Anderson 1989]. LM explicitly do not include broken symmetries in their EFT approach. I discuss this crucial issue in Section 3.4.

> **EFT4**: ***Power counting scheme:*** "*Even with the identification of all terms with the relevant symmetries of the system in question, there still exists myriads of terms that make any EFT calculation futile unless there is some systematic way of organizing the expressions in terms of relative importance. Here one employs the concept of power counting, where the different terms are enumerated in hierarchical importance related to some expansion parameter (usually related to the ratio of some soft momentum scale to a hard scale).*"

This is where the EFT approach differs from other approaches that utilize power series expansions, but do not use this method to order them. An EFT approach as such does not feature in solid state theory or semiconductor physics, see e.g. [Chaikin and Lubensky 2000], [Grundmann 2010], and [Simon 2013], none of which mentions EFTs in their index. This is also the case for books on molecular physics [Buyanal 1997] and quantum chemistry such as [McQuarrie 2008] and [Atkins and Friedman 2011] They are also not mentioned in the Nobel Lecture on quantum chemistry by Martin Karplus [Karplus 2014].

> **EFT5**: ***Equal validity of all levels*** "*This effective field theory (EFT) is not an ad hoc description of the emergent phenomena, however. If developed properly, the EFT represents an equally valid representation of the phenomenon and can be used to predict new phenomena as well as to verify the lower level theory. We remark in passing that nowadays it is widely accepted that all field theories are effective field theories, which makes the phenomenon of emergence even more natural*".

This is correct, and is essentially a physics version of Denis Noble's "Principle of Biological Relativity" [Noble 2012], which states that in biology, no emergent level is privileged over any other. The authors do not here presume there is a specific bottom-most level to which everything in physics can be reduced. They do not for example claim one can use an EFT to derive the Standard Model of Particle physics from String Theory/M Theory, regarded as the bottom level foundational theory. They do not have to, because each level is equally a sound physical description of physics at that level (Section 7.2).

The unstated underlying assumption in all of this is that the EFTs discussed are based in applications of Quantum Field Theory (QFT), so that for example the apparatus of Feynman diagrams is an appropriate method of calculation (see Figure 1 of LM). This is to be the basis of the study of emergence.

2 The scope of effective field theories

All physics theories have a limited domain of application; a key aspect of scientific understanding is stating what those limits are. EFTs are certainly powerful in examining the relation between nuclear and atomic physics, as demonstrated by LM. That does not necessarily mean they are applicable across physics as a whole, for example in the relation of atomic physics to molecular physics or condensed matter physics or soft matter physics or plasma physics or optics or acoustics, much less as regards the relation for example of physics to chemistry or biology.

In this section I consider Domains of Application of EFTs (Section 2.1), Broken Symmetries (Section 2.2), and Topological Effects (Section 2.3).

2.1 Domains of Application of EFTs

LM have in mind two theories that are related to each other by a power series expansion, with a power counting scheme. How widely is that useful? Hartmann in his overall survey of EFTs says ([Hartmann 2001]:294),

> "*In practice, however, EFTs often contain more adjustable parameters than a model of the same system. Besides, EFTs are only applicable if the energy scales of a system separate well. That is why EFTs work well in particle physics, but do not work so well in the physics of complex systems. Here models and perhaps more fundamental theories are required.*"

That is one reason why they do not in particular work for living systems. Can it apply to quantum chemistry, where methods such as the Born Oppenheimer approximation, and Density functional Theory have been used? Perhaps, but this is not made clear. Quite different methods are used at the forefront of quantum chemistry, as explained in depth in the beautiful Nobel Lecture by Martin Karplus ([Karplus 2014]):

> *"An early example of multiscale modeling, in the sense emphasized by the Nobel Prize citation, is the diffusion-collision model for protein folding, which was developed in 1976 by David Weaver and me. It used a coarse-grained description of the protein with helices as the elementary particles, and it showed how the search problem for the native state could be solved by a divide-and-conquer approach ...... These quotations raise the question as to how Nature through evolution has developed the structures of proteins so that their 'jigglings and wigglings' have a functional role. ... there are two aspects to this. First, evolution determines the protein structure, which in many cases, though not all, is made up of relatively rigid units that are connected by hinges. They allow the units to move with respect to one another. Second, there is a signal, usually the binding of a ligand, that changes the equilibrium between two structures with the rigid units in different positions*"

This does not seem amenable to an EFT description What about the Hodgkin Huxley equations governing action potential propagation in neurons? What about gene regulatory networks? Neural networks? Darwin's theory of evolution? Election results?[4] EFTs have nothing useful to contribute to these areas, which are all strongly emergent (Section 5.2).

Emergence in condensed matter physics However this is all rather far from the domain where LM apply EFTs. So are EFTs as they describe they at least universally useful in physics? No, because they do not deal with two key effects where strong emergence takes place in condensed matter physics: namely broken symmetries and topological effects. One can indeed obtain EFTs for Superconductivity and the Fractional Quantum Hall Effect, but not using the LM version of EFTs, and not as a bottom-up only derivation of these effects, because they depend on broken symmetries in the first case and topological effects in the second. I now discuss these cases in turn.

[4]Sabine Hossenfelder once claimed to me in an online exchange that Darwin's theory could be regarded as the outcome of an Effective Field Theory, and states in [Hossenfelder 2019] that EFTs can in principle be used to calculate election results. This is an extraordinary act of faith, extrapolating the method way beyond where it has been proven to work, and with no scientific justification provided for the claim.

2.2 Broken symmetries

Broken symmetries are key to emergence in condensed matter physics ([Anderson 1972], [Kvorning 2018]). Phil Anderson states in writing about the BCS theory of superconductivity ([Anderson 2001]),

> *"Though, in terms of the fundamental, unifying, microscopic laws, BCS made not the slightest change, it taught us a new way in which quantum fields could act, and also called our attention to the very general phenomenon of broken symmetry which is one of the key ways in which complexity can emerge from those laws"*

Spontaneous symmetry breaking naturally leads to a class of emergent entities with broken symmetries . The simplest example is a crystalline state ([Anderson 1989]:587):

> *"Why do we call the beautifully symmetric crystalline state a 'broken symmetry? Because, symmetrical as it is, the crystal has less symmetry than the atoms of the fluid from which it crystallized: these are in the ideal case featureless balls, while the crystal has no continuous symmetry or translation symmetry"*.

Thus the symmetry of a crystal breaks the Lorentz invariance of the theory that underlies it, and leads to the Bloch wave functions that are key to much of solid state physic, for example, as stated in the Wikipedia article on Bloch waves, Bloch's theorem states that "*the energy eigenstates for an electron in a crystal can be written as Bloch waves (more precisely, it states that the electron wave functions in a crystal have a basis consisting entirely of Bloch wave energy eigenstates). This fact underlies the concept of electronic band structures*". This underlies electric resistivity, optical absorption, and so on, see Wikipedia on Band Structure, which are all measurable phenomena.

What this means is that physical properties of the emergent state (the crystal structure) reach down to influence the motions of electrons moving in the lattice. That's a downward effect underlying key physical properties of metals [Ellis 2016]. I return to this in §3.3.

Molecular structure A contrasting case is quantum chemistry, see [Bishop 2005] for a discussion. Here "ab initio" calculations usually do the needed lower level symmetry breaking by using the Born-Oppenheimer approximation which separates out the electronic and nuclear modes ([McQuarrie 2008], [Atkins and Friedman 2011]). This then underlies the symmetry breaking at the heart of molecular biology, based in the conformational structure of macro molecules [Karplus 2014], [Ellis and Kopel 2019].

2.3 Topological Effects

Topological order refers to topological phases characterised by patterns of long-range quantum entanglement that lead to existence of quasiparticles with fractional quantum order [Kvorning 2018], for example the Fractional Quantum Hall effect. Strong emergence is a result of the topological nature of the higher-level variables concerned, which cannot, even as a matter of principle, be reduced to lower level variables. It is a question of topology, which is essentially non-local. The current hot topic in this area is topological insulators [Murakami 2011]. The same kind of effect happens in soft matter physics, as discussed by [McLeish *et al* 2019]. Kvorning explains the essential point as follows ([Kvorning 2018]:2):

> *"Different topological phases do not differ by anything that directly could be observed by a microscope, whatever its resolving power. In terms of the Landau characterization of phases they are all liquids, in the sense that no spontaneous symmetry breaking has occurred - the different phases do not have different symmetries. What then can be the difference? The answer lies in structures of the quantum entanglements of the states. Or in other words, non-separable information in the states."*

This leads to the possibility of topological interactions. He says ([Kvorning 2018]:3)

> *"In topologically ordered matter there are particles called anyons with a very special property: their interaction. At first sight these particles do not seem to interact at all, at least not at long distances. But with a closer look one will find that there is a subtle form of interaction: topological interaction. The state of the system will depend not only on how the individual particles move, but also on how the particles have braided (i.e. encircled each other). This is something that cannot be associated with any particular particle: it can only be associated with the particles as a collective, which means that it is some kind of interaction".*

This leads to two kinds of anyons: both Abelian anyons and non-Abelian anyons occur. In the latter case the interactions entail a further topological effect, namely Berry Phase. [Guay and Sartenaer 2018] state,

> *"Considering anyons as emergent quasiparticles is philosophically significant on three different levels. First, from the ontological point of view ... it makes the FQHE the place for the advent of new entities that are to be considered as as fundamental or ultimate as the other fundamental entities they are emerging from. Put differently, with the FQHE, a new physical domain is made accessible. Second, as an epistemological correlate of this, this new physical domain is representationally broken off the old one, in the sense that the epistemic resources of the latter are irrelevant or inadequate to account for the former"*

(The third level is methodological).

There are thus distinct states of matter characterized by their topological interactions, which are stable to perturbations precisely because they are topological. One can however develop effective field theories for them provided one takes the topological states into account in doing so ([Zang *et al* 1989], [Hansson *et al* 2020], [Kvorning 2018]). One can do this by introducing into the Lagrangian the kinds of non-local variables introduced by [Wilczek 1982] and [Arovas *et al* 1985]. These variables are not locally defined.

Thus you cannot as a matter of principle derive topological effects in a strictly bottom up way: you first need to know what the emergent states will be in order to formulate the EFT (see Sections 3.2 and 3.3). This is compatible with LM's principle **EFT1**, and characterizes them as strongly emergent states in the sense characterized by David Chalmers (2006) and LM (see Section 3.4). Why can topological effects be taken as evidence of strong emergence? Because they cannot be characterized locally, so a purely bottom up derivation is impossible in principle.

3 Relation to emergence

LM make a number of statements regarding the relation between EFTs and emergence, which I summarise in Section 3.1. They claim that EFTs allow a bottom up derivation of emergent properties, which one would expect if causation is bottom up. However Section 3.2 gives strong statements by various condensed matter physicists claiming this is not possible. Section 3.3 discusses why these problems arise.

Section 3.4 is the heart of the argument on emergence in relation to condensed matter physics. I show first that one cannot derive the properties **P** occurring in condensed matter theory using the EFT approach of LM, hence that method cannot prove one way or the other whether strong emergence takes place in this case. Next I demonstrate that strong emergence does indeed take place in condensed matter systems whose emergent properties are a result of Spontaneous Symmetry Breaking **SSB**(**M**) (defined in §1). However one can nevertheless obtain an EFT for these cases by introducing the idea of quasiparticles, such as phonons. This implies downward causation takes place, because their existence depends on the existence of a crystal structure. These EFTs cannot be derived in a purely bottom up way. Finally Section 3.5 proves a decisive case of strong emergence in physics: the various arrows of time, including that implicit in the Second Law of Thermodynamics.

3.1 EFTS and Emergence according to LM

The statements LM make regarding the relation between EFTs and emergence are as follows:

> **EM1**:"*The EFT description naturally leads to a bottom-up approach, where upper level emergent phenomena and their associated larger length scales/lower energies are built from lower-level (more) fundamental constituents. The level below the EFT is required to calculate certain properties from more basic constituents, like e.g. the values of the low-energy constants (LECs).*"

Certainly the emergent phenomena are built from lower level fundamental constituents (electrons, protons, neutrons for example). The emergence of higher levels depends on this fact. But some important lower level effective entities such as phonons are not fundamental constituents of the lower level: they themselves are emergent phenomena, as are anyons. They only exist because of the higher level context, e.g. a specific crystal structure. I discuss this below (Section 3.3).

> **EM2**: "*within the EFT prescription, it is the symmetries of the lower level that dictates the allowed interaction terms at the higher level, but not the other way around*"

Well lower level interactions certainly do allow higher level structures to emerge, but they can — and do — have interaction terms with different symmetries than the lower level elements. These are not dictated by the lower level. And it is the higher level broken symmetries that cause effective interaction terms with broken symmetries to exist at the lower level in condensed matter systems, such as phonons and anyons (Section 3.3).

> **EM3** *"It is natural to think then that causation follows this same bottom-up (or upward) direction as well"*

This philosophical assumption is where I disagree with LM ([Ellis 2016]). Sections 3.3 and 3.4 shows how downward effects are important in condensed matter physics, and this is also discussed in depth in [Ellis and Drossel 2019]. For those worried about causal completeness at the micro level, please see that paper and my full response in [Ellis 2019].

