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A new look at emergence. Or when *after* is different

Alexandre Guay[1] · **Olivier Sartenaer**[1]

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Abstract In this paper, we put forward a new account of emergence called "transformational emergence". Such an account captures a variety of emergence that can be considered as being diachronic and weakly ontological. The fact that transformational emergence actually constitutes a genuine form of emergence is motivated. Besides, the account is free of traditional problems surrounding more usual, synchronic versions of emergence, and it can find a strong empirical support in a specific physical phenomenon, the fractional quantum Hall effect, which has long been touted as a paradigmatic case of emergence.

Keywords Emergence · Synchronic emergence · Diachronic emergence · Transformational emergence · Fractional quantum Hall effect · Quantum electrodynamics

1 Introduction

Current discussions about emergence have reached a stalemate. Either they revolve around crafting metaphysically-loaded versions of the notion that fail to have direct

✉ Olivier Sartenaer
olivier.sartenaer@uclouvain.be

Alexandre Guay
alexandre.guay@uclouvain.be

1 Institut Supérieur de Philosophie, Université Catholique de Louvain, Collège Mercier, Place du Cardinal Mercier 14, bte L3.06.01, 1348 Louvain-la-Neuve, Belgium

scientific relevance or empirical support, or they verge on devising science-friendly versions that are metaphysically shallow. This paper is about breaking this deadlock, by putting forward a new account of the concept, called "transformational emergence" (hereafter [TE]).

In Section 2, we first propose an analysis of emergence in the light of which we localize [TE] in the conceptual landscape of the possible varieties of the notion. On this basis, and after having given reasons why we believe [TE] is a variety of emergence in its own right (Section 3.1), we turn to providing a metaphysical account of it (Section 3.2), which we operationalize to allow for empirically exemplifying it (Section 3.3). We then compare [TE] to its main competing accounts on the current philosophical market (Section 3.4), and highlight the ways in which it solves or avoids most of the traditional, vexing issues that the more widespread way of looking at emergence unavoidably faces (Section 3.5). Finally, in Section 4, we show that the account has strong empirical support.

2 Varieties of emergence

2.1 The hallmark of emergence

Emergence is an empirical relation between two *relata*, namely an emergent E and its emergence basis B, such that the two following theses simultaneously obtain:

- (DEP) E is dependent on, or determined by, B; and yet
- (NOV) E is novel with regard to, or autonomous from, B.

While a given emergent and its corresponding basis have to be of a same nature (e.g. E and B can be events, properties, laws, etc.), their common nature may vary depending on the underlying ontological framework one chooses to adopt or the philosophical task one seeks to accomplish.

From a temporal perspective, (DEP) and (NOV) can be construed in two different ways. In the case of (DEP), the determinative relation going from B to E can be considered as being either *synchronic* – it can be, say, constitution –, in which case E and B are individuated differently in terms of the "levels" to which they respectively belong (E will usually be said to belong to a "higher-level" than its "underlying", simultaneous basis B). Or, the determinative relation going from B to E can be *diachronic* – for instance, it can be causation –, in which case E can (but doesn't need to) belong to the "same level" as its antecedent basis B (for E and B can be distinctly individuated by appealing to the different times of their occurrence). Analogously, when it comes to (NOV), one can consider E as being either *hierarchically* novel with regard to its underlying and simultaneous basis B, or *historically* novel with regard to its antecedent basis B, insofar as, for example, E exhibits in both cases features that B simply doesn't have.

Adopting the conventional notation that X_t^l denotes an entity X – whatever its exact nature – at time t and belonging to "level" l, one can devise the concepts of synchronic and diachronic emergence on the following model:

$E_t^{l'}$ synchronically emerges on B_t^l (with $l' > l$) iff:
(DEP$_s$) B_t^l synchronically determines (e.g. constitutes) $E_t^{l'}$; and yet
(NOV$_s$) $E_t^{l'}$ is hierarchically novel with regard to B_t^l.

$E_{t'}^{l'}$ diachronically emerges on B_t^l (with $t' > t$ and $l' \geqslant l$) iff:
(DEP$_d$) B_t^l diachronically determines (e.g. causes) $E_{t'}^{l'}$; and yet
(NOV$_d$) $E_{t'}^{l'}$ is historically novel with regard to B_t^l.

As they have been expressed, (DEP) and (NOV) are, both in their synchronic and diachronic declinations, (i) obviously ambiguous and (ii) *prima facie* in tension, for it can require some intricate speculation to convince that a given entity E is *at the same time* dependent on, and novel with regard to, a corresponding basis B. It is then not surprising that a great deal of the emergentists' energy turns out to be spent on finding (i) precise ways of capturing or fleshing out (DEP) and (NOV) and (ii) ways of holding them together in a non-contradictory fashion.

2.2 The conceptual landscape of emergence

There actually exist numerous approaches that have been put forward in order to make sense of, and consistently reconcile, (DEP$_s$) and (NOV$_s$) or (DEP$_d$) and (NOV$_d$). The landscape of the possible accounts of emergence is thus today quite rich and complex. Accordingly, it can prove useful to compartmentalize it with the help of the following two distinctions:

Epistemological vs. ontological emergence Whereas it is usually the case that (DEP) is to be taken in an ontological sense, for it refers to a determinative relation – e.g. constitution or causation – that is supposed to be "out there" in the natural world, (NOV) can be construed either epistemologically or ontologically, depending on whether the autonomy or novelty in question is to be found in our representations of the natural world or in the natural world itself. Examples of the former kind of novelty, associated with the so-called "epistemological" version of emergence, are reductive unexplainability, unpredictability, non-derivability of laws, the impossibility to describe in a lower-level vocabulary, etc. By contrast, cases of ontological emergence usually go along with the advent of new, irreducible laws, powers or properties.

Weak vs. strong emergence As its name suggests, this distinction allows for the possibility of a contrast between different degrees of a given type (e.g. epistemological

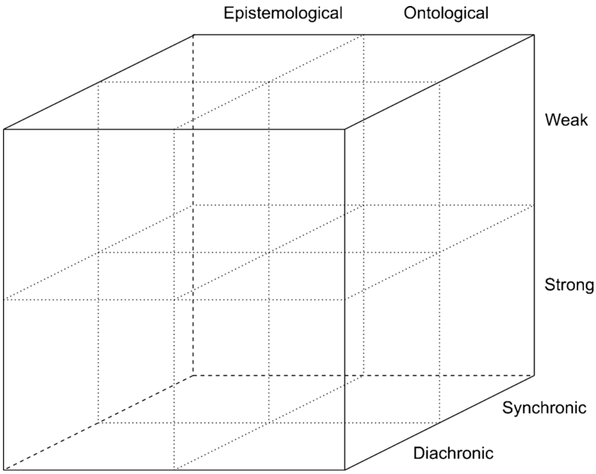

Fig. 1 A compartmentalization of the conceptual landscape of emergence

or ontological) of emergence.[1] When it comes to forms of epistemological emergence, the weak/strong distinction marks a dividing line between cases of, say, unpredictability that hold only in practice or that are to be relativized to a given epistemic situation at a given time, and cases of unpredictability that are supposed to hold in principle. With regard to ontological emergence, the weak/strong distinction can be appealed to in order to demarcate between emergentist views that embrace more or less anti-reductionistic commitments (e.g. while two synchronic, ontological emergentists are committed to the advent, upon emergence, of new causal powers, only the "weak" emergentist also embraces – whereas the "strong" emergentist denies – supervenience).

It is noteworthy that the aforementioned distinctions cut across each other, to the effect that, together, they can help compartmentalize the conceptual landscape of emergence in eight different regions (see Fig. 1). Other distinctions could be put forward to further refine this picture, but this coarse-grained analysis is precise enough to constitute the starting point of the discussion to come.

