IOP Concise Physics

The Physics of Emergence

Robert C Bishop

Chapter 1

Brief history of the debate

1.1 The modern emergentists

Modern debates about emergence begin with the work of Samuel Alexander [1], Conway Lloyd Morgan [15], and C D Broad [7], known as the British emergentists. For instance, Broad described 'Pure Mechanism' as

> (1) a single kind of stuff, all of whose parts are exactly alike except for differences of position and motion; (2) a single fundamental kind of change, viz change of position. Imposed on this there may of course be changes of a higher order, e.g. changes of velocity, of acceleration, and so on; (3) a single elementary causal law, according to which particles influence each other by pairs; and (4) a single and simple principle of composition, according to which the behaviour of any aggregate of particles, or the influence of any one aggregate on any other, follows in a uniform way from the mutual influences of the constituent particles taken by pairs [7, pp 44–5].

Broad called the properties and effects produced by this kind of composition or aggregation *resultant* ('the whole is the sum of its parts'). Think of a vector whose magnitude and direction in Euclidean space is the resultant of its $\hat{x}$, $\hat{y}$, and $\hat{z}$ components. Any properties or effects that were not resultant in this sense were termed *emergent* ('the whole is different than the sum of its parts'). Some property or effect might be resultant, but could not be predicted from or explained by its constituent parts because of computational or other limits. This would be an example of epistemological emergence and ontological reductionism. In contrast, by 'emergent' Broad meant to distinguish those properties and events that in principle *could never* be derived from or explained by their constituents not because there were epistemic limitations; rather, because as a matter of ontology and logic, emergent properties and events are never implied or determined by the configuration

doi:10.1088/2053-2571/ab0b3ach1

and interactions of their constituents. These would be cases of ontological emergence seemingly of a radical type.

Emergentists, such as Broad, thought most of the properties of chemistry were emergent rather than resultant. They argued that the physics of atoms could not ontologically or logically reduce the properties of chemical compounds to the properties of constituent atoms. The codification of quantum mechanics (QM) in 1925 took the air out of the sails of the emergentists. As QM was developed and progress was made in relating chemical properties to quantum descriptions of atoms, it looked as if the physics of atoms could reduce chemical properties after all. This view was summed up by Paul Dirac in 1929: 'The underlying physical laws necessary for the mathematical theory of a large part of physics and the whole of chemistry are thus completely known, and the difficulty is only that the exact application of these laws lead to equations much too complicated to be soluble' [8, p 714]. It looked like there was only epistemological emergence, at best, reflecting human limitations on our computational and explanatory abilities.

1.2 Einstein, Pauli, and Schrödinger

Emergence doesn't completely disappear from physics discussions after the advent of QM, but there were no genuine reduction/emergence debates taking place. The following are brief summaries of how three important physicists thought about reductionism and emergence in the first half of the 20th century to give a flavor of how the topic was being addressed during this period.

1.2.1 Albert Einstein

Einstein's view of the Universe seems to combine ontological reductionism with epistemological emergence. For instance, in his address 'Principles of Research,' he said

> Man tries to make for himself in the fashion that suits him best a simplified and intelligible picture of the world; he then tries to some extent to substitute this cosmos of his for the world of experience, and thus to overcome it…. He makes this cosmos and its construction the pivot of his emotional life, in order to find in this way the peace and security which he cannot find in the narrow whirlpool of personal experience.
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> What place does the theoretical physicist's picture of the world occupy among all these possible pictures? It demands the highest possible standard of rigorous precision in the description of relations…. In regard to his subject matter…the physicist has to limit himself very severely: he must content himself with describing the most simple events which can be brought within the domain of our experience; all events of a more complex order are beyond the power of the human intellect to reconstruct [10, pp 2–3].

Here, Einstein focuses on scientific descriptions in a way that is clearly consistent with epistemological emergence. He goes on to say that such limited descriptions are based on general laws taken to be universally valid for all natural phenomena. ‘With them, it ought to be possible to arrive at the description, that is to say, the theory, of every natural process, including life, by means of pure deduction, if that process of deduction were not far beyond the capacity of the human intellect’ [10, p 3]. So Einstein thought that *in principle* it was possible to reduce the description of all natural phenomena—including life—to general, universal laws by means of deduction. A key assumption for this reductive possibility to be taken seriously, according to Einstein, is that ‘Our experience hitherto justifies us in believing that nature is the realization of the simplest conceivable mathematical ideas’ [9, p 17] because this would provide uniqueness for both the theoretical descriptions and their representations of what underlies experience. Short of this, physics only has descriptions that fit into a theoretical system of thought.

In a revealing exchange with Hedwig Born, Max Born’s wife, Einstein points out the limits of epistemological reductionism: Hedwig: ‘Well then, do you believe that it will be possible to depict simply everything in a scientific manner?’ His reply: ‘Yes,... that is conceivable, but it would be no use. It would be a picture with inadequate means, just as if a Beethoven symphony were presented as a graph of air pressure’ [6, p 158]. Einstein was quite aware of the limitations of scientific descriptions and their relations to other domains of life (e.g., scientific descriptions were ‘hopeless’ for explaining purpose [6, p 157]). Nevertheless, ontological reduction of all domains to the laws of physics remains a background assumption.