> **EM4:** "*The EFT description ... is consistent with the laws that govern the lower level constituents. Any prediction it makes, regardless of how 'disconnected' or 'unexpected' when viewed from the lower level theory, is consistent with the laws that govern the lower level constituents. Such predictions, and the associated causal impacts that accompany them, are in principle deducible from the lower level constituents.* "

The first part is certainly correct; the last sentence is where the disagreement lies. Both strong emergence and downward causation do not violate any lower level physical laws. The last sentence states that strong emergence cannot take place. This is not correct in the case of condensed matter physics; see Sections 3.2 and 3.4, where the properties of metals and semiconductors cannot be deduced from the EFTs considered by LM.

Laws and outcomes Physical laws *per se* do not lead to specific outcomes. Rather, as well as boundary conditions and initial conditions, contextual effects such as structural and time dependent constraints shape how these laws act to produce specific outcomes, without altering or violating the laws in any way. This enables outcomes that cannot be predicted even in principle from knowledge of the physics equations alone, for example the existence of teacups [Ellis 2005]. This is why the implications of **EM4** - weak emergence but not strong emergence takes place - can be challenged.

3.2 EFTs and upwards derivation of emergence

Do EFTs it in fact allow bottom up derivation, at least in principle, of emergent properties, and so deny the possibility of strong emergence?

In the abstract, LM state "*Effective Field Theories have been used successfully to provide a 'bottom-up' description of phenomena whose intrinsic degrees of freedom behave at length scales far different from their effective degrees of freedom.*" The phrase "bottom up description" is a glossing over of what actually happens: one derives a good EFT description on the basis of a knowledge of what emergent effects actually occur. It is not a purely bottom up process. One does not derive the emergent phenomenon: one rather explains it in terms of lower level mechanisms, but only by use of higher level concepts, as LM in fact agree (see **EFT1** in §1.4). You can get a bottom-up description once you know what the answer is, and introduce higher level variables that are not specifically implied by the lower level theory. Indeed they state:

> *"The detailed consequences of our theories are often extraordinarily hard to work out, or even in principle impossible to work out, so that we have to 'cheat' at various intermediate stages and look in the back of the book of Nature for hints about the answer. For instance, there is nothing in the quantum mechanics of the chemical bond which implies the genetic code in its detailed form, yet there is equally nothing in the operations of molecular biology which is incompatible with our quantum-mechanical understanding of the chemical bond, intermolecular forces, and so on."*

That is exactly right: it is a statement that the genetic code is strongly emergent (Section 5.2). This fact does not in any way deny the validity of the underlying physics. But what about condensed matter physics? The same conclusion applies there too.

The view from condensed matter physics Anthony Leggett in his article "On the nature of research in condensed-state physics" ([Leggett 1992], quoted in [Drossel 2020]) writes as follows:

> *"No significant advance in the theory of matter in bulk has ever come about through derivation from microscopic principles. (...) I would confidently argue further that it is in principle (my emphasis) and forever impossible to carry out such a derivation. (...) The so-called derivations of the results of solid state physics from microscopic principles alone are almost all bogus, if 'derivation' is meant to have anything like its usual sense.*"

Thus he is proclaiming strong emergence. He gives Ohm's Law as a specific example:

> *"Consider as elementary a principle as Ohm's law. As far as I know, no-one has ever come even remotely within reach of deriving Ohm's law from microscopic principles without a whole host of auxiliary assumptions ('physical approximations'), which one almost certainly would not have thought of making unless one knew in advance the result one wanted to get, (and some of which may be regarded as essentially begging the question)*" ([Leggett 1992]).

[Laughlin and Pines 2000] state that there are higher organising principles in physics, such as localization and the principle of continuous symmetry breaking, that cannot be deduced from microsopics even in principle, and are transcendent in that they would continue to be true and lead to exact results even if the underlying Theory of Everything was changed. This theme is developed interestingly in [Laughlin *et al* 2000], which includes considerations of how this relates to protein folding in biology. As for superconductivity, Robert Laughlin has this to say ([Laughlin 1999]):

> "*One of my favorite times in the academic year occurs in early spring when I give my class of extremely bright graduate students, who have mastered quantum mechanics but are otherwise unsuspecting and innocent, a take home exam in which they are asked to deduce superfluidity from first principles. There is no doubt a special place in hell being reserved for me at this very moment for this mean trick, for the task is impossible [my emphasis]. Superfluidity, like the fractional quantum Hall effect, is an emergent phenomenon - a low-energy collective effect of huge numbers of particles that cannot be deduced from the microscopic equations of motion in a rigorous way and that disappears completely when the system is taken apart. ..... The students feel betrayed and hurt by this experience because they have been trained to think in reductionist terms and thus to believe that everything not amenable to such thinking is unimportant. But nature is much more heartless than I am, and those students who stay in physics long enough to seriously confront the experimental record eventually come to understand that the reductionist idea is wrong a great deal of the time, and perhaps always."*

The actual way the theory of superconductivity was arrived at is described in depth in [Anderson 1987] and [Wilczek 2016].

Can one derive the results in a purely bottom up way? No. One can derive the micro-macro relation in an adequate way provided one inserts some of the macro picture either into the effective Lagrangian as a symmetry breaking term (see §3.4), or into the micro-macro relation, as Weinberg does in his effective field derivation ([Weinberg 2009]):

> *"Notable here is the use of the power-counting arguments of effective field theory to justify the approximations made in the BCS theory of superconductivity. Instead of counting powers of small momenta, one must count powers of the departures of momenta from the Fermi surface. Without that ingredient, the derivation fails".*

You can only derive the Fermi surface position from the macro theory. Thus it is not a purely bottom up derivation. If you try one, you will fail ([Laughlin 1999], quoted above. For example Polchinski attempted an EFT derivation of superconductivity, more precisely deriving the effective field theory of low energy excitations in a conductor, without making such an assumption. He uses essentially a renormalisation group method with very elaborate set of steps and approximations, but at the end the conclusion is "*It appears that the low energy excitations are not described by the effective field theory that we have described, but by something different — Notice that we have not discussed the mechanism for superconductivity itself; the normal state is puzzling enough. If one can figure out what the low energy theory is, the mechanism of condensation will presumably be evident*" [Polchinski 1992].

What one must distinguish here is between deriving and justifying. One does not derive the macro theory from the micro theory in a rigorous way, as emphasized by Anthony Leggett and Bob Laughlin. One justifies the micro-macro connection after the fact, when one knows what the macro level variables are. How this works is discussed in Section 3.4.

3.3 Why is it difficult? Phonons and quasi particles

It is not a question of not having enough computing power. It is a question of having the right concepts at hand. And you can't get those by studying the low level dynamics per se, in most cases, because they involve high level concepts. Trying to do it purely bottom up won't work because you need the high level concept to crack the issue. This can be seen in the difficult path to the understanding of superconductivity and superfluidity [Anderson 1989].

The derivation is difficult because Spontaneous Symmetry Breaking (**SSB**) takes place, so the symmetries of the equations are not shared by the solution. This symmetry breaking is crucial to to emergence in general [Anderson 1972] and to condensed matter physics in particular [Anderson 1981]. This leads to the properties **P** of emergent highly ordered structures such as crystals that, despite their ordered nature, can lead to very complex lower level behaviours such as high temperature superconductivity and superfluidity. This emergence is an essentially quantum phenomenon with two key aspects.

Interlevel Wave-particle duality The existence of quasiparticles such as phonons due to the broken symmetries of the emergent lattice structure is a situation where they come into being at the lower level because they are dynamically equivalent to collective vibrations of a higher level structure (the crystal lattice). While they are vibrational modes of the lattice as a whole, and hence emergent entities, they nevertheless have particle like properties. Steven Simon expresses it like this ([Simon 2013]:83):

> "*As is the case with the photon, we may think of the phonon as actually being a particle, or we can think of the phonon as being a quantized wave. If we think about the phonon as being a particle (as with the photon) then we see*

that we can put many phonons in the same state (i.e., the quantum number n can be increased to any value), thus we conclude that phonons, like photons, are bosons."

Thus the lattice vibrations at the macro scale are dynamically equivalent to a particle at the micro scale. Adding them to the micro scale description as quasi-particles such as phonons, one now has a symmetry breaking micro theory that can be the basis of an EFT derivation of a symmetry breaking macro theory. The phonons are as essential element of the micro theory (see [Simon 2013], pp. 82 on). This is an essentially quantum phenomenon: a form of the standard wave-partical duality of quantum physics.

> **Wave-particle duality: There exists a *wave(macro)-particle(micro) duality* in crystal structures which provides the crucial interlevel link in emergence theories.**

This lies outside the domain of the EFT theories considered by LM due to their **EFT3** (§1.4) and **EM2** (§3.1). But this is key to what happens physically. [Guay and Sartenaer 2018] discuss in depth the philosophical implications of the existence of quasi-particles.

Downward emergence One can view this in another way. Downward constraints shape the lower level (electron) dynamics due to the higher level (crystal) structure, these constraints being represented by symmetry breaking terms introduced in the electron-proton Hamiltonian that are not directly implied by the standard model of particle physics. This results in the causal significance at the lower level of quasiparticles such as phonons. As an example, ([Ellis and Drossel 2019]:§4) demonstrate in detail how symmetry breaking terms alter the Hamiltonian in the case of transistors, thus leading to phonons.

> **Downward emergence: The higher level context alters the lower level dynamics by introducing into it quasi-particles such as phonons that play a crucial role in solid state physics**

Without introducing them at the micro level, you cannot derive all the emergent properties that occur at the macro level in metals ([Ziman 1979], [Chaikin and Lubensky 2000], [Grundmann 2010], [Phillips 2012], [Simon 2013]), and indeed in all condensed matter physics. Effective symmetry broken micro states are the key to symmetry broken macro states. The Cooper pairs responsible for superconductivity are similarly downwardly emergent lower level effective variables, which can be regarded as produced either by electron-phonon interactions at the lower level, or by crystal distortions at the higher level. If they are taken into account in the lower level theory, one can use an EFT to produce the macro theory (Section 3.4).

3.4 Does strong emergence occur in condensed matter physics?

The issue is whether strong emergence takes place in physics. LM, following [Chalmers 2000], define strong emergence as follows:

> **Strong Emergence**: *strong emergent phenomena are not deducible even in principle from the truths in the low-level domain.*

The strong claim in LM is **EM3** (§3.1): '*Higher level] predictions, and the associated causal impacts that accompany them, are in principle deducible from the lower level constituents*", therefore strong emergence is not possible. They base this claim on their faith in the efficacy of EFTs. However this efficacy depends on the type of EFT considered.

Microphysics To be clear about the context, what kind of micro theory $\mathbf{m}$ do people usually have in mind? Robert Bishop clarifies as follows, in relation to patching physics and chemistry together [Bishop 2005]:

> *"For instance, in quantum chemistry, one first specifies the fundamental physical interactions (electromagnetic, strong- and weak-nuclear, etc.), then enumerates the relevant particles and their properties (nucleon, electron, charge, mass, etc.). Next, one lists the pairwise interactions among the particles. Finally, one writes down the kinetic and potential energy operators and adds them to get the system Hamiltonian (an expression for the total energy of the system). With the Hamiltonian in hand, one then proceeds to derive the properties and behaviors of the chemical system in question."*

This is what I will have in mind in referring to microphysics $\mathbf{m}$ below.[5]

Broken symmetries As mentioned above, Anderson claims that the key to emergence in solid state physics is broken symmetries. Thus the micro theory $\mathbf{m}$ may be invariant under a symmetry $\mathbf{S}$ such as translational invariance, rotational invariance, Lorentz invariance, or chiral invariance. Hence $\mathbf{S}(\mathbf{m}) = \mathbf{m}$. Consider when the macro theory for behaviour of the system $\mathbf{M}$ is not invariant under this symmetry: $\mathbf{S}(\mathbf{M}) \neq \mathbf{M}$. If $\mathbf{M}$ is produced by coarse graining the micro theory $\mathbf{m}$ through a coarse graining operation $\mathbf{C} : \mathbf{C}(\mathbf{m}) = \mathbf{M}$, for example by using simple coarse graining or an EFT process or the renormalisation group, how does this symmetry breaking happen? That is the somewhat puzzling question.

Spontaneous Symmetry Breaking The answer is that it occurs via Spontaneous Symmetry Breaking (**SSB**). However there is a crucial issue here. **SSB** can take place because of the nature of the macrostructure $\mathbf{M}$. As discussed in Section 1.1, I call these cases **SSB**($\mathbf{M}$). But **SSB** can also take place at the micro level $\mathbf{m}$. I call this **SSB**($\mathbf{m}$). This distinction plays a key role in the discussion below.