3 A new look at emergence

In this section, we probe a specific region of the conceptual landscape of emergence that has been under-appreciated in recent discussions, namely diachronic, weakly

[1]In this we follow van Gulick (2001)'s suggestion. We must bring to the reader's attention that this construal of the weak/strong distinction is not the most widespread. It is indeed often appealed to in order to mark a dividing line between what we have chosen to refer to here as the epistemological *versus* the ontological character of emergence (see for instance Smart 1981; or Bedau 1997). Accordingly and for example, whereas Bedau qualifies his own account as "weak" – for it is to be contrasted with ontological accounts essentially based on downward causation –, we will rather consider it as "strongly epistemological", insofar as the (epistemological) irreducibility involved has an objective – rather than merely subjective – character. At the end of the day, this turns out to be purely terminological.

Table 1 Sample of varieties of synchronic emergence in the philosophy of mind. Nagel is of course not to be considered as a philosopher of mind, but his account of emergence is built upon a criticism of Broad (1925)'s emergence, which *was* supposed to capture the mind/body relation

	Epistemological	Ontological
Weak	Nagel (1961)	Gillett (2002)
Strong	Searle (1992)	Popper and Eccles (1977)

ontological emergence. In particular, after having vindicated the fact that diachronic emergence is emergence in its own right (Section 3.1), we put forward an account of [TE]. We first devise it in a metaphysical sense (Section 3.2), before operationalizing it in a way that makes it possible to find evidence that it can be exemplified in our world (Section 3.3). Finally, after having compared [TE] to its neighboring accounts in the conceptual landscape of emergence (Section 3.4), we defend its fruitfulness in solving or avoiding some traditional vexing issues that bear on the contemporary debates (Section 3.5), but also in having a strong empirical support in contemporary science (Section 4).

3.1 Preamble: diachronic emergence *is* emergence

Since the recent resurgence of emergence, different sets of fields have focused on different specific parts of the conceptual landscape of emergence. In the main context within which emergence has been – and still is – a hot topic, namely the philosophy of mind, all of the philosophers' attention seems to have been systematically drawn on the synchronic varieties of the concept (see Table 1).

Apart perhaps from some exceptions, synchronic varieties of emergence fail to apply in a realistic way to situations encountered in the natural sciences, where systems usually encapsulate an important temporal dimension that seems to play a crucial role in any putative emergence ascription.[2] To see this, suffice it to draw the attention on the fact that most of the empirically-informed accounts of emergence taking shape within the context of the natural sciences are developed in an essentially diachronic fashion (see Table 2).

Without formulating any hypothesis about the reasons of such a discrepancy between both communities of philosophers in the way they make use of emergence, it has to be noted that synchronic emergence is often claimed to be the only "genuine" kind of emergence, diachronic emergence being simply dismissed as a recent proposal that deviates too much from the "classical conception", which is usually traced back to Broad (1925)'s synchronic account (see Kim 1999, p. 20; or Kim 2006, p. 555).

[2]A similar diagnosis is made, in the peculiar case of cognitive science, by Stephan (2006). It should be noted that there of course exist in contemporary philosophy of science accounts of emergence that encapsulate *both* a synchronic and a diachronic dimensions (e.g. Morrison 2006; or Batterman 2011). To avoid any ambiguity, in what follows we then reserve the generic term of "synchronic emergence" to denote accounts that can be considered as "purely" synchronic.

Table 2 Sample of varieties of diachronic emergence in philosophy of science

	Epistemological	Ontological
Weak	Rueger (2000)	Wilson (2010)
Strong	Bedau (1997)	Humphreys (1997)

It is actually not difficult to resist such line of thought, particularly if one chooses to evaluate the "classicality" of emergence in terms of its historical genesis. It indeed turns out that the first explicit characterization of emergence to be found in history was essentially diachronic, though also *concomitantly* synchronic. After Lewes' somewhat anecdotal contribution in 1875, the first philosophical doctrine that can be considered an emergentist school, namely Lloyd Morgan's "emergent evolutionism", was indeed entirely built upon a notion of emergence that was supposed to be the philosophical tool allowing a reconciliation between Darwinian gradualism and the successive and incessant advent of *historical* novelties in evolution, to the effect that "there is more in the world to-day than there was in the primitive fire-mist" (Morgan 1913, p. 30). As a characterization of emergence that was supposed to achieve such a reconciliatory job, we can find in Morgan's writings that there is emergence at play, for example in the chemical synthesis of two compounds, when (DEP_x) the synthesized compound is the product of the reactants and (NOV_x) the synthesized compound has "new and distinctive properties which are not merely the algebraic sum of the properties of the component things *prior to synthesis*" (*Ibid.*, p. 28, our italics). As an operationalization of (NOV_x), Morgan proposed that these new properties were "unpredictable from what one may perhaps speak of as the fire-mist's point of view" (*Ibid.*, p. 30). This being said about what certainly is the most "classical" construal of emergence, one may wonder whether clauses (DEP_x) and (NOV_x) turn out to be something *else* than a particular version of (DEP_d) and (NOV_d). "Classical" emergence is then clearly (also) diachronic emergence.

3.2 Transformational emergence: a metaphysical account

This being said, we can turn to providing a new account of one possible declination of diachronic emergence, namely [TE].

To start with, let us consider a natural system S at two successive times t_1 and t_2 of its evolution. One will say – and in this lies the general, metaphysical account of [TE] – that the given system at t_2 (S_2) transformationally emerges from the same system at t_1 (S_1) if and only if there exists a transformation **[Tr]** such that:[3]

[3] Whereas we claim that, as such, the account proposed here is unprecedented in the literature, it is of course not without forerunners. In particular, we owe a great debt of gratitude to Paul Humphreys, who presented to us the original idea and coined the term "transformational emergence". A similar intuition is also to be found in Ganeri (2011), though in a very different context.

- (DEP$_d$) S_2 is the product of a spatiotemporally continuous process going from S_1 (for example causal, and possibly fully deterministic). In particular, the "realm" R to which S_1 and S_2 commonly belong (e.g. the physical realm) is closed, to the effect that nothing outside of R participates in S_1 bringing about S_2.[4] And yet:
- (NOV$_d$) S_2 exhibits new entities, properties or powers that do not exist in S_1, and that are furthermore *forbidden* to exist in S_1 according to the laws $\{L_1^i\}_{i=1}^n$ governing S_1. Accordingly, different laws $\{L_2^i\}_{i=1}^m$ govern S_2.

It is noteworthy that the "forbidden" expression occuring in (NOV$_d$) introduces a modality aspect to [TE], according to which, upon emergence, an ontological domain that was previously barred – including entities and their properties, subject to specific laws – becomes accessible.[5] It should also be emphasized that, at best, the sets of laws $\{L_1^i\}_{i=1}^n$ and $\{L_2^i\}_{i=1}^m$ partially overlap. It is indeed part of the account that at least one law L_2^a of S_2 is inconsistent with the set $\{L_1^i\}_{i=1}^n$.[6]

In a nutshell, the proposed account operates a perspective shift with regard to the more usual way of looking at emergence. The general frame one has generally in mind when making an emergence ascription is schematically captured in the upper left corner of Fig. 2. When some given n_1-level entities in isolation at time t_1 – be they atoms, cells or organisms – are put together in a specific configuration at time t_2, they can collectively give rise to a hypothetical n_2-level whole. On this basis, one can choose to adopt two different perspectives in order to formulate an emergence ascription. On the one hand, and this is the most widespread, usual way of looking at this, one can consider there being emergence because of the very special nature of the inter-level determinative relation **[C]** that occurs between the parts and the putatively emergent whole at t_2 (case (i) on Fig. 2) and, accordingly, one can leave aside or abstract away the historical process prior to t_2. Here the real drive of emergence is to be localized in a synchronic part-whole relation **[C]** of a very special nature – e.g. as capturing the conjunction of (mereological) supervenience (DEP$_s$) and irreducibility (NOV$_s$). In this first respect, one often rhetorically claims that "the whole is more than the sum of its parts" or that "more is different".

On the other hand, and *this* is the perspective shift encapsulated in [TE], one can choose to leave aside these holistic considerations and ground an emergence ascription in a transformation **[Tr]** of a very special nature, which the entities at t_1 encounter upon entering into their interactive configuration at t_2 (case (ii) on Fig. 2). Here the real drive of emergence is to be found in a diachronic determinative relation **[Tr]** that captures (DEP$_d$) and (NOV$_d$) as formulated above (and to be operationalized below).