1.2.2 Wolfgang Pauli

Pauli generally sought to eschew ‘isms’ and was suspicious about validly drawing metaphysical conclusions from scientific investigation. Partly, this is because he believed that scientists must restrict their work to the reproducible:

> I include in this anything for the reproduction of which nature herself has provided. I do not assert that the reproducible in itself is more important than the unique, but I do say that the essentially unique lies outside the range of treatment by scientific methods; the aim and purpose of these methods is after all to discover and test laws of nature, upon which alone the attention of the investigator is directed, and must remain directed [18, pp 128–9].

This doesn’t mean that Pauli thought there were no metaphysical or epistemological implications of scientific understanding. For instance, he insisted that QM taught us that ‘the observer and the conditions of experiment’ must be included ‘in a more fundamental way in the physical explanation of nature.... It is therefore only the experimental arrangement that defines the physical state of the system, whose characterisation thus essentially involves some knowledge about the system’ [18, p 132]. The epistemological consequence is that to gain knowledge through an act of observation means the loss of some other knowledge of the system. Pauli, following Bohr, emphasized that the free choice of the observer was crucial to determining the particular knowledge obtained and what (complementary) knowledge was lost. The specification of the experimental arrangement and free choice of the scientist indicates an ‘indivisibility or wholeness’ to physical states.

The possible metaphysical implication of such holism is that ontological reductionism would fail; meaning that there was some form of ontological emergence for Pauli. This is apparent in his reflections on matter and mind, or *physis* and *psyche*, together with Carl Gustav Jung. Building on Bohr’s notion of complementarity, Pauli proposed a generalization, where ‘physis and psyche could be seen as complementary aspects of the same reality’ [17, p 260]. The implication of the quantum analogy is that the order of nature is neither material nor mental. There are two features of this analogy. One is that wave and particle descriptions in QM are complementary in the sense that they are mutually exclusive, yet both are needed to fully describe quantum phenomena. Such descriptions involve non-commutative observables and have a non-Boolean logical structure; similarly for material and mental aspects of reality. The other feature is quantum holism, the nonlocality inherent in quantum descriptions (e.g. entanglement). The domain underlying the material and the mental is modeled after quantum holism, where quantum objects are neither waves nor particles; similarly it is neutral with respect to the material and the mental.

Decomposition of this neutral domain produces distinguished material and mental aspects that become the phenomena of our experience. Neutral symmetry breaking is produced by decomposition processes or relations (the breaking of quantum holism by decomposition is a crucial part of this analogy). If distinguished material and mental aspects are generated by decomposition of a holistic neutral domain, *then the former do not stand in a reductive relationship to the latter*. Pauli’s view is one of ontological emergence of material and mental domains from the decomposition of a material/mental-neutral holistic domain.

1.2.3 Erwin Schrödinger

Schrödinger, along with being a founder of wave mechanics and the discoverer of quantum entanglement, had a deep, lifelong interest in biology. It is from his lectures on the physical basis of life that we can see his attitude towards emergence most clearly:

> What I wish to make clear…is, in short, that from all we have learnt about the structure of living matter, we must be prepared to find it working in a manner that cannot be reduced to the ordinary laws of physics. And that not on the ground that there is any ‘new force’ or what not, directing the behaviour of the single atoms within a living organism, but because the construction is different from anything we have yet tested in the physical laboratory [22, p 81].

Schrödinger’s idea can be illustrated with an analogy. An engineer might recognize and even know well each part that goes into a car, but the way in which the parts were organized made for a new construction that operated with entirely new functions not present in the parts. Similarly, the workings of cells, organs and organisms might be composed of molecules familiar to the chemist, but represent an organization that produces entirely new functions beyond the properties of chemical molecules.

Compare the decay events of radioactive materials or the interactions of large numbers of molecules in a gas with the functioning of cells and organs. One sees distinctly different kinds of order; the former produce a statistical kind of order whereas the latter exhibit a complex, sustained functional order matched to its environment. The quintessential example of biological order for Schrödinger was the chromosome[1].

Was Schrödinger offering an account of epistemological or ontological emergence of biological order? It turns out he was offering an epistemological account as the opening of his lectures made clear:

> How can the events in space and time which take place within the spatial boundary of a living organism be accounted for by physics and chemistry?
>
> The preliminary answer which this little book will endeavour to expound and establish can be summarized as follows:
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> The obvious inability of present-day physics and chemistry to account for such events is no reason at all for doubting that they can be accounted for by those sciences [22, pp 3–4].

Like Dirac, Schrödinger was confident that physics and chemistry could ontologically reduce biological order even if there were epistemological barriers to explaining how it arose.