In the light of this clarification, I now consider in turn,

A) Whether EFTs as described by LM allow the disproof of strong emergence;

B) Whether Spontaneous Symmetry Breaking **SSB**($\mathbf{m}$) occurring at the micro level $\mathbf{m}$ can lead to strong emergence in solid state physics;

C) Whether Spontaneous Symmetry Breaking **SSB**($\mathbf{M}$) occurring at the macro level via emergence processes $\mathbf{E} : \mathbf{m} \to \mathbf{M}$ can lead to strong emergence in solid state physics.

D) Downward Causation, Strong Diachronic Emergence, and Strong Synchronic Emergence. A main theorem on downward causation is given in subsection **c**).

E) A different context: The Caldeira-Leggett model

F) Topological Emergence

An underlying issue of importance is the multiple realisability of higher level structures and functions in terms of lower level structures and functions. I relegate discussion of that issue to Appendix B.

[5] This is made explicit by [Laughlin and Pines 2000] in their equations [1] and [2]; they say "Eqs. [1] and [2] are, for all practical purposes, the Theory of Everything for our everyday world."

A) Emergence due to the EFTs considered by LM As they comment, the LM version of EFTs does not lead to strong emergence. However it does not include symmetry breaking (see **EFT3** in Section 1.4), so it fails, even in principle, to allow derivation of the kinds of emergence occurring in condensed matter physics.

> **Conclusion:** ***LM are correct that the EFT methods they use cannot produce strongly emergent outcomes. But they also cannot produce the experimentally verified outcomes of solid state physics. Thus they fail to disprove strong emergence, for these EFTs fail, as a matter of principle, to derive inter alia metallic and semiconductor properties.***

B) The case of SSB(m) Here the needed spontaneous symmetry breaking takes place at the micro scale, for example via the Higgs mechanism resulting from the Mexican Hat shape of the Higgs potential. Then macro symmetry breaking is in principle deducible in a bottom up way through coarse graining this symmetry broken micro state. Strong emergence does not take place. In notional terms, if the coarse graining operation **C** commutes with the symmetry **S**, then[6]

$$\{\mathbf{SSB(m)} : \mathbf{S(m)} \neq \mathbf{m},\ \mathbf{C(m)} = \mathbf{M},\ \mathbf{CS} = \mathbf{SC}\} \Rightarrow \mathbf{S(M)} \neq \mathbf{M}. \tag{1}$$

However the known symmetry breaking mechanisms that occur at the microscale level produce their symmetry breaking effects at that level. While their knock-on effects reach up to scales relevant to the Standard Model of Particle Physics, they do not, in a daily life context,[7] reach up to the scale of atomic physics or higher, and so do not affect phenomena such as solid state physics or chemistry or microbiology. This is reflected in Phil Anderson's statement in [Anderson 1972] that is quoted at the end of Section 5.1

> **Conclusion** ***SSB(m) cases can produce the required symmetry breaking at higher levels without a need for strong emergence. However while of fundamental importance in the standard model of particle physics, this is not relevant to situations such as the emergence of properties of metals and semiconductors, which arise from SSB(M).***

A key question here is what is the origin of the Higgs potential: why does it have a shape that allows this possibility? I will not pursue that issue further here.

C) The case of SSB(M) Here the needed symmetry breaking does not take place at the micro scale, but rather through emergence of the macro scale, due to interactions that minimise energy of the emergent structure; think of atoms crystallizing to form a crystal, for instance. This is spontaneous emergence of the breaking of symmetry **S** at the macro scale **M**, hence is a case of **SSB(M)**. In notional terms, if **E** is the process of emergence,

$$\{\mathbf{S(m)} = \mathbf{m},\ \mathbf{E(m)} = \mathbf{M}\} \Rightarrow \mathbf{M} :\ \mathbf{S(M)} \neq \mathbf{M}. \tag{2}$$

The emergence process **E** alters the macro symmetry by processes of energy minimisation based in the underlying microphysics **m**, and this is weak emergence. But that is not the

[6] Complexities arise regarding the commutation here because of the "≠" relation. The implication "⇒" here and in (5) should be read "can imply" rather than "implies". This complication does not apply to (6) and (31) because those implication do not use commutation of an inequality.

[7] I am excluding discussion of the context of the very early universe where cosmic inflation took place. In that case, **SSB(m)** had a major effect at macro scales.

concern here. The issue is **P**: how do we determine the physical properties of the emergent structure **M**, such as electrical conductivity, once it exists?

As discussed above (§3.3), existence of the macrostructure changes the context of the microphysics, resulting in effective interactions such as are represented by quasiparticles. Thus the emergent broken symmetry at the macro scale reaches down to affect conditions at the micro scale, thereby causing effective symmetry breaking at that scale. This produces from **m** an effective micro theory **m'** that breaks the symmetry **S**, for example by including phonons or other quasi-particles in the dynamics, and that therefore can produce the required symmetry-broken macro theory by coarse graining. In notional terms

$$\mathbf{SSB}(\mathbf{M}) \Rightarrow \mathbf{m} \to \mathbf{m'} : \ \mathbf{S}(\mathbf{m'}) \neq \mathbf{m'} \tag{3}$$

Typically this is done by introducing at the micro level a variable $\mathbf{a}(\mathbf{M})$ that is defined in macro level terms, and breaks the symmetry **S**:

$$\{\mathbf{m} \to \mathbf{m'} = \mathbf{m}(\mathbf{a}),\ \partial\mathbf{m'}/\partial\mathbf{a} \neq 0,\ \mathbf{S}(\mathbf{a}) \neq \mathbf{a}\} \Rightarrow \mathbf{S}(\mathbf{m'}) \neq \mathbf{m'} \tag{4}$$

This is the way that EFTs for physics involving symmetry breaking can be derived: you apply a coarse graining process **C** to **m'**, not **m**, and thereby obtain the macro theory **M** that breaks the relevant symmetry and accords with experiment: that is,

$$\{\mathbf{C}(\mathbf{m'}) = \mathbf{M}\} \ \Rightarrow \ \mathbf{S}(\mathbf{M}) \neq \mathbf{M}. \tag{5}$$

How this works in the case of functioning of transistors is explained in depth in Section 4 of [Ellis and Drossel 2019]. In quantum chemistry, this is done via the Born-Oppenheimer approximation (cf.§3.3)). Here one replaces the basic micro theory **m**, as described in ([Bishop 2005] (quoted above), with an effective theory **m'** that incorporates the approximations needed to make it work. In this case, one uses the fact that nuclei are far heavier than electrons to derive a new micro theory **m'** that gives the required results. It is not the same as the theory you started with: it is the lower level effective theory you need..

Why does one introduce the effective theory **m'** at the low level, rather than using the fundamental theory **m** based in Newton's Laws, QFT, Maxwell's equations, and so on? The answer is that if we use **m**, unless the coarse graining operation **C** explicitly breaks the symmetry **S**, the correct emergent results cannot even in principle be deduced in a purely bottom up way. In notional terms,

$$\{\mathbf{S}(\mathbf{m}) = \mathbf{m},\ \mathbf{C}(\mathbf{m}) = \mathbf{M},\ \mathbf{CS} = \mathbf{SC}\} \ \Rightarrow \ \mathbf{S}(\mathbf{M}) = \mathbf{M} \tag{6}$$

contradicting the known macrolevel symmetry breaking of **M**. You cannot get **M** from **m** by coarse graining via any method that does not explicitly break the symmetry **S**, so that $\mathbf{CS} \neq \mathbf{SC}$. The EFTs considered by LM respect those symmetries (see **EFT3** in §1.4).

> **Conclusion:** ***Strong emergence takes place when SSB(M) occurs: the symmetry broken higher level dynamics cannot even in principle be obtained by coarse graining the fundamental theory m because S(m) = m. One has to coarse grain the effective micro theory m', of such a nature that S(m') ≠ m', to get the correct result M by coarse graining. This covers the way emergence of properties occurs in condensed matter physics and in quantum chemistry***

In short: you have to add a symmetry breaking term into the micro theory in order to get the correct macro theory, because it's not there in the fundamental physics; but you only can work out what symmetry breaking term to add from your knowledge of the correct macro theory **M**. You have to use variables defined by that theory to get the symmetry broken effective micro theory **m'** which gives the correct macro result **M**.

Caveat The above is of course not a formal proof, rather it is an indicative argument tracing the key causal relations in what is going on. To give a more formal proof, one would have *inter alia* to parse the micro dynamics **m** into a reliable and unchanging relation **L** ('the Laws of Physics') between initial conditions described by data d and outcomes o, which is valid in some domain $\mathcal{D}$. That is,

$$\mathbf{L} : d \in \mathcal{D} \to \mathbf{L}(d) = o \in \mathcal{D} \tag{7}$$

in a reliable way, whether **L** is an exact or statistical law.[8] To carry out a more formal proof, one would have to represent the emergent macro dynamics **M** in a similar way to (7), and then carry out an analysis analogous to that above.

I have not attempted this more complex project here firstly because it would be much more complex, and secondly because I do not believe it would throw much light on what is going on: rather it would probably obscure the key relations. I believe that the symbolism used above enables one to clearly understand the relevant causal links in a adequate way. Of course a more formal proof would be welcome. I am confident it would confirm the chain of relationships traced in the argument above.

There is a final note of significance as regards (7).

> **The Laws of Physics are Effective Laws** ***Despite the fact that they are eternal and unchanging, all the well established and tested laws on which physics and engineering are based are effective laws (effective theories in the sense of [Castellani 2002]). This applies equally to Newton's Laws of motion, Newton's Law of Gravitation, Maxwell's equation, Einstein's gravitational Theory, the Schrödinger equation, and Dirac's equation. They all only hold in a restricted domain $\mathcal{D}$.***

This is discussed in Section 7.2. This implies that a key aspect of establishing any physical law or theory is determining its domain of validity. And that applies of course to EFTs.

D) Downward causation & Diachronic and Synchronic Emergence Equation (4) is where the downward effect of the macro state on the micro state is explicitly represented, through the modification **m** → **m'**. The point is that **a** is a variable that cannot even in principle be represented in terms of the microlevel variables occurring in **m**. The reason is that

> ***All the variables occurring in microphysics m respect the symmetry S, whereas a(M) - and so m' - does not***

And as has been shown above, we must use **m'** as the micro level theory if we want to get the correct macro level results. The theory **m** is unable to do the job. The key effect underlying this physically is the quantum theory wave(macro)-particle(micro) duality discussed in Section 3.3, which leads to crucial lower level effective variables (quasiparticles) existing, without which the theory would not work.

[8] Note that the laws of physics are not algorithms - it's Newton's Laws of Motion, not Newton's algorithm - and they do not compute, see [Binder and Ellis 2016].

Causal completeness? It is claimed by some that this downward causal influence is not possible because of the alleged causal completeness of physics at the microlevel, see for example [Hossenfelder 2019], who gives links to Kim who originated the argument. There has to be something wrong with this claim, because of the remark just made: the allegedly causally complete[9] dynamics **m** must be replaced by **m'** if you want your Effective Theory to accord with experiment. And **m'** can only be obtained by introducing variables not present in **m**. The fact ie that **m** cannot do the job (see (6), so it must be causally incomplete. Robert Bishop refutes the causal completeness claim in the context of fluid convection [Bishop 2008]. In [Ellis 2019], I give a refutation based firstly in the issue of multiple realisability of a higher level state by lower level states (see Appendix B), and secondly in the difference between synchronic and diachronic supervenience.

Here I will tackle it directly. To investigate the issue of strong emergence from a causal completeness perspective, it is useful to distinguish between Synchronic Emergence $\mathbf{P(s)}$ and Diachronic Emergence $\mathbf{P(d)}$, using the definitions given in Section 1.1). The argument is quite different in the cases of biological and physical systems. Biology is never static, so neither $\mathbf{E(s)}$ nor $\mathbf{P(s)}$ apply. I now look at the other cases in turn.

a) Diachronic emergence P(d): Biology Consider a biological system. Downwards effects occur between higher and lower levels because of physiological processes, see The Music of Life by Denis Noble, and [Noble 2008], [Noble 2012]. These downward processes are mediated at the molecular level by developmental systems [Oyama et al 2001] operating through gene regulator networks [Wagner 2014] and cell signalling networks [Berridge 2014], guided by higher level physiological needs. They reach down to the underlying physical levels via time dependent constraints on the lower level dynamics [Ellis and Kopel 2019], which is why the lower level physics *per se* is not causally complete. The *set of interactions* between elements at that level is uniquely characterised by the laws of physics **L**, but their *outcomes* are determined by the biological context in which they operate, leading to effective laws **L'**. Equation (7)) should be modified to read

$$\mathbf{L} : d \in \mathcal{D} \to \mathbf{L'}(d, C) = o \in \mathcal{D},\ C = C(\mathbf{a}, \mathbf{p}, \mathbf{q}),\ \partial C(\mathbf{a}, \mathbf{p}, \mathbf{q})/\partial \mathbf{a} \neq 0 \tag{8}$$

where $C = C(\mathbf{a}, \mathbf{p}, \mathbf{q})$ are constraints on microlevel coordinates $\mathbf{p}$ and momenta $\mathbf{q}$ that are dependent on biological variable $\mathbf{a}$ representing conditions at a higher level. Now comes the essential point: because $\mathbf{a}$ is a biological variable, it will be time dependent:

$$\mathbf{L} : d \in \mathcal{D} \to \mathbf{L'}(d, C(\mathbf{a}(t), \mathbf{p}, \mathbf{q})) = o \in \mathcal{D},\ \partial \mathbf{a}/\partial t \neq 0 \Rightarrow \partial C/\partial t \neq 0. \tag{9}$$

The lower level physics is not causally closed: outcomes depend on the time variation of the constraint C(t,**p**,**q**).[10]

Examples are the voltage across a voltage gates ion channel [Ellis and Kopel 2019], the presence or not of a ligand bound to a ligand gated ion channel, or heart rate. Pacemaker activity of the heart is via cells in the sinoatrial node that create an action potential. This is an integrative characteristic of the system as a whole [Fink and Noble 2008].