[4] As it has been stated, what (DEP$_d$) tolerates is that contextual elements jointly participate with S_1 to bring about S_2. What (DEP$_d$) denies, though, is that these elements act as radically extrinsic influences that should bring the novelty in emergence from the outside. It should also be pointed out that we take determinism to mean that, should S's evolution be deterministic, S's history would be univocally fixed. This doesn't entail that S's future evolution can be predicted (Earman and Butterfield 2007), nor that previously inexistent laws cannot appear now and then during S's evolution (Sartenaer 2015).

[5] This definition supposes that S's dynamics is entirely captured by the relevant set of natural laws.

[6] We thank an anonymous reviewer for having drawn our attention on this point.

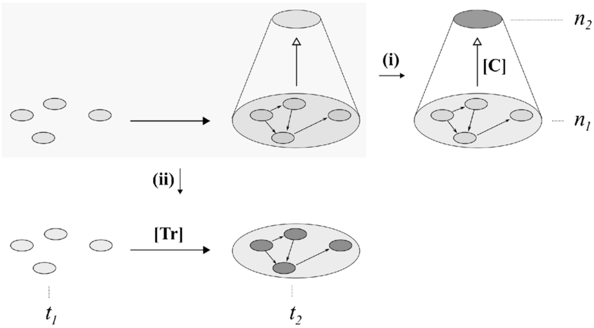

Fig. 2 A perspective shift on emergence. One can ground any emergence ascription by putting the burden of a suitable reconciliation of (DEP) and (NOV) either on (i) the synchronic relation **[C]** between levels or (ii) the transformational relation **[Tr]** between successive times

In contrast with the more widespread way of looking at emergence, here one can claim that "the whole *is* the sum of the *transformed* parts" or that "*after* is different".[7]

3.3 The epistemic effects induced by transformational emergence

This far, we have cooked up an account that captures a relation that remains something like a mere metaphysical possibility not yet fully investigated by philosophers. Even restricted to this, [TE] already offers several non-negligible advantages over some of its competitors on the philosophical market and, as such, it is worthwhile to consider it as a convenient theoretical tool to solve or avoid some traditional issues surrounding the emergence/reduction debate, while preserving some strong intuitions about emergence (see in particular Section 3.5). However, we have reasons to think that [TE] captures more than a metaphysically plausible relation. As we will show in Section 4, we believe there are empirical cases of [TE] in *our* world. In this respect, beside being of possible interest for metaphysicians, [TE] has also some philosophical work to do in the natural sciences.

To see this, it is necessary to provide beforehand what we consider an operationalization of [TE], that is, a translation of its underlying metaphysical intuitions into formal requirements that can enter into dialogue with the sciences. Because we cannot claim to have a privileged and direct access to the ontology of natural systems, the best we can do is to recast ontological claims like (DEP$_d$) and (NOV$_d$) into claims about the traces that **[Tr]** leaves in the formal constructs we use to investigate these natural systems, on the following model (see also Fig. 3):

[7] As the first of these slogans makes clear, the very notion of a "whole" is radically deflated in the transformational perspective, as it is claimed to be simply identical with – or reducible to, in the synchronic sense – the sum of its transformed parts (the notion of "sum" is taken here metaphorically, as a way of echoing the traditional slogan; it can actually capture any kind of combinatorial principle, linear or not). Accordingly, one can of course still talk about wholes or collectives, but this is simply a linguistic shortcut that doesn't have any ontological import over and above what happens at the level of the parts (which is the only ontologically significative level). Of course, one could combine this diachronic and "flat" approach to emergence with a synchronic and hierarchical perspective, and hence devise an hybrid notion that encapsulates both the perspectives discussed here. But this simply isn't [TE] as we conceive of it.

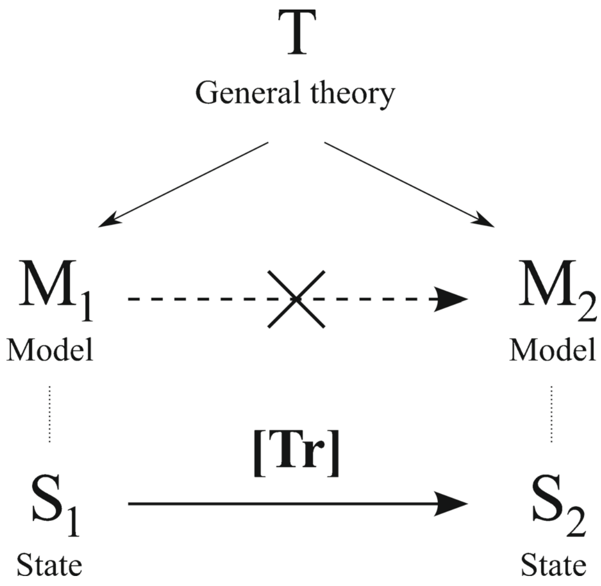

Fig. 3 The traces that **[Tr]** leaves in our way of investigating S

- (C_1) M_1 and M_2, which both describe the same system at two successive stages S_1 and S_2 of its evolution, are models of one and the same non-trivial theory T. And yet:
- (C_2) M_2 is not derivable from M_1 as a matter of principle, for M_2 contains features that are forbidden in M_1 according to theory T. More precisely, S_2's dynamics as described by M_2 is not continuously deformable into S_1's dynamics as described by M_1.[8]

As intended, (C_1) and (C_2) capture the epistemic effects induced by the ontology of [TE] and, as such, they are also the best available pieces of evidence – at least when they are successfully met in a given situation – that there is [TE] at play. (C_1) states that S_1 and S_2 are states of one and the same system or, to put it differently, that S_1 and S_2 are states of a same kind, defined by theory T. Nothing exterior to the realm R to which S_1 and S_2 commonly belong, and which should be modeled in the context of another theory T', is at stake in **[Tr]**. Through in-principle non-derivability, (C_2) captures the effect of the novelty involved in [TE]. The fact that it is impossible

[8]Here we take "dynamics" in an unrestricted sense that can be distinctively implemented in different disciplinary contexts, and that can be construed as whatever fixes the possible kind of evolution of a system with respect to a given model. In the case of physics, one can expect to detect (C_2) into what codes for the dynamics of systems, namely their Lagrangian or Hamiltonian. It is noteworthy that focusing on the way in which the dynamics evolves has already been considered elsewhere as the best way to ground claims about what counts as "truly" novel or not in the evolution of a physical system. See for instance Rueger 2000 or Morrison 2006. It is also noteworthy that here we take **[Tr]** as what leads from S_1's dynamics to S_2's dynamics, but not as a dynamical process in itself. As with respect to the possible relation between laws and dynamics, the scope of this paper compels us to remain agnostic.

to describe S_2's dynamics in M_1, that is, to describe S_2's dynamics as a smooth deformation of S_1's dynamics, combined with the idea that a system's dynamics as we capture it through our model is the best (and only indirect) access we have to the system's ontology, constitute the most convincing clue that S_2 exhibits new features that are forbidden to exist, according to natural laws, in S_1. As an epistemic side-effect, it also follows from (C_2) that, prior to t_2, it is impossible in principle to predict or etiologically explain the nature and behavior of S_2 from complete knowledge of S_1 (though this is possible from knowledge of theory T and the appropriate conditions that define S_2).

As we will see in Section 4, the way of physically cashing out **[Tr]** will be accomplished through the notion of a transition between distinct topological orders: there will be [TE] in our world as soon as a given system exhibits a transformation such that its post-transformation state corresponds to a state of matter in a topological order that is not accessible to any of its pre-transformation states, according to the laws governing these pre-transformation states.

3.4 Transformational emergence in the conceptual landscape of emergence

At this point, it can prove helpful to localize [TE] in the conceptual landscape of emergence exposed in Section 2.2. In particular, [TE] lies in the region of diachronic, weakly ontological varieties of the notion (see Fig. 4).

As it is already clear in the account proposed above, [TE] is a diachronic relation, as the putative emergent and its basis are related by a temporally extended determinative relation that allows for the advent of historical novelties. [TE] is also ontological, for it leads to the advent of new entities, powers, forces and laws in nature, and this in spite of the fact that transformational emergents are the continuous products of their bases. Of course, as we have seen, such additions to the world's ontology are systematically accompanied by principled epistemological effects – non-derivability of models, etiological unexplainability and unpredictability –, which we can use – and, as it turns out, which we *will* use below – as evidence in favor of the existence of transformational emergents in our world. Finally, [TE] is only ontological in a weak sense, insofar as it is a monism-friendly relation. If one considers S as being a physical system, the emergence of a state S_2 on a previous state S_1 indeed turns out to be perfectly consistent with physicalism as well as with the causal closure of the physical world.

This being said, we can now compare [TE] to its neighboring accounts in the conceptual landscape of emergence (see again Fig. 4). A first way of looking at [TE] is as a moderation of Humphreys' original "fusion account" (Humphreys 1997). If one considers $P^i_m(x^i_r)(t)$ as being the instantiation of an i-level property P^i_m by an i-level entity x^i_r at time t, and $[. * .]$ as being the "fusion operation", then fusion emergentism states that $[P^i_m(x^i_r)(t) * P^i_n(x^i_s)(t)] = [P^i_m * P^i_n][(x^i_r) + (x^i_s)](t')$ and $[P^i_m * P^i_n][(x^i_r) + (x^i_s)](t') = P^{i+1}_l(x^{i+1}_l(t'))$. Among the ideas encapsulated in these expressions, there is the fact that fusion is a diachronic operation ($t' > t$), which gives rise, from i-level property instances, to an $(i+1)$-level property instance [*level jump*], and which is such that, at t', the fused property instances have ceased to

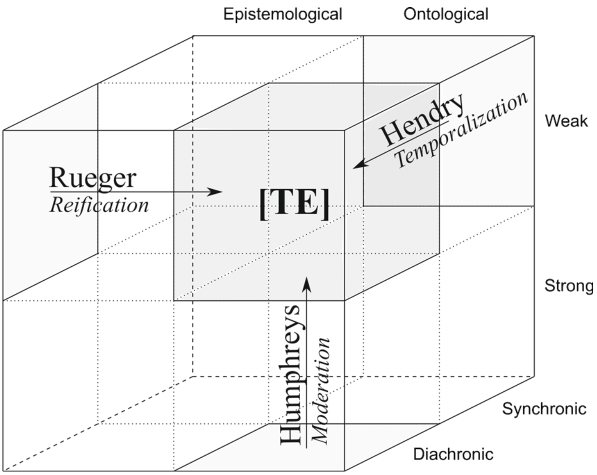

Fig. 4 [TE] as a form of diachronic, weakly ontological emergence, which can be seen as a moderation of Humphreys (1997), a reification of Rueger (2000), or a temporalization of Hendry (2010)'s accounts of emergence

exist as separate entities [*basal loss*]. Consequently, there is no supervenience of $P_l^{i+1}(x_l^{i+1})(t')$ on any underlying, simultaneous basis, there is no threat of causal overdetermination that could prevent us from considering that $P_l^{i+1}(x_l^{i+1})(t')$ can exert its own (irreducible) causal powers, and causal closure breaks down. On this basis, fusion emergentism states that $P_l^{i+1}(x_l^{i+1})(t')$ emerges – in a diachronic, strongly ontological sense – from $P_m^i(x_r^i)(t)$ and $P_n^i(x_s^i)(t)$.[9]

As such, fusion emergentism faces at least two issues. First, it is not clear that the account can be empirically exemplified (Kronz and Tiehen 2002), despite Humphreys' own "reasonably confident" claim that quantum entanglement constitutes the basis for such an exemplification. Second, the whole account heavily rests on the existence (and the definability) of a discrete hierarchy of levels, a commitment that Humphreys himself considers "misleading and probably false" (Humphreys 1997, p. 5), but that he nonetheless accepts as a hypothesis given the initial rationale of the fusion account, namely formulating a plausible theory of emergence that is immune to generalized exclusion-style arguments, according to which some minimal dependence relation between levels is incompatible with genuine high-level causation.

Now one is in a position to appreciate why Humphreys himself seems to have recently given up on fusion emergentism in favor of something along the lines of [TE]

[9]The diachronic and ontological nature of fusion emergence is obvious from what has just been said. The fact that it is *strongly* ontological has to be contrasted with the weakly ontological character of [TE]. As we've seen, [TE] actually tolerates causal closure as well as supervenience, beside not being committed to the existence of high-level causal powers.

(Humphreys unpublished). For one thing, the initial rationale for cooking up fusion emergence, namely to avoid exclusion-style worries, is perfectly met by [TE] (see Section 3.5). Furthermore, this is achieved without falling into the issues mentioned above, which fusion emergentism faces. Indeed, [TE] has a stronger empirical support (see Section 4) and no misleading account of a discrete hierarchy of levels has to be hypothesized (see also Section 3.5).

In 1997, fusion emergentism was an unprecedented move from the synchronic view of emergence towards a pioneering diachronic account better suited to capture the specific nature of physical systems. In 2016, [TE] constitutes a new step in the same direction, by getting rid of the last problematic remnants of the synchronic view with which fusion emergence is somewhat still marred, namely the features that are tied to commitments about the existence of a discrete natural hierarchy, like level jump, (failure of) supervenience or high-level causation.

When it comes to localizing [TE] in the conceptual landscape of emergence, a second account onto which it is interesting to draw one's attention is Rueger (2000)'s rather idiosyncratic account. In a nutshell, it consists in asserting that a system's behavior S_2 at time t_2 is emergent on the same system's behavior S_1 at time t_1 iff the following thesis obtains:[10]

– (NOV$_d$) The phase space portrait that would describe S_2 during a time lapse where no environmental parameter is modified is not topologically equivalent to the phase space portrait that would describe S_1 during a time lapse where no environmental parameter is modified.

By topological non-equivalence between phase state portraits, it is meant that there is no smooth transformation that could convert the phase state trajectory of S_2 (during a time lapse where no environmental parameter is modified) into the phase state trajectory of S_1 (during a time lapse where no environmental parameter is modified). Typically, for S_2 to emerge on S_1, it is then necessary that, between t_1 and t_2, some control parameter reach a critical value corresponding to a bifurcation into the behavior of S. Qualitatively novel – hence emergent – behaviors are also considered by Rueger to be "irreducible", in the non-commonsensical "intralevel" sense that S_2's description doesn't "smoothly go over" into S_1's description in the appropriate limit of the control parameter.

[10]The way we formulate Rueger's novelty thesis here is somewhat cumbersome, but we don't know of a better way to phrase it, insofar as it rests on a confusion within Rueger's own account. At some point, Rueger indeed states that the *relata* of emergence are the behavior of a system at a given moment and the behavior of the *same* system at some earlier moment (typically when, in between, a critical point in a control parameter has been reached; see p. 300). But at some other places (p. 303), the *relata* of emergence are supposed to be a given system (for which a control parameter is at critical value) and *another* so-called "reference" system (for which the control parameter is *not* at critical value). Perhaps the fact that both interpretative options are available is the reason why Rueger doesn't explicitly formulate a dependence thesis, for it doesn't fully make sense in the second case. In any case, we embrace the first option here – viz. when the *relata* of emergence are successive behaviors of one and the same system –, for we think it captures Rueger's intuition and it involves embracing a dependence thesis along the lines of (DEP$_d$).