In this way downward causation takes place in biology and enables strong diachronic emergence of properties $\mathbf{P(d)}$, as discussed in Section 5.2.

[9] This ignores the effects of the Bohr uncertainty principle in terms of setting precise initial data, irreducible quantum uncertainty in terms of the values of individual quantum outcomes, as well as limits on classical determinism due to the impossibility of infinite precision [Del Santo and Gisin 2019].

[10] A simple example of this effect is a pendulum with time dependent length, see the Appendix of [Ellis and Kopel 2019].

Strong Diachronic Emergence (biology): ***Diachronic Emergence P(d) in biology is strong emergence because of the downwards effects of time dependent constraints that alter lower level dynamical outcomes due to higher biological needs. Equation (7) is replaced by (9). All emergence of properties P in biology is diachronic emergence P(d).***

b) Diachronic emergence P(d): Solid State Physics Consider dynamic properties of a metal, such as its optical properties and electrical conductivity. Again one has an equation like (8) rather than equation (7). The constraints are provided by the symmetry-breaking lattice structure that is relatively rigid in comparison with the electrons and so may be at first approximation be regarded as fixed (the is the Born-Oppenheimer approximation). The resulting potential $V(\mathbf{q}, \mathbf{x})$ is the context in which the lower level dynamics takes place; the symmetry breaking occurs via the fact that $\partial V(\mathbf{q}, \mathbf{x})\partial \mathbf{x} \neq 0$. In this case, equation (7) is modified to give the effective laws **L'** as follows:

$$\mathbf{L} : d \in \mathcal{D} \to \mathbf{L'}(d, V) = o \in \mathcal{D},\ V = V(\mathbf{q}, \mathbf{x}),\ \partial V(\mathbf{q}, \mathbf{x})/\partial \mathbf{x} \neq 0. \tag{10}$$

Now, in parallel to the last case, comes the essential point: because the inhomogeneity leads to lattice vibrations, the potential will be time dependent:

$$\{\partial \mathbf{V}/\partial x \neq 0 \Rightarrow \partial V/\partial t \neq 0\} \Rightarrow \mathbf{L} : d \in \mathcal{D} \to \mathbf{L'}(d, V(\mathbf{q},\mathbf{x}, t)) = o \in \mathcal{D}. \tag{11}$$

The lower level physics is not causally closed: outcomes depend on the higher level lattice vibrations, as indicated by the time dependence of the potential $V(\mathbf{q},x, t)$. They are equivalent to the existence of quasi-particles such as phonons(Section 3.3).

Strong Diachronic Emergence (solid state physics): ***Diachronic Emergence P(d) in solid state physics is strongly emergent because of the downwards effects discussed in Section 3.3 that alter lower level dynamical outcomes due to higher level symmetry breaking. Equation (7) is replaced by (11). It is P(d) that is of interest in studies of dynamical effects such as superconductivity and superfluidity.***

This supports the analysis in [Ellis 2019] arguing for strong emergence when diachronic supervenience take place. In both cases,

Effective Microdynamics and Laws ***In order to derive the correct macrodynamics M, the microdynamics m and fundamental laws L must be replaced by effective microdynamics m' and laws L' respectively. The maps m → m', L → L' represent the effects of context on the functioning of physics at the micro level. That is, they represent downward causation.***

The above discussion demonstrates the followng point:

Main result: Causal completeness of the microdynamics m. ***The microdynamics m arising purely out of the Laws of nature L is incomplete in this sense: it cannot derive in a bottom-up way properties occurring in condensed matter physics and in biology, as just demonstrated. Causally complete dynamics can however be attained by including downward effects in m that result in an effective lower level theory m' that is able to give the correct emergent results.***

c) Synchronic Emergence P(s): Metals The strength of metals is an example of synchronic emergence $\mathbf{P}(\mathbf{s})$, for it is a static rather than dynamic property in the sense clarified in Section 1.3 (although testing it is a dynamic process). Other examples are stiffness and toughness.

Metals are crystals. Their strength comes from the distribution of dislocations in the crystal, see Chapter 2 of [Miodownik 2014] for a brilliant popular exposition. He explains, "*Dislocations ... are defects in the metal crystals, and represent deviations from symmetry in an otherwise ordered state*". The plastic behaviour of metals is due to dislocations moving through the crystal; the melting point indicates how easily the dislocations move. These properties change when one makes alloys by adding a few percent of other metals to a crystal lattice. These intruder atoms sit inside the host crystal structure, causing mechanical and electrical perturbations that make it more difficult for dislocations to move, and hence making the metal harder.

A key example is Steel, an alloy of iron with just the right trace amount of carbon. Its strength is strongly emergent for three reasons.

First, metallic strength is based in the patters of dislocations that give it its strength. This is a state of double symmetry breaking. The crystal structure in each domain breaks the symmetry of the underlying Laws of Physics $\mathbf{L}$, as explained by Anderson (Section 2.2), but has its own emergent symmetry as an ordered lattice. But additionally, the existence of dislocations is a second level of symmetry breaking: it breaks the ordered state of a perfect lattice. The underlying physics $\mathbf{m}$ has no record of either of these broken symmetries, so it is impossible in principle to deduce any resulting properties in a strictly bottom-up way. Thus it is a case of strong emergence as argued above, based in (6).

Second, and this is a key point: that doubly broken symmetry is not a weakly emergent process of Spontaneous Symmetry Breaking $\mathbf{SSB}(\mathbf{M})$. The dislocation structure was deliberately introduced into the alloy by a complex manufacturing process such as the Bessemer process ([Miodownik 2014]:26). Thus it exists in the form it does because of processes of purposeful causation (5.3). Both the macro properties of the steel - its tempered form - and its crystal level structure - the distribution of dislocations - cannot in principle be determined in an upward way from the underlying atomic physics, because they are what they are due to a careful manufacturing process. Using the classification given in Section 1.3,

> **The nature of metals: *All* metals *are manufactured, in contrast to rocks, which occur naturally. They are thus cases of SB(PD), their symmetry breaking being due to purposeful design and manufacture.***

Thus it is a process of micro symmetry breaking by design.[11]. This is also a strongly emergent process: it does not happen spontaneously, specifically because you need both the right combinations of materials to make it, and the right manufacturing process. Both have taken millennia to be achieved. It is process of purposeful design which is strongly emergent (Section 5.3).

Third, this process of design has a historical dimension to it. Determining the best process to create hardened steel was a process of trial and error that started in Roman times and continues today. This historical process is discussed in ([Miodownik 2014]:18-27) and the Wikipedia articles on history of the steel industry and on ferrous metallurgy.

[11] This is similar to what happens in the case of transistors with their very careful doping

Because it does not occur naturally, strong steel has been developed over centuries by a process of discovery that has an evolutionary nature, analogous to what has happened in biology (Section 5.2). It is a strongly emergent process of purposeful exploration.

Thus we have a strongly emergent causal chain:

$$\text{Discovery} \Rightarrow \text{Design} \Rightarrow \text{Manufacture} \ \Rightarrow \mathbf{SB(M)} \Rightarrow \mathbf{SB(m)} \tag{12}$$

where *multiple realisability* (Appendix B) occurs at the last step: you don't care (and cannot control) what specific micro structure **m** occurs. You are happy provided the micro outcome belongs to equivalence class resulting in the needed macrostructure **M**.

> **Strong Synchronic Emergence (metals):** ***Synchronic Emergence P(s) in the case of metals is strongly emergent because firstly, the relevant double levels of symmetry breaking cannot be determined in a bottom up way from the underlying symmetric dynamics m; secondly, metals are manufactured artefacts that do not occur naturally, and hence are a cause of Purposeful Design; and thirdly, that process is a process of search with a contingent historical nature.***

d) Slipping in higher level variables Two related points arise as regards efforts to derive dynamical outcomes in these domains in a purely bottom-up way.

The first is whether the approximations made in developing an effective theory (see e.g. [Burgess 2007]) can be justified in a purely bottom up way, or whether they rather require knowledge of the macrostate before one makes them. While the first may be true in some contexts, such as nuclear physics, I have provided substantial evidence that the second is true in the solid state physics project of determining properties of metals and semiconductors. You peek at the answer in order to obtain the lower level model.

The second is that if one adds a term to the Lagrangian as a crucial part of obtaining an effective theory, can that addition be justified in a purely bottom up way, or does it require some form of macro condition in order to justify that addition? In that case the derivation is in fact not a purely bottom up derivation; indeed such a derivation may not be possible as a matter of principle. The issue arises for example in the case of the Caldeira-Leggett model, which I discuss next.

E) The Caldeira-Leggett model To see how this works in a rather different case, consider the Caldeira-Leggett model for dealing with quantum dissipation in the context of the dynamics of a system coupled to its environment [Caldeira and Leggett 1981], [Caldeira 2010]. It is shown in ([Ellis 2016]:368-369) that this case works as outlined above: a term is introduced in the Lagrangian that is not implied by the microphysics. Details are as follows (quoting equations from [Caldeira 2010]).

The system of interest is S. The environment is regarded as a heat reservoir R comprised of a set of non-interacting harmonic oscillators with coordinates q_k, masses m_k, and natural frequencies ω_k. Each of them is coupled to S by a coupling constant C_k.

One starts with the Lagrangian $L_{\mathbf{m}}$ for the micro theory $\mathbf{m}$ given by

$$L_{\mathbf{m}} = L_S + L_I + L_R \tag{13}$$

where

$$L_S = \frac{1}{2}M\dot{q}^2 - V(q) \tag{14}$$

$$L_I = q\sum_k C_k q_k \tag{15}$$

$$L_R = \sum_k \frac{1}{2}m_k\dot{q_k}^2 - \sum_k \frac{1}{2}m_k\omega_k^2 q_k^2. \tag{16}$$

Here L_S is the Lagrangian for the system of interest, L_I that for the interaction with a heat reservoir, and L_R that for the heat reservoir.

However this does not produce the macro results one wants. So a "counter-term" L_{CT} is added to produce the Lagrangian $L_{\mathbf{m'}}$ for a modified theory **m'**:

$$L_{\mathbf{m'}} = L_{\mathbf{m}} + L_{CT}, \;\; L_{CT} = -q^2\sum_k \frac{1}{2}\frac{C_k^2}{m_k\omega_k^2}\,, \tag{17}$$

and this theory is very successful [Caldeira and Leggett 1983].

The point then is that the Lagrangian $L_{\mathbf{m}}$ completely represents all interaction accounted for by the microphysics **m**: the dynamics of the system, the dynamics of the heat bath, and the interaction between the system and the heat bath are all included - all that you can use for a purely bottom up derivation. But this does not give the correct emergent results: $L_{\mathbf{m}}$ does not do the job. So the counter term is added to give an effective micro theory **m'** that does give the correct results. But **m** does not imply the need for the term L_{CT}. Thus it is a term that does not arise from the local physics *per se*, so it can plausibly be regarded as a downward effect from the environment to the effective microdynamics.

The justification for its use is given in the Wikipedia article on the topic (none is given in [Caldeira 2010]) as follows:

> "*The last term is a counter-term which must be included to ensure that dissipation is homogeneous in all space. As the bath couples to the position, if this term is not included the model is not translationally invariant, in the sense that the coupling is different wherever the quantum particle is located. This gives rise to an unphysical renormalization of the potential, which can be shown to be suppressed by including the counter-term*".

Thus this is not a direct consequence of the micro physics **m**, but entails extra consideration deriving from macro scale issues (it would for example appear to be unjustified if the system is spatially inhomogeneous). Thus this is a plausible candidate for strong emergence, as it is not derived in a purely bottom up way. This would be disproved if one could use the EFT methods of LM to derive it in a strictly bottom up way.

F) Topological emergence This case does not involve **SSB**, but is rather due to topological effects, which are essentially non-local. Strong emergence also takes place in this case too, following the same logic. One has to introduce into the Lagrangian a topological term **a**(**M**) that is not implied by the microphysics **m** because of its non-local nature, in order to get a micro theory **m'** that will be able to produce the correct macro theory via some form of coarse graining. This was discussed in Section 2.3).