Rueger's account of emergence can be considered as diachronic and weakly epistemological.[11] It is epistemological, insofar as the criteria for emergence – topological non-equivalence and (intralevel) irreducibility – are about relations between *descriptions* of behavior. And it is epistemological in a weak sense, as it is compatible with in-principle – and actually even with *practical* – predictability or etiological explainability of the emergents from knowledge of their basis.[12] On this basis, one can consider [TE] as a reification or an ontologization of Rueger's emergence, where qualitative novelty between successive behaviors of a given system is not to be restricted to a mere descriptive feature, but has rather to do with genuine additions to the system's ontology. More precisely, instead of merely considering that, upon emergence, the phase space portrait of a system can be modified in a discontinuous way, [TE] requires that whole areas of the system's phase space, which were prohibited according to the natural laws governing the pre-emergence state, become accessible to the system upon emergence. Accordingly, the epistemological effect of such an ontological novelty is more drastic than the one associated with Rueger's account: with [TE], "intralevel irreducibility" amounts to in-principle unpredictability or etiological unexplainability from knowledge of any pre-emergence state. A consequence of [TE] being more ontologically engaged than Rueger's emergence is that it is more philosophically fruitful – it has higher stakes with regard to scientific practice – but less empirically mundane.

Finally, a third neighboring account of [TE] has recently been put forward by Hendry (2010). Hendry's account essentially rests on what he refers to as a "counternomic criterion", according to which the behavior of an emergent entity would be different were it determined only by the laws that govern its composing sub-entities. Framed along the lines we have chosen to use in this paper, Hendry's criterion is basically that a given entity E is emergent on a basis B as soon as the following obtain:

– (DEP$_s$) E is composed of B; and yet
– (NOV$_s$) New, *sui generis* laws govern the behavior of E, conferring it new, irreducible causal powers (and, in particular, downwardly oriented causal powers).

This is obviously an ontological account of synchronic emergence and, as such, Hendry is in need of operationalizing it in order to investigate its possible empirical

[11] Rueger himself qualifies his account as "weak", but this seems to cover what we refer to here as "epistemological". For him, "weakly" emergent properties are indeed properties that are also structural or "resultant", that is, properties that are defined in terms of lower-level properties and relations (in the diachronic, purely intralevel case, this notion is somewhat degenerate). This is in sharp contrast with ontological accounts that consider non-structurality as a necessary (but not necessarily sufficient) requirement for emergence (e.g. Humpheyrs 1997 in the diachronic case; O'Connor 1994 in the synchronic case).

[12] This can be seen on the basis of the empirical illustration of Rueger's diachronic emergence that is the originally damped oscillator that becomes undamped (so the control parameter – the damping – reaches its critical null value). There is emergence in this context, for the undamped oscillator has a phase space portrait that looks like an ellipse, whereas the phase space portrait of the damped oscillator is a topologically non-equivalent spiral. In spite of this emergence, one could thoroughly predict in practice what would be the behavior of an undamped oscillator from knowledge of the laws governing its damped counterpart.

exemplifications. This is achieved through a strategy we will also use in Section 4 with regard to [TE], namely recasting thesis (NOV$_s$) (in our case (NOV$_d$)) into terms about what captures the ontology of laws and powers – physicists would say "dynamics" – in physical systems, viz. their Hamiltonians (or, in our case, their Lagrangians). Here is (our reconstruction of) the core of Hendry's move in this respect:

– (C_1^H) The Hamiltonians capturing the dynamics of E and B are models of one and the same non-trivial theory T, namely quantum mechanics. Accordingly, E and B are both quantum-mechanical systems. And yet:
– (C_2^H) E's dynamics is captured by a "configurational" Hamiltonian, i.e. a Hamiltonian that is not resultant from – or is of an "independent kind" of Hamiltonian with regard to – the Hamiltonians that capture the dynamics of B.

According to Hendry, molecular structures meet his counternomic criterion and, in its wake, (C_1^H) and (C_2^H). Accordingly, molecular structures are ontologically emergent from a quantum mechanical basis made of electrons and nuclei interacting via Coulomb forces. In Hendry's view, molecular Hamiltonians are then cases of configurational Hamiltonians, and hence cannot be seen as merely resulting from underlying atomic Hamiltonians. This *formal* fact is appealed to in order to justify the *ontological* fact that molecules do have powers irreducible to that of their underlying elements – electrons and nuclei –, and the former obey *sui generis* laws that do not govern the behavior of the latter.[13] This can be empirically motivated: as cases of isomers attest, molecular structures play a causally relevant role in many chemical phenomena through their symmetry properties, although these properties cannot be traced to – nor recovered from – atomic considerations.[14]

In the terminology we are by now used to, Hendry's emergence can be considered as a form of synchronic, weakly ontological emergence. The fact that it is synchronic – and hence hierarchical – as well as ontological – and hence induces principled epistemic effects – is obvious from the reconstruction laid down above. It is also weakly ontological in the sense that it remains ontologically shallow with regard to other accounts of synchronic ontological emergence that involves non-structurality, a failure of supervenience, unrealized powers or a denial of physicalism.[15] In this respect, Hendry's emergence constitutes a synchronic counterpart to [TE], or the latter can be seen as a temporalization – i.e. a conversion of level discreteness into temporal ordering – of the former.

[13]Of course the fact that irreducible (classes of) Hamiltonians are supposed to mirror irreducible laws and powers is questionable, especially given that philosophers of science sometimes consider Hamiltonians as being mere models. We think nonetheless that this is a key component of Hendry's intuition about the relationship between physics and metaphysics.

[14]It is at this point that Hendry appeals to a specific construal of the Born-Oppenheimer approximation, which is systematically used in order to be able to solve molecular Schrödinger equations that otherwise would remain untractable. According to Hendry, far from being a mere approximation, this procedure leads to adding a structure to molecules by hand, insofar as it involves breaking the symmetry of what the solutions (of spherical symmetry) to the exact molecular Schrödinger equation would be.

[15]True, Hendry's account leads to a breaking of the causal closure of physics, but it remains consistent with the weaker principle that is the "ubiquity of physics", according to which "physical principles constrain the motions of particular systems though they may not fully determine them" (Hendry 2010, p. 188).

3.5 Transformational emergence: some advantages

In this final subsection before turning to providing empirical support for [TE], we stress the sense in which the account solves or avoids some traditional issues that surround the current debates about emergence, while keeping untouched the main stakes and intuitions that underlie most of the uses of the concept.

As we've already touched upon above, one first advantage of [TE] is that the account doesn't need to posit a discrete hierarchy of levels of nature, within which each system should find a proper place. Such a feature of [TE] actually constitutes the core of the perspective shift that the account captures, in the light of which the drive of emergence is to be found in the way some entities are temporally – instead of hierarchically – related. In a word, [TE] can thus perfectly tolerate a thorough hierarchical egalitarianism. Of course, this doesn't entail that organization, collective behavior, composition, etc., don't have an important role to play in the nature or in the representation of natural systems. Rather, these notions are secondary when it specifically comes to ascriptions of [TE], and can be seen under a deflationary, heuristically-inclined perspective about levels (e.g. construed in terms of scales; see Potochnik and McGill 2012). From the outset, such an ontological indifference about hierarchies makes [TE] well-suited for scientific contexts where level-talk always seems artificial and problematic, e.g. in physics.

As a beneficial side-effect of this, [TE] is not threatened by exclusion-style arguments, which can be devastating for synchronic versions of ontological emergence (see, for instance, Kim 1999). In a nutshell, those types of arguments are devised to show that the conjunction of some construals of (DEP$_s$) and (NOV$_s$) are plainly inconsistent with some highly plausible metaphysical theses like the causal closure of the physical world and the impossibility of systematic causal overdetermination. In the face of such worries, and if they don't want to simply get rid of emergence altogether by giving up either on (DEP$_s$) – hence moving towards dualism – or (NOV$_s$) – hence embracing reductionism –, synchronic emergentists tend to be forced to making bold moves like, to mention but one example, introducing an exotic and unprecedented, neither causal nor compositional, determinative relation like "machresis" (Gillett 2010). By contrast, [TE] is unconcerned with exclusion worries, for the simple reason that transformational emergents do not causally compete with their bases – so there isn't a risk of facing causal overdetermination –, since these are not simultaneously instantiated. More specifically, there is also no room in [TE] for the controversial notion of downward causation – or any peculiar declination of it, under the form of downward constraint, regulation or determination –, so there is no need to settle long-standing disputes about whether causation should be seen as productive or counterfactual, synchronic or diachronic, efficient or also formal, etc. in order to devise the account. As such, the *prima facie* plausibility of [TE] as a legitimate version of emergence undermines Kim's contention that "downward causation is the very raison d'être of emergence, but it may well turn out to be what in the end undermines it" (Kim 2006, p. 548).

It is important to note that, even if [TE] gets rid of tenets that play a crucial role in other forms of ontological emergentism, it preserves the most important intuitions of the doctrine. First, as far as causation is concerned, [TE] captures the idea that the advent of emergents makes a difference in the world, in the spirit of the so-called anti-epiphenomenalist *dictum* of Alexander – "To be real is [...] to possess causal powers" –, without having to adopt a dualistic stance. The new causal powers that arise through [TE] can even be said to be "irreducible" in most of the usual senses of the word. As a consequence of (NOV_d), and more particularly of the clause stating that transformationally emergent powers are *forbidden* to exist, according to natural laws, prior to their emergence, transformationally emergent powers are not identical to the powers of their bases, they are not a subset of the powers of their bases, they are not realized in the powers of their bases – so there is no issue of "causal inheritance" between them –, they are not the mere manifestation of some initially latent powers of their bases, etc.

Second, with respect to epistemological concerns, [TE] preserves the intuition that emergents are non deducible, not predictable or not explainable from complete knowledge of their bases. And what matters here is that [TE] does so without having to be committed to some problematic ideas like downward causation or that emergents are brute, *sui generis* empirical facts that must be "simply swallowed whole with that philosophic jam which Professor Alexander calls 'natural piety"' (Broad 1925, p. 55). As we will indeed see in Section 4, there can be a perfectly legitimate physical explanation of why transformational emergents are to appear at some point in the evolution of systems. Of course, the fact that one can explain the advent of transformational emergents seems to be in conflict with the idea that transformational emergents are in some sense unexplainable in principle. The conflict envisioned here is actually simply apparent : transformational emergents are unexplainable in principle *from knowledge of their bases*, but they are not unexplainable *tout court*, to the effect that [TE], in contrast with classic emergent evolutionism, does not have to fall into obscurantism.[16] Put differently, when it comes to providing illumination about the advent of transformational emergents, [TE] states that some explanatory paths are forever impracticable – typically the paths going directly from the bases to the emergents –, but *not* that no explanatory path whatsoever should be available.

To summarize, [TE] is a *bona fide* account of emergence that makes sense of the very hallmark of the notion, namely a reconciliation of theses (DEP) and (NOV). It does so in a diachronic fashion, consistently with some of the original intuitions that have historically led to the advent of the first emergentist doctrine. It also does so while preserving some widespread intuitions about emergence, viz. that emergents have irreducible causal powers and that, accordingly, they are epistemologically broken off from their bases. Finally, it does so while avoiding some traditional perplexities stemming primarily from the commitment to the existence of a discrete hierarchy of levels in nature. Now, all transformational emergence needs in order to be more than a nice philosophical tool is at least one concrete empirical exemplification. We provide one in what follows.

[16]That'd better be the case, for, as we will see, people won the Nobel prize for their discovery and account of phenomena that we will qualify as transformationally emergent.

4 Transformational emergence in the physical world

Our goal in this section is to put some scientific meat on the two requirements (DEP$_d$) and (NOV$_d$) using the theoretical clues (C$_1$) and (C$_2$) discussed above. We will show two things: there exists a *theoretical possibility* of [TE] in quantum physics (Section 4.1). In particular, we will show it in the context of quantum field theory, but it can also be achieved in non-relativistic quantum mechanics. We will then argue that such a case has been *experimentally produced* (Section 4.2). In other words, we believe there is empirical support for [TE].

4.1 Theoretical exemplification of transformational emergence

We will argue that if a certain physical transformation [**Tr**] could transform a physical system in state S_1, dynamically described by a model of quantum electrodynamics in 3+1 dimensions (QED_4), into the same physical system in a state S_2, dynamically described by a model of quantum electrodynamics in 2+1 dimensions (QED_3), then this transformation should be considered as leading to [TE] (Fig. 5).

The first step is to show that such a [**Tr**] meets (DEP$_d$) and, in particular, the clue (C$_1$) it is associated with. In this regard, we claim that QED_4 and QED_3 are both models of one and the same non-trivial theory T, namely QED, the general quantum field theory that characterizes electromagnetic interactions. QED is defined as the quantum field theory for which the following – not necessarily independent – requirements are true:

1. **Poincaré invariance**. The dynamics should be invariant under translation in time and space, rotations in space and boosts. Obviously the exact composition of the symmetry group will depend of the dimensionality of spacetime.
2. $U(1)$ **local gauge invariance**. The theory should be invariant under the following transformations: $A_\mu \rightarrow A_\mu + \frac{1}{e}\partial_\mu \Omega$, $\psi \rightarrow e^{i\Omega}\psi$, where A_μ is the gauge potential, ψ the matter field, e the electric charge associated with matter, and Ω a smooth function of the spacetime manifold. This symmetry is the signature of an electromagnetic interaction.

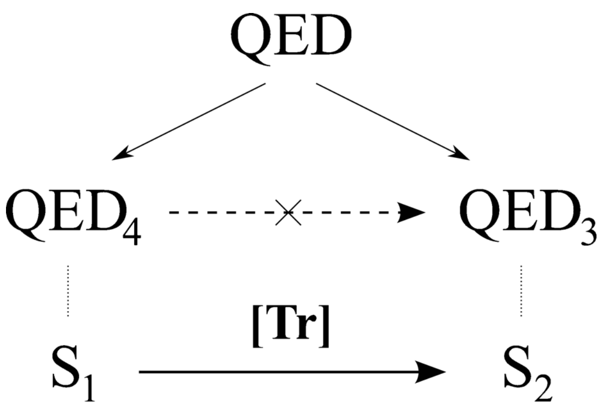

Fig. 5 Theoretical exemplification of [TE]

3. **Minimal coupling**. The interacting term in the Lagrangian density should be of the form $\mathcal{L}_I = -J^\mu A_\mu$, where J^μ is the charged particles' current. In other words, A_μ acts geometrically like a connection in a principal fibre bundle. This requirement aims to exclude exotic interaction terms that would not be assimilable to electromagnetism.
4. **The gauge equations are of the Maxwell type**. The equations of movement for the gauge field do not make reference to the vector potential but only to the the field-strength tensor. In 3+1 dimensions, we should obtain the Maxwell equations and the known Bianchi identity for the dual field-strength tensor.
5. **Usual matter solutions**. For example, in the case of massive spinor electrodynamics, the matter terms of the Lagrangian should be $\mathcal{L}_M = \bar{\psi}(i\partial\!\!\!/ - m)\psi$, where m is the matter mass. This choice guarantees that in absence of electromagnetic interaction, the Dirac equation will be the Euler-Lagrange equation. A similar requirement goes for other kinds of matter. This necessary condition excludes the possibility of introducing exotic matter directly into the Lagrangian. Possible new matter solutions could only come through new solutions to the same Lagrangian ingredients. This condition is not as fundamental as the others and could be relaxed.

Together, these five requirements theoretically circumscribe a type of phenomenon. Any model/theory falling under these describes a type of quantum electrodynamics phenomenon.

Obviously, QED_4 (electrodynamics of fermions) is a model of QED. But what about QED_3? Let us look at a particular model. What follows is the Lagrangian density of a QED_3 model for spinors:

$$\begin{aligned}\mathcal{L}_{QED_3} &= \mathcal{L}_{Matter} + \mathcal{L}_{Interaction} + \mathcal{L}_{Gauge}\\ &= \bar{\psi}(i\partial\!\!\!/ - m)\psi - J^\mu A_\mu + \frac{1}{4}(F_{\mu\nu})^2 + \frac{\theta}{4}\varepsilon^{\alpha\mu\nu}A_\alpha F_{\mu\nu},\end{aligned}$$

where θ is a constant and $\varepsilon^{\alpha\mu\nu}$ is the total antisymmetric tensor. The last term of the Lagrangian is called the Chern-Simons term.