3.5 A conclusive case of strong emergence: Arrows of time

Can I give a conclusive example where one cannot, as a matter of principle, provide a strictly bottom up derivation of some higher level physical behavior from its lower level underpinnings? Indeed I can: the Second Law of Thermodynamics , which is crucial in macrophysics. This also provides a conclusive proof that downward causation takes place in physics, based in the distinction between laws and their solutions.

The issue is that the microdynamics **m** relevant for daily life[12] is time symmetric, whereas macrodynamics **M** is not.

Define the time reversal operator **T** by

$$\mathbf{T} : \{t \rightarrow t' := -t\} \Rightarrow \{\dot{q} \rightarrow -\dot{q}\}, \tag{18}$$

Then

$$\mathbf{T}(\mathbf{m}) = \mathbf{m}, \ \mathbf{T}(\mathbf{M}) \neq \mathbf{M}. \tag{19}$$

How does it happen that there is a preferred direction of time - an **arrow of time** - at the macro scale **M**, but not at the macro scale **m**?

I will consider first **A)** the case of the The Second Law of Thermodynamics in terms of the usual kind of derivation, then **B)** the reliability of the Second Law, and finally **C)** the general case of all the other arrows of time: diffusion, viscosity, wave phenomena (water, sound, elastic media), electrodynamic, quantum, and gravitational.

A) The Second Law and Loschmidt The entropy S of an isolated system is a macro level quantity: $S = S(\mathbf{M})$. The Second Law states that S never decreases:

$$dS/dt \geq 0 \tag{20}$$

for the usual (future directed) time parameter t. This implies an associated arrow of time such that (20) is true. If the opposite direction of time t' is defined as in (18), we do not expect $dS/dt' \geq 0$ to hold: it contradicts (20) except in the equilibrium case $dS/dt = 0$.

However there is a major problem. Proofs that derive the Second Law in a bottom up way, and so imply a unique direction of time, are very convincing until one realizes that the proof necessarily, because of the time symmetry $\mathbf{T}(\mathbf{m}) = \mathbf{m}$ of the relevant underlying physics **m**, runs equally well in the opposite direction of time. This is Loschmidt's Paradox ([Leibowitz 2008], [Penrose 1990], [Penrose 2006], [Penrose 2017]). Replace t by t' in your derivation, and you will, by carrying out exactly the same proof step by step, show that

$$dS/dt' \geq 0 \tag{21}$$

Therefore the thermodynamic arrow of time associated with the Second Law is strongly emergent. It cannot even in principle be deduced in a bottom up way from Newtonian dynamics or Quantum Field Theory. Calculations claiming to prove emergence of the Second Law that are based in either of them are in fact time direction agnostic. I will now show this for the case of Quantum Field Theory.

[12]This does not include the weak force, where time symmetry breaking take place at a level that is very hard to detect. It is irrelevant: see [Laughlin and Pines 2000]: "Eqs. [1] and [2] are, for all practical purposes, the Theory of Everything for our everyday world."

The arrow of time and quantum field theory Steven Weinberg in his book on Quantum Field Theory gives a derivation of the Second Law on the basis of that theory ([Weinberg 1995]:150-151). However this derivation is subject to Loschmidt's Paradox ([Ellis 2016]: 281-282). Details are as follows:

Entropy of a system of particles with probability p_i of being in a state (i) is defined by

$$S = -k \sum_i p_i \ln p_i \,. \tag{22}$$

Differentiating with respect to time t gives

$$\frac{dS}{dt} = -k \sum_i \left(\frac{dp_i}{dt} \ln p_i + \frac{dp_i}{dt} \right) = -k \sum_i \frac{dp_i}{dt} \ln p_i \tag{23}$$

on using the fact that the calculation is done in the rest frame of the particles:

$$\sum_i p_i = 1 \;\;\Rightarrow\;\; k \sum_i \frac{dp_i}{dt} = 0 \,. \tag{24}$$

Fermi's Golden rule gives a master equation for the average rate of jumps from state β to state α:

$$\frac{dp_\alpha}{dt} = \sum_\beta \nu_{\alpha\beta}(p_\beta - p_\alpha), \;\; \frac{dp_\beta}{dt} = \sum_\alpha \nu_{\beta\alpha}(p_\alpha - p_\beta), \tag{25}$$

where the time reversibility of the microphysics ensures that

$$\nu_{\alpha\beta} = \nu_{\beta\alpha} \,. \tag{26}$$

Equation (25) is where the direction of time enters. From it, one finds

$$\frac{dS}{dt} = \frac{1}{2} k \sum_{\alpha,\beta} \nu_{\alpha\beta}(p_\beta - p_\alpha) \ln(p_\beta - p_\alpha). \tag{27}$$

The two expressions in brackets will have the same sign, so for an isolated system the Second Law holds:

$$\frac{dS}{dt} \;\geq\; 0. \tag{28}$$

But now Loschmidt strikes! There was nothing special about the direction of time t chosen for the derivation. Choose the opposite direction of time t' as in (18), and precisely the same derivation goes through, step by step, using t' as the time parameter. All the equations (22) - (25) are unchanged in form if one sets $t \to -t$, and swaps $\alpha \leftrightarrow \beta$ in (25). Thus (27) remains true with the new time parameter t', so one has shown that

$$\{t' := -t\} \;\;\Rightarrow\;\; \frac{dS}{dt'} \geq 0. \tag{29}$$

One has deduced, in precisely the same way as before, that the Second Law holds in the opposite direction of time. One cannot deduce the forward direction of time from the derivation of the Second Law in [Weinberg 1995], because that derivation is based in the time-symmetric micro physics **m**.

Where then does the arrow of time associated with the Second Law of Thermodynamics come from? The plausible explanation is that it is determined by the Direction of Time arising from the cosmological context of the expanding universe ([Ellis and Drossel 2020]), together with special initial conditions at the start of the universe ([Albert 2000]). The error in trying to determine it by any coarse graining process or EFT lies in the assumption that in physics, only upwards causation takes place. Here the causal chain is from conditions on a cosmological scale down to local physics scales. The issue is discussed in depth in [Ellis 2013], [Ellis 2014], and [Ellis and Drossel 2020].

> **The outcome** *The arrow of time implied by the Second Law of Thermodynamics is not determined in a bottom up way by microphysics; it is determined in a top down way by the cosmological context **C**. Thus a broken symmetry of the form **SB(C)** leads to strong emergence.*

This implies that the thermodynamic direction of time should be the same everywhere in a causally connected domain in the universe. There should be no local time anomalies in the visible universe - which would be possible if the direction of time was upwardly emergent. It would be locally determined in that case, with no mechanism to ensure coherence everywhere. There could be patches of space with opposing directions of time.

B) Reliability of the Second Law After discussing its nature in depth, Arthur Stanley Eddington stated the significance of the Second Law in strong terms in a famous passage in his 1927 Gifford Lectures ([Eddington 1929]:74):

> *"The law that entropy always increases - the second law of thermodynamics- holds, I think, the supreme position among the laws of Nature. If someone points out to you that your pet theory of the universe is in disagreement with Maxwell's equations?then so much the worse for Maxwell's equations. If it is found to be contradicted by observation?well, these experimentalists do bungle things sometimes. But if your theory is found to be against the second law of thermodynamics, I can give you no hope; there is nothing for it but to collapse in deepest humiliation."*

But it is only a statistical law, and subject to fluctuations where it could in principle be disobeyed. So since Eddington wrote that paragraph, there has been a vigorous debate about its applicability in non-equilibrium cases where it could possibly fail,[13].

This issue has now been settled via a series of Fluctuation theorems (FTs) giving rigorous results concerning the validity of the second law when fluctuations occur, see [Evans and Searles 2002], [Spinney and Ford 2013], [Harris and Schütz 2007]. The abstract of the Evans and Searles paper states,

> *"The Fluctuation Theorem does much more than merely prove that in large systems observed for long periods of time, the Second Law is overwhelmingly likely to be valid. The Fluctuation Theorem quantifies the probability of observing Second Law violations in small systems observed for a short time. Unlike the Boltzmann equation, the FT is completely consistent with Loschmidt's observation that for time reversible dynamics, every dynamical phase space trajectory and its conjugate time reversed 'anti-trajectory', are both solutions of the underlying equations of motion."*

[13] See for example section 5.3 in https://web.stanford.edu/ peastman/statmech/thermodynamics.html

Thus this confirms that in non-equilibrium cases too, Loschmidt's paradox holds: the underlying dynamics cannot determine a unique arrow of time in a bottom up way. The result follows from time reversible nature of the exact equation of motion for the N-particle distribution function – the Liouville equation. Indeed [Harris and Schütz 2007] state "*The key ingredient underlying all FTs is time reversal, well-understood in thermal equilibrium but not so well-explored in non-equilibrium systems.*"

The Second Law can indeed fail at very small scales, but at larger scales the certainty of its validity rapidly approaches one. These theorems can be taken as proving it is indeed valid at macroscopic scales in a rigorous sense – confirming what all engineers know. The conclusion that the Second Law is strongly emergent at macroscopic scales remains.

C) The General Case In addition to Thermodynamics being time asymmetric, so are electrodynamics, quantum physics,[14] all wave phenomena on an everyday scale (water, sound, elastic media), diffusion processes, heat conduction and radiation, viscous processes, and so on. Time symmetry at the macro scale is strongly experimentally disproved. There is even a mechanical version: ratchets. Through an anchor escapement, mechanical clocks indicate the future direction of time, not the past.

Loschmidt's paradox applies equally to all these arrows of time. The underlying physics $\mathbf{m}$ relevant for daily life is time symmetric but the emergent macroscopic physics $\mathbf{M}$ is not. In notional terms:

$$\mathbf{T}(\mathbf{m}) = \mathbf{m},\ \ \mathbf{T}(\mathbf{M}) \neq \mathbf{M}. \tag{30}$$

If the coarse graining operator $\mathbf{C}$ does not explicitly involve time, it will commute with $\mathbf{T}$; and this implies macrophysics $\mathbf{M}$ should be time symmetric. Thus

$$\{\mathbf{T}(\mathbf{m}) = \mathbf{m},\, \mathbf{M} = \mathbf{C}(\mathbf{m}),\, \mathbf{CT} = \mathbf{TC}\} \;\Rightarrow\; \mathbf{T}(\mathbf{M}) = \mathbf{M}. \tag{31}$$

However this is not true by (30).

> **Conclusion:** ***One cannot, as a matter of principle, derive macrophysics with a unique direction of time in a bottom up way, and this applies in particular to the Second Law of Thermodynamics. Arrows of time are therefore strongly emergent, giving a proof that strong emergence does indeed occur in standard physical theory. No EFT method based in time symmetric fundamental physics can determine the arrow of time, unless it involves a process that explicitly introduces a time asymmetry not implied by the underlying physics***

The origin of arrows of time In these more general cases, the conclusion remains that the strong emergence that takes place is a case of $\mathbf{SB(C)}$, symmetry breaking occurring due to the cosmological context of the evolving universe with a cosmological Direction of time determined by its expansion. Special initial conditions ensure the Second Law and all the other arrows of time agree with the cosmological Direction of time. Thus time emerges in a consonant way in all these domains: the arrow of time for electrodynamics is the same as that for thermodynamics, for example.

This is a key case of top-down causation from cosmology to local physics (details are given in [Ellis and Drossel 2020]. It is a clear example of the following key point:

> **Laws and Outcomes** ***The microscale laws of physics m are not changed by this downward process, but their solutions are constrained to only***

[14] Assuming one takes into account the wavefunction collapse process that leads to physical outcomes

take place in the forward direction of time determined by cosmology. It is a form of downward constraint on those solutions.

The arrow of time then cascades upwards in the hierarchy of emergence to macrophysics, chemistry, biology, psychology, social systems, and ecology [Ellis 2013] [Ellis 2014]. This is the origin of the arrow of time in daily life.

How is the issue handled in standard physics practice? Usual physics textbooks do not even mention that there is a problem as regards the direction of time, and many senior physicists are simply unaware there is an issue of importance to be solved.[15]

How can this be possible?
The answer is that the macro result of the existence of a unique arrow of time is known to be true, and is simply imposed *a priori* on solutions of the equations, even though it is not implied by them. This happens for example in rejecting the advanced solutions in Quantum Field Theory and electrodynamics, and the time reversed solutions in wave phenomena. The justification is that one is looking for "physically relevant" solutions, and this *ad hoc* procedure gives the result one wants, in agreement with experiment, even though it cannot be justified in a bottom up way.

This process is simply taken for granted, except in some studies of issues of time reversal properties of quantum physics, and of course the CPT theorems.

4 Anderson and emergence

In their Section 4, LM criticize the way that I and many others (e.g. [Gu *et al* 2009], [Binder 2009]) interpret the paper "More is different" by Phil Anderson ([Anderson 1972]) as supporting emergentism. In this section I discuss Anderson's attitude to emergence (§4.1) and then comment on the distinction between Laws and Mechanisms (§4.2).

4.1 More is Different

LM criticise statements I make in [Ellis 2016] regarding Phil Anderson's famous paper "More is different" ([Anderson 1972]). In that paper he apparently has an ambivalent attitude as regards reduction and emergence, as discussed by [Drossel 2020]. He is indeed a reductionist in this sense: he believes that

> *"The workings of our minds and bodies, and of all matter [. . .], are assumed to be controlled by the same set of fundamental laws, which [. . .] we know pretty well"*

(this is the quote from [Anderson 1972] given by LM, which Anderson emphasized again in [Anderson 2001]). But as LM say, he states also that being a reductionist does not imply the ability to start from the basic laws and construct all the higher levels.

In fact, he was also an emergentist. This was not his only paper on emergence! In another paper he states ([Anderson 1989]: 588)

> *"Thus the characteristic crystalline property of rigidity, elasticity (as opposed to the shear flow of a viscous fluid) and anisotropy (as e.g. birefringence) are true emergent properties, properties which are only properties of large and*

[15] When I wrote about this in relation to an FQXI essay, I received sarcastic comments from a Californian Postdoc stating that I ought to know better: that there was no problem because of Weinberg's QFT derivation of the Second Law. When I was a graduate student, the issue was common knowledge.

complex systems .... magnetism is a well-known example so is superconductivity of metals and the very similar superfluidity of two forms of helium and of neutrons in neutron stars".

Sylvan Schweber sees it this way [Schweber 1993]:

> *"Anderson believes in emergent laws. He holds the view that each level has its own "fundamental" laws and its own ontology. Translated into the language of particle physicists, Anderson would say each level has its effective Lagrangian and its set of quasistable particles. In each level the effective Lagrangian - the "fundamental" description at that level - is the best we can do. But it is not enough to know the "fundamental" laws at a given level. It is the solutions to equations, not the equations themselves, that provide a mathematical description of the physical phenomena. "Emergence" refers to properties of the solutions - in particular, the properties that are not readily apparent from the equations"*

Jeffrey Goldstein discusses this all very interesting in his introduction to a reprinted version of 'More is different' [Anderson and Goldstein 2014], pointing out clearly that Anderson was opposed to 'strident reductionists'.

Furthermore, on his 90th Birthday a conference was held in his honor entitled "PWA90: Emergent Frontiers of Condensed Matter", and the proceedings were published in a book *Pwa90: A lifetime of Emergence* ([Piers *et al* 2015]) . The introduction states,

> *"As codified in his oft quoted statement 'More is Different', Phil has been the most forceful and persuasive proponent of the radical (in the 1970s), but now ubiquitous, viewpoint of emergent phenomena: truly fundamental concepts can and do emerge from investigations of nature at each level of complexity or energy scale. The workshop's title* Pwa90: A Lifetime of Emergence *was thus inspired by Phil's ideas of emergence that have deeply influenced developments in their original realm of condensed matter physics as well as in high energy physics, astrophysics, economics, computational optimisation, and computer science".*

Thus he apparently does not see a conflict between the two views: they are both true at the same time. That is what is enabled by downward causation from the emergent levels to the underlying physical levels without violating any aspect of the underlying physics ([Ellis 2016]). This has to be the case, because the emergent structure affect what happens at lower levels, for example an emergent crystal structure determines the band structure of metals and so the flow of electrons at the electron level. How this happens in the case of transistors is discussed in [Ellis and Drossel 2019].

LM state *"Anderson at no point argues that the new conceptual structure of the higher level of organization cannot be deduced from the lower-level constituents in principle*". Here I disagree. He states in the article ([Anderson 1972], right hand column, page 1)

> *"At each level of complexity, entirely new properties appear ... At each stage entirely new laws, concepts, and generalizations are necessary, requiring inspiration and creativity to just as great a degree as in the previous one. Psychology is not applied biology, nor is biology applied chemistry."*

This is quite different than claiming you can deduce these structures in a bottom up way. Furthermore in the introduction to [Anderson 1994]: vii), he states

> *"The contribution of physics is the method of dealing both with the substrate from which emergence took place, and with the emergent phenomenon itself. Examples are legion: for one superconductivity cannot be understood simply as a phenomenology without understanding electrons and their interactions, nor on the other hand as a property of a small number of electrons without taking into account the macroscopic system".*

This is what is what is argued *inter alia* by Laughlin and Leggett, as quoted above in Section 3.2. Anyhow LM themselves say one can't determine the relevant emergent variables in a purely bottom up way: see **EFT1** in Section 1.4.

4.2 A Caveat: Laws and Mechanisms

Returning to the phrase quoted above from [Anderson 1972], in full it is

> *"The workings of our minds and bodies, and of all the animate or inanimate matter of which we have any detailed knowledge, are assumed to be controlled by the same set of fundamental laws."*

While I agree with this in broad terms — unaltered physical laws do indeed underlie all emergence — the word "controlled" is troublesome, and is in fact misleading. The point is the difference between laws and mechanisms. Laws such as Newton's laws of motions do *not per* se cause anything specific to happen. It is mechanisms and associated constraints that do so. For example a clock is a mechanism that reliably tells the time. Why is this so? Because its macro structure — spring, escapement, gears, and so on — constrains the motion of billions of atoms that make up its micro structure, and thereby cause the hands to turn reliably in a clockwise way, and so reliably represent the passage of time. The laws of physics enable this downward causation to the atomic level to happen, but are not themselves responsible for the specific outcomes of that result.

Anderson refers specifically to molecular biology and cell biology, and essentially the same is true in that case: through molecular biology, the way cell biology works is also to a large degree a case of causation channeled by biological mechanisms, enabled by the structure and function of proteins [Petsko and Ringe 2009]. The physics does not control outcomes: it enables them. Molecular biology for example entails an extraordinarily complex strongly emergent interlocking family of mechanisms, that are enabled by the conformational properties of biomolecules, in particular nucleic acids on the one hand and proteins on the other. Mechanistic explanations of protein function emerge from their structure, as explained in detail by Petsko and Ringe. Biology conscripts the underlying physics to its purposes without in any way violating the imperatives of physical laws via the downward action of time dependent constraints ([Ellis and Kopel 2019]).

One should see causality in physiology and the brain through the metaphor of mechanisms ([Gillett 2007], something completely outside the scope of EFTs. As explained by [Wright and Bechtel 2007], mechanistic approaches serve to bridge levels rather than reduce them. However there is a key point to be made. All machines have a function determined by their purpose, and do what they are told by their operator. This context controls in a top-down way what the underlying physics does (turn the automobile starter switch on, and billions of electrons flow through the coils in the starter motor and the engine turns). Biology is similar (see the next section). All biological entities have purpose or function, and that controls in a top-down way what happens at lower levels [Noble 2012] reaching down to the underlying physical levels. The physics does not control the higher levels, rather - without any violation of the laws of physics (7) - it does what the biology asks it do. The enabling factor is time dependent constraints at the lower level that are regulated by higher level biological variables [Ellis and Kopel 2019].

5 Emergence and life

LM discuss this topic in their Section 5, without referring to what EFTs might possibly add to the argument.

I will discuss the nature of life in general (Section 5.1), give evidence that strong emergence certainly occurs in biology (Section 5.2), and respond to their comments on the purposeful design that occurs when intelligence has emerged (Section 5.3).

5.1 Life in general

The heading of this section in LM is *"Purpose" in life and physics.* This phrasing is presumably intended to imply that the concept "Purpose" is suspect or meaningless. No solid argumentation of any kind is put forward to justify this insinuation. This usage of course leads to the question, Did LM perhaps have any purpose in writing their paper? The scare quotes in their section heading suggest this could not have been the case. If that were indeed so, how did the paper written by LM come into existence?

Leaving that aside, it is clear that they do not like the idea that biological organisms have purpose. That is contrary to the view of Nobel Prize winning biologist Leland Hartwell and colleagues as expressed in [Hartwell *et al* (1999)]:

> *"Although living systems obey the laws of physics and chemistry, the notion of function or purpose differentiates biology from other natural sciences. Organisms exist to reproduce, whereas, outside religious belief, rocks and stars have no purpose. Selection for function has produced the living cell, with a unique set of properties that distinguish it from inanimate systems of interacting molecules. Cells exist far from thermal equilibrium by harvesting energy from their environment. They are composed of thousands of different types of molecule. They contain information for their survival and reproduction, in the form of their DNA. Their interactions with the environment depend in a byzantine fashion on this information, and the information and the machinery that interprets it are replicated by reproducing the cell."*

I do not believe that the view from nuclear physics can disprove this careful statement by an expert group of top level biologists. Even proteins have functions [Petsko and Ringe 2009].

This relates to the next point: LM state

> "*We also caution in using terminology that may be precise at one level, e.g. purpose, but ill-defined at another level as this ultimately adds confusion.*"

I disagree. A central point as regards the nature of emergence is that words that correctly describe causation at higher levels simply do not apply at lower levels. It is not a point of confusion, it's a central aspect of emergence. They quote from [Anderson 1972], "*each level can require a whole new conceptual structure*". Just so; and that means new terminology. In the case of biology, unless that new structure includes the concepts of purpose and function, it will miss the essence of what is going on, as pointed out by [Hartwell *et al* (1999)]. You also, for example, need to introduce the concepts "alive" and "dead", which do not occur at any lower level than the cellular level, but does not occur in any physics.

But how does all this emerge from physics? Through symmetry breaking, as discussed above, together with time dependent constraints and the extraordinary dependence of molecular biology on the conformational shape of biomolecules [Ellis and Kopel 2019]. Wonderful examples are given in [Karplus 2014]. This all came into being via Darwinian processes of natural selection [Mayr 2001]: one of the best-established processes in biology, which is strongly emergent. Physics in general, and effective field theories in particular, do not begin to have the resources to deal with this theory, *inter alia* because the concepts of being alive or dead cannot be captured in strictly physics terms so 'survival' is not a concept physics can deal with. Whether an animal is alive of dead is a biological issue. And that is what underlies evolutionary theory.

LM state in this section

> *"However, it may very well be that the 'purpose' of some biological organism, seen from our limited point of view, is procreation and the continuation of its species, but at the same time is equivalent to the minimization of energy in some very complex phase space."*

This is nothing other than the concept of a Fitness Landscape as proposed by Sewell Right [Wright 1932l], and developed by many others (see for example [McGhee 2006]). But this does nothing to further the reductionist project of LM. This is an *Effective Theory* in the sense explained in [Castellani 2002] (quoted in §1.3), but has nothing to do with EFTs as described by LM (§1.4), involving a power series expansions in terms of a physical parameter. A Fitness Landscape cannot be derived even in principle from the underlying physics by any deductive process that purely involves physics concepts. It can however be developed as a productive effective theory if one introduces biological concepts.

As regards their comments about Schrödinger's book *What is Life?* [Schrödinger 1944], I am not advocating any modification whatever to the laws of physics themselves: those are plausibly timeless, eternal, and unchanging. It is the *outcomes* of those laws that are strongly contextually dependent, through the existence of physiological structures and time dependent constraints [Noble 2012], [Ellis 2016]. It is through these effects that biology modifies outcomes of those laws at the physical level [Ellis and Kopel 2019].

Interesting as this debate about life is, it is a debate about strongly emergent properties that have nothing to do with EFTs, or the nuclear physics domain where EFTs are a powerful tool. As stated in [Anderson 1972],

> *"The more elementary particle physicists tell us about the nature of the fundamental laws, the less the relevance they seem to have to the very real problems of the rest of science, much less to those of society".*

And that applies to the nature and functioning of life too.

5.2 Strong emergence in biology

There are many reasons why biology is strongly emergent. I note first that biological emergence is based in supramolecular chemistry [Lehn 1993] [Lehn 1995] and the nature of biomolecules such as nucleic acids and proteins [Petsko and Ringe 2009]. Given this understanding, reasons biology is strongly emergent are as follows:

- Firstly, because organisms are made of biomolecules where the properties **P** of those molecules are strongly emergent due to their symmetry-breaking nature, see the discussion in Section 3.4. Using the distinctions introduced in Section 1.1, this is a case of **P(s)** (the symmetry breaking is there whenever the molecules are present).
- Secondly, because of the functional emergence **P(d)** of the properties of organisms at any specific time out of the underlying biomolecules. These are the processes of physiology, which are dynamic.
- Thirdly, because of the emergence **E(d)** of each individual organism over time out of the component biomolecules through the processes of developmental biology.
- Fourthly, because of the historical emergence **E(d)** over evolutionary timescales of organisms, of the biomolecules out of which they are made, including the DNA that is our genetic material, and of the developmental processes whereby biomolecules give rise to organisms. This is an intricate intertwined process of evolution and development (hence *Evo-Devo* [Carroll 2005], [Carroll 2008], [Oyama et al 2001]). Because of this core feature of biology, it has an ineliminable historical element which results in its present day nature.

All these dimensions of biology are strongly emergent. I consider in turn, A) Why natural selection is a strongly emergent process, B) the specific case of proteins, C) the case of neurons, and D) The relations of evolution, structure, and function.

A) Why Natural Selection is Strongly Emergent Developmental processes leading to the existence of biomolecules take place by reading the genome via processes controlled by gene regulatory networks. The genome has famously been shaped by processes of natural selection taking place over evolutionary timescales.