Let us check whether this $\mathcal{L}$ meets the definitional requirements of QED. This Lagrangian density is clearly Poincaré invariant (1). $\mathcal{L}_M + \mathcal{L}_I$ is gauge invariant. As for $\mathcal{L}_G$, it transforms by a total derivative in the following way: $\mathcal{L}_G \to \mathcal{L}_G + \partial_\alpha(\frac{\theta}{4e}\varepsilon^{\alpha\mu\nu}F_{\mu\nu}\Omega)$. For vanishing $F_{\mu\nu}$ and Ω at the borders, this derivative equals 0 (2). We have a minimal coupling (3). The Euler-Lagrange equations for the gauge field are of the Maxwell type (4). Finally, $\mathcal{L}_M$ generates the Dirac equation if we use the 2-dimensional realization of the Dirac algebra for the γ matrix and a dimensionally-reduced ψ (5).

Before going further, let us note some characteristics of the Chern-Simons term:

– It is topological, that is, it does not depend on the spacetime metric and does not contribute to the energy. It only depends on the topology of the spacetime manifold.
– It generates a topological mass for the "photon" (spin 1 excitation states of the gauge field) (Deser et al. 1982).

– It endows the "charged particles" with magnetic fluxes (Deser et al. 1982). These composite flex-tube-particles have fractional statistics (Wilczek 1982). As far as we know, this possibility *does not exist* in 3+1 dimensions. We would even affirm that this modality should be interpreted strongly. If we cannot invoke a no-go theorem excluding the possibility of fractional statistics for all models of QED in 3+1 dimensions, the constraints put on this possibility by topological arguments in the context of non-relativistic quantum mechanics seem difficult to overcome (MacKenzie 2000). In consequence, we will assume that in 3+1 dimensions, only two kinds of statistics exist.[17]

Before discussing (C_2), let us address a worry. If we have good reasons to believe that QED_3 is well behaved, we have even better reasons to believe this is not the case for QED_4. Indeed, Haag's theorem asserts that no unitarily consistent representation of QED_4 could include interacting and free fields (Earman and Fraser 2006). However, both ingredients seem necessary, especially if one wants to interpret QED_4 in terms of particles. Our response is to notice that this result should not be interpreted as a logical inconsistency of QED_4 in general. The theorem does not exclude the possibility of finding adequate representations for free or interacting fields. It only asserts that these representations will not be unitarily equivalent. The remarkable success of certain applications of QED_4 proves that this model is at least consistent in limited domains. In this context, the more economical solution is to sustain a local approach of veracity (see Ruetsche 2015).

Now that we've shown that (C_1) holds and that, consequently, (DEP_d) can be supported, let us turn to (NOV_d). We need to show that, following (C_2) and with regard to the **[Tr]** envisioned here, it should not be possible to obtain QED_3 from QED_4 and, moreover, there is no continuous limit that could get QED_3 from QED_4, to the effect that one should not consider QED_3 as just being QED_4 with one less dimension. A 2+1-dimensional quantum system is not just a restricted 3+1-dimensional quantum system. This is due to the presence of a new topological term in the Lagrangian, depending on the dimensionality, which is responsible for the fact that QED_3 exhibit new topological orders, new possible states of matter, that are not accessible to systems modeled by QED_4.

Since topological orders are not as known as more traditional states of matter, let us say a few words to define what they are.[18] Topological orders are quantum states of matter that cannot be completely characterized by symmetry breaking of (local) order parameters. They are a subset of quantum orders in which all excitations have finite energy gaps. The associated quantum phase transitions are defined by the singularities of the ground-state energy as a function of the parameters of the Hamiltonian. This made Xiao-Gang Wen assert that "the concept of topological order is (partially) defined by ground-state degeneracy, which is robust against *any* perturbations that can break all of the symmetries" (2004, p. 342).

[17] Note that the long range interaction implied here does not contradict the second characteristics above because the interaction necessary for the fractional statistics is of the Aharonov-Bohm type and, in consequence, does not require displacement of energy.

[18] For a good survey of orders based on symmetry breaking, see Chaikin and Lubensky 1998.

As it has been well shown by studies in topological quantum field theory, even if the Chern-Simons term does not contribute to the Hamiltonian, it makes a significative difference to the ground-state degeneracy. In other words, it does contribute in a significant way to the structure of the ground state (Witten 1989; Fröhlich and King 1989). In fact, when the Chern-Simons term does not vanish, the physical system can exhibit new states of matter as a topological quantum fluid (Zee 2010, pp. 322–330). These states are not accessible to a physical system described by QED_4. Furthermore, these states are forbidden in QED_4, since they can exhibit fractional statistics. QED_4 is topologically limited to Bose-Einstein and Fermi-Dirac statistics.

In summary, if there exists a physical transformation [**Tr**] able to make a system in state S_1, for which the dynamics is described by QED_4, becomes in state S_2, for which the dynamics is described by QED_3 with a non vanishing Chern-Simons term, then this situation should be interpreted as a case of [TE].

4.2 The empirical support for transformational emergence

The fractional quantum Hall effect (hereafter FQH effect), discovered experimentally in 1982 by Tsui and Störmer, is, at first sight, a variation of the integer quantum Hall effect where the Hall conductance takes fractional values of e^2/h. All FQH states share the same symmetry. They possess a rich internal structure of patterns but cannot be qualified as solid. They are quantum fluids. These patterns are dynamical. The particular structure depends of the ground-state degeneracy which is robust against perturbation. According to Wen, this robustness is the sign of universal internal structures, namely topological orders (2004, p. 342).

A detailed description of the FQH effect is beyond the scope of this paper. We refer the interested reader to the relevant sections of Lederer (2015). Let us just say that in the initial state S_1, we start with an electron gas in a conductor. The behavior of this gas is modeled by QED_4. [**Tr**] consists in the experimental manipulations on this system in order to get one of the states exhibiting a FQH effect, typically we impose a very strong magnetic field perpendicular to the conductor, confine the electrons to a thin spatial slice by controlling the electronic band structure, work at a low enough temperature, inject a current and measure the resistance perpendicular to the current and the magnetic field. If the experiment is a success, the state S_2 obtained is a quantum fluid exhibiting fractional statistics.

It has been shown that a pure Chern-Simons theory (with only Chern-Simons terms) is an adequate effective theory to capture the universal properties of the FQH state (Schakel 2008). However, this theory is not rich enough to describe the complex dynamics involved in the effect. To do so, we have to add to the pure Chern-Simons theory an interaction term between the gauge field included in the Chern-Simons terms and the matter field. We have also to add kinetic/potential terms for the charged matter (Arovas et al. 1984; Wen 2004). In fact, this more complete effective theory is a particular case of QED_3 without the kinetic term for the electromagnetic field and with a connection to a classical external magnetic field (both facts are expected in the particular experimental conditions of the effect). Note again that in this model, even if we start with matter fields represented by spinors, we can obtain non fermionic (or even bosonic) solutions, namely anyons. This is why the discovery of the FQH effect was such a surprise. It is the manifestation in our 3+1-dimensional world of a kind of physics that theoretically could *only* exist in 2+1 dimensions. The FQH experimental setup is an exemplification of [**Tr**]. We interpret the fact that this effect has been experimentally produced as an empirical proof that a case of [TE] exists.[19]

Before going further, let us discuss some possible objections.[20] 1) We have described the FQH experimental setup as an exemplification of the passage from a state described by QED_4 to a state described by QED_3. But before the application of the magnetic field, the conductor is probably already planar. In these circumstances, why not have as a initial model a 2+1-dimensional model, and thus avoid the problems related to Haag's theorem discussed above? It might be possible to exemplify an appropriate modality difference for [TE] between two 2+1-dimensional models of QED. However, it is not clear how we could prove that the initial state is best described by a 2+1-dimensional model. A planar space seems necessary to be able to describe the FQH effect, and it is not the case for a very thin conductor.[21] Therefore, this seems less controversial to start from a 3+1-dimensional model. 2) In solid state physics, because of the nature of the systems studied, non-relativistic quantum models (finite number of degrees of freedom) are preferable to quantum field models (infinite degrees of freedom). This point does not mean that the FQH effect is not a case of transformational emergence, but that our theoretical representation of the transformation is maybe not the best one. As mentioned below, it is possible to make the same argument in the context of non-relativistic quantum mechanics. Nevertheless, it is much easier to show the modal difference between initial and final states in the context of a quantum field model. This is why we have made this choice. 3) QED_3 and QED_4 are Poincaré invariant. The setup of the FQH effect is not. In fact, non-trivial boundary conditions are essential features to understand certain aspects of the effect (Wen 2004, chapter 7). Are the chosen models of QED adequate for our purpose? We have not claimed that QED_3 and QED_4 model the FQH experimental setup in detail. But as we discussed above, they capture well the universal properties of the system in the initial and final states. If our goal was to describe specific aspects of the effect, for example to compute the ground state energy, we would have chosen other models.