When this occurs, the outcomes cannot even in principle be deduced from the underlying microphysics, because both of the random aspect of the processes of natural selection, and their top-down nature. Apart from random drift, which is a significant effect in evolutionary history, life today is determined by adaptation to a variety of physical, ecological, and social contexts in the past. There was randomness in the process due to mutation, recombination, and drift at the genetic level. Time-dependent downward influences took place due to the time varying niches available for adaption, which determined what superior variation was selected. According to Ernst Mayr ([Mayr 2001]),

> *"Owing to the two step nature of natural selection, evolution is the result of both chance and necessity. There is indeed a great deal of randomness ('chance') in evolution, particularly in the production of genetic variation, but the second step of natural selection, whether selection or elimination, is an anti-chance process."* [16]

He then gives the eye as an example. Neither step is predictable from physics, even in principle, because physics does not have the conceptual resources available to undertake the discussion. They are essentially biological in nature, and hence strongly emergent.

Thus we also have here **SB(NS)**: the specific nature of the broken symmetries occurring in biomolecules today, and so shaping current biological outcomes, has been determined by Darwinian processes of natural selection (**NS**) during our past evolutionary history. To strengthen the point, I will now consider cases of strong emergence **ESB(NS)** in biology[17]. due to **SB(NS)** at the molecular level and at the cellular level.

[16] However note that the issue of randomness is complex and subtle; see for example [Wagner 2012].

[17] The detailed nature of symmetry breaking in biology is a description of its structure

B) The Molecular level Biological function at the molecular level is determined by the physical nature of biomolecules, with proteins being the workhorses of biology. Due to the nature of the underlying physical laws and the values of the constants occurring in the Laws of Physics (7), only certain proteins are possible in physics terms. Thus there is an abstract possibility space for the existence of proteins, as discussed by Andreas Wagner in his excellent book [Wagner 2014]. It is of enormous dimension, as he emphasizes.

The proteins that actually exist on Earth, out of all the possible ones that might have existed but have not been selected for, have a very complex structure that is determined by the functions they perform [Petsko and Ringe 2009] (note the use of the word "function"). They were selected by Darwinian processes [Mayr 2001] so as to have a structure that will adequately perform a needed function. I will give two examples.

The Arctic Cod Wagner discusses selection for proteins in Chapter 4 of his book ([Wagner 2014]:107). He takes as an example the Arctic cod, which lives within 6 degrees of the North Pole in sea water whose temperature regularly drops below 0 degrees Celsius. This ought to destroy the cells in the fish, as ice crystals should form within the cells and tear them apart.

To deal with this problem, the arctic cod survives by producing antifreeze proteins that lower the temperature of its body fluids. What has been selected for is not just the genome that codes for the protein that will do the job, but the entire developmental system that produces the protein, involving gene regulatory cascades ([Wagner 2014]:Chapter 5). This is a case of downward causation from the environmental level (the cold nature of the sea water) to details of the DNA sequence that does the job ([Ellis 2016]).

Squid eyes The squid eye has evolved to be adapted to the problem of seeing clearly when under water. To do so, it uses a precisely patterned distribution of a particular family of proteins. This leads to a graded refractive index in its lenses. The abstract of a paper [Sweeney *et al* 2007] that discusses this is as follows:

> "*A parabolic relationship between lens radius and refractive index allows spherical lenses to avoid spherical aberration. We show that in squid, patchy colloidal physics resulted from an evolutionary radiation of globular S-crystallin proteins. Small angle x-ray scattering experiments on lens tissue show colloidal gels of S-crystallins at all radial positions. The proteins demonstrate an evolved set of linkers for self-assembly of nanoparticles into volumetric materials.*"

Thus the need for clear vision in an underwater environment lead to selection of a genotype that produces this outcome via squid developmental systems.

The underlying physics enables this all to happen, but does not determine the specific outcomes: it cannot do so as a matter of principle. These are clearly strongly emergent, because physics *per se* (electrons, protons, neutrons, and the interactions between them) does not begin to have the resources needed to handle the issue. These examples illustrate why it is essential to use language appropriate to the higher level in order to get a model that can provide a reductionist understanding of mechanisms.

C) The Cellular level Similar issues arise at the cellular level. An important case in neuroscience is the phenomenological Hodgkin-Huxley equations for nerve impulse propagation [Hodgkin and Huxley 1952]. They contain constants that cannot as a matter of principle be determined from the underlying physics in a bottom up way [Scott 1999]. The reason is that these effective equations are determined by the neural physiology: axon structure with voltage gated ion channel proteins of a particular kind. These proteins are the outcome of evolutionary processes, constrained by physiological possibilities, that led to powerful brain functioning and so enhanced survival prospects. This resulted in a specific part of the genome being written that leads to existence of this particular voltage gated ion channel proteins through developmental processes. It is super-astronomically improbable that they would have come into existence by chance.

Section 3 in LM states, "*Indeed the values of the low-energy constants LECs required by an EFT can only be calculated from the lower level theory*". This criterion for emergent constants in an Effective Theory to be determinable in a bottom up way is not fulfilled in this case: it can not be done even in principle. Bottom up deduction cannot succeed in determining these constants because they were determined by evolution in the context of physical possibilities and biological need. This is another case of strong emergence.

D) The Relation of Evolution, structure, and function There is an important point here. If one wants to simply explore biological properties $\mathbf{P}(\mathrm{d})$ [18] today, why does one have to take into account these evolutionary processes of emergence $\mathbf{E}(\mathbf{d})$?

The answer is key: biological emergence $\mathbf{E}(\mathbf{d})$ is historically determined. Present day biological functioning is crucially determined by the nature of biomolecules such as proteins ([Petsko and Ringe 2009]) which are present in cells today. Proteins are strongly emergent in the following sense: the possibility of particular protein structures is determined by the underlying physics, this relation being characterised by the study of quantum chemistry ([McQuarrie 2008], [Karplus 2014]1). However the proteins that actually exist in biological reality, as described by Petsko and Ringe, have been selected for by processes of Darwinian evolution ([Wagner 2014]). Thus emergence $\mathbf{E}(\mathbf{d})$ of those proteins in the distant past has key causal effects in biological functioning $\mathbf{P}(\mathbf{d})$ today [Ellis and Kopel 2019]. They are inextricably intertwined, because biology today is historically based.

> **Conclusion**: ***Biology is not reducible to physics via an effective field theory or any other way. It is an indubitable case of strong emergence because it does indeed involve function and purpose, as stated cogently by [Hartwell et al (1999)] (see §5.1), whereas physics does not; because it involves strong emergence associated with molecular biology (§3.4) and with physiology; and because of the nature of the process of Natural Selection that led to life on Earth, which involves both randomness and downward causation.***

This emergence results in testable Effective Theories, such as Fitness Landscapes mentioned in Section 5.1, the Hodgkin-Huxley equations, and Darwinian evolution [Mayr 2001]. However Quantum Field Theory is irrelevant to dynamics at this level [Anderson 1972]. EFTs as envisaged by [Burgess 2007] and LM have nothing to say about these matters.

5.3 Purposeful Design

In commenting on some statements in my book [Ellis 2016] on the nature of life, LM conflate statements I made about life in general, and statements I made about intelligent life, resulting in a misrepresentation of what I claim in the latter case.

[18] I am using the definitions in Section 1.1.

I used the phrase "Purposeful design" in the context of brain function, referring to how the human brain can result in the construction of artefacts such as aircraft and teacups. Such purposeful design is indeed intelligent design and has nothing to do with the "Intelligent Design" (ID) movement as regards evolutionary theory, which is what LM seem to fear. It is a straightforward outcome of the existence of a technological society resulting from our ability to reason in a symbolic way [Deacon 1997].

The key point is that intelligent life does indeed engage in intelligent design, and thereby creates complex systems such as aircraft, cities, digital computers, and teacups [Ellis 2005],[Ellis 2016]. This falls under the rubric of *The Sciences of the Artificial* as discussed by Nobel Prize winner Herbert Simon in his famous book of that name ([Simon 2019]). Computer science ([Abelson et al 1996]), and the consequent causal power of algorithms ([MacCormick 2011]), is an example of the outcome of intelligent thought.

A nuclear physics example of intelligent design is the existence of the apparatus nuclear physicists construct in order to carry out their experiments, such as RHIC. That's a classic case of strong emergence, No effective field theory determines either the existence or the detailed structure of that equipment: the design is in principle not determined by physical interactions *per se*. The real link to physics is via the way the structure of proteins underlies brain functioning and so enables Deductive Causation (Section 6 of [Ellis and Kopel 2019]) by nuclear physicists to lead to their existence.

6 Testability and Popper

LM query whether the proposal of strong emergence is scientific:

> *"Using Popper's scrutiny the concept of strong emergence is not 'scientific'. We are not aware of any predictions its theories have made. To be very clear on this issue, we refer to a prediction by a quantifiable statement of a theory or model that is amenable to an experimental test."*

The issue of testability and science is of great concern to me, and I have considered it in depth for decades, particularly in the case of cosmology. I have for example together with Joe Silk defended the notion of science as being a testable enterprise in a *Nature* paper entitled *Defend the integrity of science* [Ellis and Silk 2014], and consequently have earned the opprobrium of some members of the string theory community, who have referred to us as "Popperazzi" — a form of *ad hominem* attack that avoids dealing with issues of substance.

Popper's criterion has been the subject of substantial criticism [Shea 2021], nevertheless this is indeed a key issue that requires a response. I agree that theories and models should be testable. So how can this work in the case of strong emergence?

To set the scene, in Section 6.1, I consider strictly Bottom up Prediction of Weakly Emergent Properties. This turns out to be very difficult and rare. In the following two sections I consider two different ways of relating strong emergence to testability. In Section 6.2, I consider Strongly Emergent Properties: Testable Predictions?, and in Section 6.3, Bottom up Prediction of Strongly Emergent Properties. Finally in Section 6.4, I consider Inspired Prediction of Strongly Emergent Properties.

6.1 Bottom up Prediction of Weakly Emergent Properties

In the case of weak emergence, because the higher level outcomes are fully determined in a bottom up way, one might think that prediction of these outcomes should at least in principle be straightforward. It is in fact very rare, if understood in a rigorous way.

> **Weakly emergent predictions** ***A genuine weak emergence prediction makes a prediction of a weakly emergent phenomenon in a strictly bottom up way, without knowing in advance what the emergent outcome will be. Relevant emergent variables arise in a bottom up way.***

This is not how the majority of physics is done: usually one is trying to explain higher level properties that are already known in advance. But there are notable examples where strictly bottom up prediction has succeeded. In physics they include,

- Maxwell's prediction of electromagnetic waves
- Einstein's prediction of light bending and gravitational lensing
- Einstein's prediction of gravitational waves
- Dirac's prediction of anti-particles
- The prediction from General Relativity of the existence and nature of black holes

Each is a major discovery with important outcomes. When a phenomenon is weakly emergent, it is in principle derivable in a bottom up way; in these cases, that derivation was doable in practice, and often not hard.The essential point is that this was done before the higher level phenomenon had been conceived of.

> **The key point:** ***The needed higher level concepts were not known beforehand, they were developed in a bottom up way.***

That is the difficult part. The issue is to ask the right question; once one does that, the derivation follows. The result may then seem "obvious" in hindsight, but it did not occur to the majority of physicists at the time to ask the questions that led to these outcomes. Such successes remain exceptional in physics because it requires an inquiring mind exploring as yet unknown possibilities:"The Unknown Unknowns".

6.2 Strongly Emergent Properties: Testable Predictions?

On one interpretation of the need for experimental tests, the issue is this:

> **Testability of strong emergence** ***Can one give examples where strong emergence takes place, so the outcomes are even in principle not determined by the underlying physics, yet the emergent theory makes specific predictions that can be experimentally verified?***

The answer is yes. I will give a series of example where this is indeed the case.

Condensed matter physics It was demonstrated in Section 3.4 that strong emergence occurs in condensed matter systems where spontaneous symmetry breaking occurs. Have there been predictions in this area? Yes indeed [Anderson 1994], [Piers *et al* 2015]. The current hot topic of strong emergence due to topological effects also gives many examples. The existence of quasiparticles with fractional quantum numbers was predicted by Laughlin, and later observed in several experiments (see [Kvorning 2018]). Topological insulators are strongly emergent because of their topological nature [Moore 2010] and give many examples. Soft matter physics is another area where strong emergence occurs due to topological effects, with testable consequences [McLeish *et al* 2019].

Macro Physics The existence of the Large Hadron Collider (LHG) is a case of strong emergence because it is a case of intelligent design (§5.3). It was predicted by its designers that turning on the LHC would end up with around 600 million collisions per second, and this was indeed observed. The design and construction of the LHC on the one hand, and turning it on on the other, are both strongly emergent phenomena. This is an example of downward causation in particle physics: when the operators at the LHC turn the machine on, this causes particle collisions to take place due to that high level action.

Technology Innumerable examples include industrial design such as the design and manufacture of an aircraft as a result of purposeful design (§5.3). The design of the aircraft is carried out on a computer system. That design is an emergent abstract object, realized via electronic states in the computer transistors. The design has been arrived at by computer simulations of airflows over aerofoils and fuselages and control surfaces based in Newton's Laws of motion and the equations of fluid dynamics. The prediction is that the aircraft will fly and meet certain performance specifications. The result is (usually) that it does in fact fly to within the design performance specifications. This is top down causation from an abstract concept to the dispositions of billions of particles in the physical world [Ellis 2016]. The aircraft is a strongly emergent entity: its nature and existence are not even in principle implied by the laws of physics [Ellis 2005]. The whole process is enabled by Deductive Causation ([Ellis and Kopel 2019]: Section 6)

The arrow of time It was demonstrated in Section 3.5 that all the arrows of time are strongly emergent phenomena. A prediction one can make is that all the arrows of time should point in the same direction everywhere in the observable universe: time should not run in the opposite direction in other parts of our Galaxy or in the Andromeda galaxy, for instance, or for that matter at the Last Scattering Surface in the early universe. Should this not be the case it should be detectable via astronomical observations, for example observing a binary neutron star system doing the reverse of coalescing to form a black hole. Observations of gravitational radiation emission by LIGO and VIRGO confirm that in fact they do coalesce to form a black hole, as expected on the basis of the usually understood direction of time.

Complexity and astrology At the conclusion of this section in their paper, LM state, referring to strong emergence and predictions:

> "*Furthermore, If there are any predictions [from strong emergence] it seems that the mere complexity of the systems in which it is intended to be applied to leaves very little room for direct falsifiability: there is always some conditional statements which can be concocted (after the fact) to 'argue away' negative findings. Under these circumstances strong emergence does not appear worthier than astrology.*"

This statement will surprise all those engaged in the subjects of molecular biology, cell biology, physiology, neuroscience, ecology, and so on, as well as the editors of *Nature* and *Science*. These academic fields are all strongly supported by a mass of experimental evidence. It represents a regrettable particle physics view of the rest of science.

It does however support the interpretation of what LM want in terms of testability that is proposed in this section. I have given many examples showing it is indeed fulfilled.

6.3 Bottom up Prediction of strongly emergent properties

Here is a second possible interpretation of the requirement for experimental proof of strong emergence, that leads to interesting tests:

> **Prediction of strongly emergent properties** ***It is not possible to predict strongly emergent properties in a strictly bottom up way***

Actually that's a tautology. But it gives an interesting challenge to physicists, that will test the claims made in Section 3.4 that strong emergence takes place in condensed matter physics. Thus it is a genuine test as to whether strong emergence takes place. So here is a prediction which can be used to test the claims of Section 3.4:

> *Neither LM nor any of their nuclear physics or particle physics colleagues will be able to derive the experimentally tested properties of superconductivity or superfluidity in a strictly bottom up way. In particular they will be unable to thus derive a successful theory of high temperature superconductivity.*

The reason I make this prediction is because I claim these are strongly emergent properties (Section 3.4). The task is thus impossible, even in principle, as stated by Robert Laughlin in [Laughlin 1999]. If they succeed,[19] they will disprove the arguments presented in this paper, as well as Laughlin's claims.

6.4 Inspired Prediction of Strongly Emergent Properties

This discussion raises a puzzling issue: if if is not possible in principle to predict strongly emergent phenomena in a bottom up way, how have successful predictions of strongly emergent phenomena in fact been done?

> **Prediction of Strongly Emergent Phenomena** ***Because they are strongly emergent, they cannot in principle be predicted in a bottom up way on the basis only of low level variables. Rather one has to explore the possible role in lower level effective theories of suitable higher level variables (cf. Section 3.4).***

Thus this is not a strictly bottom up process. As stated by Anderson in [Anderson 1972] (quoted in 4.1), this is a process of inspiration and imagination. There is no set path that will achieve this result.

Examples where it has happened are,

- Towne's prediction of the possibility of the Maser
- Laughlin's prediction of Fractional Quantum Hall states
- Josephson's prediction of the Josephson effect

One must either conceive what the possible higher level nature of a phenomenon might be and then determine the relevant higher level variables to describe this, or else start by considering known higher level variables and seeing where they might be useful in lower level dynamics A key example of the latter sort is Berry Phase [Berry 1994]. It determines strongly emergent effects because of its topological nature.

[19] No AdS/CFT has not done it [Anderson 2013], and in any case its not a strictly bottom up procedure

7 Conclusion

Overall this paper illustrates the gulf between many nuclear and particle physicists on the one side, and condensed matter and soft matter physicists on the other, and even more so with topics like organic chemistry and molecular biology. I comment in turn on the reductionism rift (Section 7.1), the issue of equal validity of effective theories at all levels (Section 7.2), and the new results in this paper (Section 7.3).

7.1 The reductionism rift

LM strongly support a reductionist view, whereas condensed matter physicists tend to take a different view. Stephen Simon in commenting on why it is worthwhile studying condensed matter physics states ([Simon 2013]:3) "*Because reductionism doesn't work*", implying one should approach the understanding of emergence through the kinds of studies undertaken by condensed matter theorists. He cites the fractional quantum Hall effect as an example which defies reductionist understanding, because of the fractional charges involved (agreeing with [McLeish *et al* 2019] and [Guay and Sartenaer 2018]). One of the problems is that LM do not deal with either broken symmetries or topological effects, both central to cases of strong emergence in condensed matter physics and soft matter physics. This separation between disciplines, commented on in [Schweber 1993], contrasts with the description given in [Anderson 2001] of how these fields had such fruitful interconnections with each other in the past. It seems nuclear and particle physicists today may have forgotten that previous unity, despite the Standard Model of Particle Physics being a key outcome of solid state physics through the work of Phil Anderson [Wilczek 2016].

An important point is that downward causation [Ellis 2016] plays a key role in what happens in condensed matter physics and soft matter physics (Section)3.4), even if it is not explicitly identified as such. It is assumed to not occur in particle physics and nuclear physics, as stated by LM. But it is relevant there too whenever irreversible processes take place, because those processes then involve an arrow of time which is strongly emergent (Section 3.5). It also occurs for example in the difference of the properties of a neutron bound in a nucleus, and a free neutron [Ellis 2016]. There may well be other examples.

Effective Theories The concept of an EFT in a very broad sense of the term may be assumed to apply in a broad range of cases, but not necessarily the kind of power-series expansion methods presumed by LM. Those methods do not for example extend to molecular biology or evolutionary biology or neuroscience.

What one in fact needs across a broad range of domains, according to Hartmann, is a suitable mix of theories, EFTs, and models He adds "*There is a whole continuum of relations between theories, models and EFTs which range from strict reductive relations through ontological bridges to rather vague associations through semantical bridges*" ([Hartmann 2001]:297), and see [Craver 2002] for an in depth discussion of the relation between theories, laws, and models. LM do not discuss the relation between these concepts, nor do they discuss the relation between models and mechanisms that I touch on in Section 4.2. These are crucial issues in undertaking an adequate study of reductionism and emergence.

7.2 Equal validity of levels

Where I agree with LM is their statement **EFT5** in Section 1.4: "*Equal validity of all levels*". This is indeed the case: this is the physics version of Denis Noble's "Principle of Biological Relativity" [Noble 2012]: all levels one deals with in studying emergence issues of relevance to daily life are equally real, none is fundamental (see the discussion following Equation (7)).

In terms of Effective Theories, this is the statement

> **Equal Causal Validity**: ***Each emergent level in physics represents an Effective Theory in the sense of [Castellani 2002] (see §1.3), so each level is equally valid in a causal sense.***

In particular, there is no known bottom-most physical level to which all of physics - or any other emergent level - can be reduced. All this is expressed very nicely by Sylvan Schweber in [Schweber 1993], see the quote above in Section 4.1. This is true because higher levels are linked to lower levels by a combination of upwards and downwards causation (sees Section 3.4 and [Noble 2012], [Ellis 2016]).

The relation of Effective Theories to levels is this: each Effective Theory has a domain of applicability $\mathcal{D}$ where it is valid (see (7).) That domain can sometimes be identified with the level where it operates.

7.3 Novel results

Much of this paper is a response to LM. But out of it has come strong new results:

- The key conceptual advance is the definition (Section 1.1) of four different kinds of symmetry breaking mechanisms: **SSB**(**m**), Spontaneous Symmetry Breaking occurring at the micro level; **SSB**(**M**), Spontaneous Symmetry breaking occurring due to the emergence processes **E** creating the macro level from the micro level, **SB**(**NS**), symmetry breaking due to Darwinian processes of natural selection; and **SB**(**C**), symmetry breaking occurring due to the cosmological context.

On this basis, I provide

- The argument in Section 3.4 that emergence based in **SSB**(**M**) is strong emergence. Such broken symmetries are the core of condensed matter physics ([Anderson 1981], [Anderson 1989]) and a similar argument applies to topologically emergent states. This implies all condensed matter physics properties **P** are strongly emergent.
- The argument in Section 3.4 **D) c)** that lower level physics **m** is causally incomplete because it cannot by itself produce experimentally established outcomes of solid state physics. It only becomes causally complete if variables **a** based in higher level conditions are included to produce effective lower level dynamics **m'** that give the correct higher level outcomes, i.e. if downward causation **m** → **m'(m,a)** takes place.
- The proof in Section 3.5 that the emergence of the various arrows of time at macro scales out of the relevant time-symmetric underlying physics is a case of strong emergence. It is an example of **SB**(**C**) due to cosmological conditions **C**.
- The argument in Section 5.2 that strong emergence takes place in the case of living systems due to both **SSB**(**M**) and **SB**(**NS**).

Broken symmetries are the key to emergence. Where then do broken symmetries come from? In the case of condensed matter physics and physical chemistry, they are due to the nature of atoms, leading to the crystal or molecular structures that form spontaneously through emergence processes **E** as the lowest energy state of a large conglomerate of atoms, thus breaking the underlying symmetries. This broken symmetry macro state then reaches down to alter dynamics at the lower state through the formation of Band structure, Fermi levels, and so on. In the case of biology, Darwinian selection processes have lead to the existence of a genome that, in the right cellular context, leads to the existence of proteins of immense complexity. As regards the various arrows of time, the crucial time asymmetry arises from the cosmological context of the expanding and evolving universe. And in some cases, symmetry breaking is due to a purposeful design processes. Interestingly, that includes not just aircraft and digital computers, but the existence of materials such as plastic and steel and concrete. This is the material basis of the emergence of society.

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A The Renormalisation group

In contrast to the emphasis placed on EFTs by LM as the universal route to understanding emergence, David Tong claims[20] that it is the renormalisation group [Wilson 1982] [Binney et al 1992] that underlies all emergence. It has for example had enormous success in explaining the universality of critical phenomena, as has been recognized by the award of the Nobel Prize to Kenneth Wilson.

Phil Anderson also emphasizes the importance of the renormalisation group (RG) in relating different scales to each other. In [Anderson 2001] he says,

> "*The renormalisation group is a way to expand the scale from the atomic to the macroscopic which shows that often the result is an enormous simplification, a division of systems into 'universality classes' all of which behave the same way in this limit; hence we may pick the simplest model for further study.*"

What is its relation to EFTs? That fount of all knowledge, Wikipedia, in its article on Effective field theory states "*Presently, effective field theories are discussed in the context of the renormalization group (RG) where the process of integrating out short distance degrees of freedom is made systematic. This allows systematic investigation of the changes of a physical system as viewed at different scales*".

Elena Castellani states [Castellani 2002], "*The EFT approach is grounded on the RG concept: the variation of the (effective) physical description with the changing scale is described by the RG equations. The emergence of the EFT idea (and approach) is in fact intertwined with the development of renormalization theory (RT).*" The articles [Georgi 1993] and [Burgess 2007] basically give renormalisation group versions of EFTs.

B Multiple realisability

A key point is that multiple realisability plays a key role in strong emergence [Menzies 2003]. Any particular higher level state can be realised in a multiplicity of ways in terms of lower

[20]See the lecture "A night at the Aspen opera house, discussing the renormalisation group and the unity of physics" linked here: https://www.damtp.cam.ac.uk/user/tong/outreach.html.

level states. In an engineering or biological cases, a high level need determines the high level function and thus high level structure that fulfills it. This higher structure is realised by suitable lower level structures, but there are billions of ways this can happen

It does not matter which of the equivalence class of lower level realisation is used to fulfill the higher level need, as long as it is indeed fulfilled. Consequently you cannot even express the dynamics driving what is happening in a sensible way at a lower level.

Consider for example the statements *The piston is moving because hot gas on one side is driving it* and *A mouse is growing because the cells that make up its body are dividing.* They cannot sensibly be described at any lower level not just because of the billions of lower level particles involved in each case, but because there are so many billions of ways this could happen at the lower level, this cannot be expressed sensibly at the level of electrons flows in axons. The importance of multiple realisability is discussed in [Ellis 2019] and [Bishop and Ellis 2020]. The latter paper also discusses the underlying group theory relations, dealing in particular with the emergence of molecular structure.

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