We have explained this example using quantum field theory but a similar demonstration could have been done using non-relativistic quantum mechanics. The surprise would have been the same, as it is expressed by the following quote by Laughlin taken from his Nobel lecture (1999, p. 869):

[19] A similar claim has been made recently by Lancaster and Pexton (2015). According to them, fractional quantum Hall states can be said to be emergent in a sense "E_3" that they construe as a modification of Humphreys' original fusion account, where basal properties are not lost upon emergence, but rather become "inherently relational" (due to a specific kind of entanglement at play, viz. *long-range* entanglement that characterize topological states of matter). Such an account of the emergence involved in the fractional quantum Hall effect differs from ours in an important respect: as with fusion emergence, it is essentially holistic and hierarchical (with levels failing to be related by a relation of mereological supervenience).

[20] We thank an anonymous reviewer for having drawn our attention to these possible worries.

[21] More on the 2-dimensional idealization can be found in Shech (2015).

> The fractional quantum Hall state is not adiabatically deformable to any noninteracting electron state. I am always astonished at how upset people get over this statement, for with a proper definition of a state of matter and a full understanding of the integral quantum Hall effect there is no other possible conclusion. The Hall conductance would necessarily be quantized to an integer because it is conserved by the adiabatic map and is an integer in the noninteracting limit by virtue of gauge invariance and the discreteness of the electron charge. So the fractional quantum Hall state is something unprecedented – a new state of matter.

Before closing this subsection, we have to answer to a legitimate objection. Is a diachronic conception of emergence necessary to interpret the FQH effect or could we have used a synchronic one? After all, Laughlin himself seems to have such a conception in mind. Moreover, this option seems particularly appealing if we understand the FQH effect in terms of emergent entities rather than emergent states or dynamics. For example, if anyons are emerging from a basis of electrons, the QFH effect could be understood as a case of synchronic emergence. We have two objections to this line of thought.

- Examples of models where anyons are understood as collective behaviors of other entities or fields presume, to our knowledge, that the basis is 2+1-dimensional (e.g. see Jain 1989; Fröhlich 1989). This is not surprising since anyons cannot exist in 3+1 dimensions. This makes the status of the putative emergence basis a problem. Are anyons emerging from 3+1-dimensional or 2+1-dimensional electrons? It is only the later option that seems theoretically justified. But opting for it pushes us towards diachronic emergence. These 2+1-dimensional electrons are indeed not just 3+1-dimensional electrons with one dimension less, since the formers have the capacity to generate anyons, a capacity that the laters do not – and even, as we have seen, cannot – have. Consequently, the experimental confinement of 3+1-dimensional electrons is a transformation that generate new capacities. This confinement is the crucial first step to produce the emergent physics. It should be understood as a diachronic process of emergence.
- The second objection is even stronger. In the context of the FQH effect, the dependance relation between 2+1-dimensional electrons and anyons could go both ways, in the sense that not only one could conceive of anyons as collectives of 2+1-dimensional electrons, but 2+1-dimensional electrons could also be seen as the results of the composition of a certain number of anyons. For example, in a FQH state where anyons possess a charge of 1/3 of an electron and exhibit a statistics of 1/3, three of them can combine and form a bound object that would be identified to a 2+1-dimensional electron (Zee 2010, p. 326–327). This may be surprising but not totally unexpected in a quantum field context where particles are only types of fields configurations. What matters here is that such a fact is inconsistent with conceiving of the FQH effect as a case of purely synchronic emergence, for the dependance relation (DEP$_s$) usually appealed to in this context – e.g. supervenience or realization – doesn't allow for such a symmetry

between the putative synchronic emergents (anyons) and the putative emergence basis (2+1-dimensional electrons).

4.3 Another emergentist approach to the FQH effect

In a recent paper, Jonathan Bain (2013) used the FQH effect as a concrete example of emergence. His philosophical conception of what is emergence is not easy to pinpoint since he moves swiftly and seemingly between epistemological (non-deducibility) and ontological (dynamical distinctiveness) considerations. Nevertheless, his treatment of the FQH effect is relatively clear.

Bain notes that a pure Chern-Simons theory captures well the universal features of the FQH effect. It does not fully describe the effect but it is a good effective field theory (hereafter EFT). He also notes that the high-energy degrees of freedom of the system are more fully described by a type of nonrelativistic QED_3. For Bain, the emergence involved *is not* the process of passing from a state (best) described by QED_4 to a state (best) described by QED_3, but from a state (best) described by QED_3 to a state (best) described by a pure Chern-Simons theory (the EFT), that is from a theory with *a* Chern-Simons term to a theory with *only* Chern-Simons terms.[22] Why should we consider such a process as emergent?

First, the dependence clause is easily filled. The pure Chern-Simons theory is an effective theory of QED_3. The degrees of freedom of QED_3 can be identified as low-energy degrees of freedom of the pure Chern-Simons theory. In consequence, both theories describe the same kind of phenomena. It is the novelty clause that is more problematic. The theories/models involved are of course different. For example, one is purely topological, the other is not. Because of these apparent differences, Bain claims that both theories are dynamically distinct. But is it enough to have emergence? Indeed the EFT describes important features of the FQH effect, but who would claim that this pure topological theory describes more than the qualitative features of the dynamics? On the contrary, as we have argued in the preceding subsection, a more complete effective theory must include kinematic terms and therefore not be purely topological. Bain goes as far to say that:

> Dynamical distinctness, coupled with the formal distinction between the field ψ that encodes the degrees of freedom of the high-energy theory and the fields a_μ, $(A_\mu + a_\mu)$ that encode the degrees of freedom of the EFT, suggest that the later characterizes physical systems (i.e., two topological Chern-Simons fields) that are *ontologically distinct* from those characterized by the former (i.e., non-relativistic composite electrons). (Bain 2013, p. 264)

This quote is puzzling. What kind of dynamical distinctiveness and formal distinction are strong enough to be qualified as emergent? In what way is a formal difference ontologically significative? These questions are however unavoidable since too weak

[22] Because of the coupling to the external magnetic field, there is more than one Chern-Simons term.

of an answer will make emergence ubiquitous. For example, in many contexts, one can describe electrons with a scalar field. This is perfectly reasonable if the spin does not play a important role in the phenomenon under study. Are these cases emergent? They are in principle formally and dynamically distinct – in the sense that they do not exhibit the same statistics – from a description of the system that includes spinors. This is why we included a *modality aspect* to the novelty clause of [TE]. The new system should not only be distinct but in a certain way forbidden. The two theories used in Bain's reconstruction, QED_3 and the pure Chern-Simons theory, do not have this property.

5 Conclusion

In this paper, we have provided a new account of emergence – "transformational emergence" – that captures the very hallmarks of the notion in a diachronic, weakly ontological sense. As such, the proposed account encapsulates a perspective shift from the most widespread, hierarchical and synchronic view according to which "more is different", to a non-holistic and dynamical perspective in the light of which "*after* is different". As we have shown, this new way of looking at emergence achieves the *tour de force* of being at the same time empirically well-supported and faithful to most of the emergentist intuitions. Accordingly, [TE] turns out to be philosophically fruitful and scientifically respectful, and should therefore be taken as a new serious contender in the debates.

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