1.3 The return of emergence

Einstein and Schrödinger held an epistemological view towards emergence along with an ontological reduction view (though Einstein is somewhat ambiguous on this latter point). Richard Feynman held a similar view regarding emergence and reductionism. Speaking of what he took to be a hierarchical organization of the world, he affirmed ontological reductionism: '[A]t one end we have the fundamental laws of physics. Then we invent other terms for concepts which are approximate, which have, we believe, their ultimate explanation in terms of the fundamental laws' [11, p 124]. According to Feynman, given the elementary particles and laws 'all of the low energy phenomena, in fact all ordinary phenomena that happen everywhere in the Universe, so far as we know, can be explained…. For example, life itself is supposedly understandable in principle from the movements of atoms, and those atoms are made out of neutrons, protons and electrons' (p 151).

Epistemological reductionism, however, breaks down:

> With the water we have waves, and we have a thing like a storm, the word 'storm' which represents an enormous mass of phenomena, or a 'sun spot', or 'star', which is an accumulation of things. And it is not worth while always to think of it way back. In fact we cannot, because the higher up we go the more steps we have in between, each one of which is a little weak. We have not

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[1] Schrödinger apparently was the first to propose the metaphor of genetic material as a 'code-script' in his 1943 lectures 'What Is Life?' [21].

> thought them all through yet…today we cannot, and it is no use making believe that we can, draw carefully a line all the way from one end of this thing [fundamental laws and particles] to the other [beauty, hope, evil], because we have only just begun to see that there is this relative hierarchy (p 125).

This is where epistemological emergence comes in for Feynman.

In contrast, Pauli held some kind of ontological emergence view. Still, these statements typically took place in discussions about physics or the sciences more generally, and these physicists were not engaging a reduction/emergence debate directly. With the successful development of quantum field theory and the great strides made in elementary particle physics from the 1950s into the 1970s, there seemed to be little motivation for thinking about emergence. Reductionism seemed to be on the steady march at least if high energy particle physics was the guide. This impression was punctured by Philip Anderson's publication of 'More is different: Broken symmetry and the nature of the hierarchical structure of science' in 1972 [2]. This seminal article reignited reduction/emergence debates.

Anderson began his article with the acknowledgment that 'the great majority of active scientists' accept reductionism [2, p 393]. He then pointed out a fallacy with some forms of reductive thinking: 'The ability to reduce everything to simple fundamental laws does not imply the ability to start from those laws and reconstruct the Universe' [2, p 393]. As it stands, rejecting this fallacy doesn't tell you whether the viable alternative is epistemological emergence or some more robust form of ontological emergence. Nor does the standard observation that as one finds higher and higher levels of complexity in nature, new properties and behaviors 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' [2, p 393] is admitted by all sides in these debates. The real question is whether this is due to epistemic and descriptive limitations (epistemological emergence) or due to transitions underdetermined by elementary particles and forces on their own (ontological emergence).

One way to see that Anderson had epistemic emergence in mind is his admission that various scientific disciplines could be organized hierarchically using the following scheme: 'The elementary entities of science X obey the laws of science Y' [2, p 393]. For example, the elementary entities of solid state and many-body physics obey the laws of elementary particle physics, the elementary entities of chemistry obey the laws of many-body physics, the elementary entities of biology obey the laws of chemistry, and so forth. If the phrase 'obeys the laws of' means *governed by*, then we are talking about ontological reductionism and epistemological emergence since the governing force of the laws translates from bottom upwards controlling everything above whatever the base or most elementary laws are. On the other hand, if 'obeys the laws of' means *constrained by*, then some form of ontological emergence not fully determined by the most elementary laws is possible. Anderson never used any language in his article indicating constraint was what he intended by 'obeys the laws of.' Indeed, he admitted that he fully accepted reductionism in the ontological sense [2, p 394].

Anderson subsequently affirmed this view in 2011: 'I was perhaps, at that time, no less a reductionist, nor less willing to mystify' [3, p 135]. His intention in 1972 was to point out that with respect to the descriptions of elementary particle physics even an ‘ideal Cartesian computer’ could not deduce all the consequences leading to phenomena such as superconductivity, stars and cells. New concepts are needed at different higher descriptive levels because these ‘allow enormous compression of the brute-force calculational algorithm, down to a set of ideas which the human mind can grasp as a whole’ [3, p 136]. The basic idea was to emphasize ‘the idea of intellectual autonomy of the two levels of understanding,’ elementary particle physics and condensed matter physics, respectively [3, p 137]. Emergence, for Anderson, is epistemological in this sense.

The main focus of Anderson’s article was symmetry breaking, what he called an emergent property in the sense that broken symmetry is distinct from the laws that carry symmetries. In the case of sugar molecules, for instance, parity symmetry has been broken so such molecules never undergo inversions and we always find such molecules in biological systems to always exhibit one chirality. Yet, when artificially prepared in thermal equilibrium, sugars appear in equal numbers of both chiralities on average. As another example, many crystals have elementary unit cells with a net dipole moment (pyroelectricity). Yet, if one applies an electric field to some of these kinds of crystals, this symmetry can be broken with the dipole moments reversing as the crystals seek their lowest energy state in the applied field.

Anderson draws three inferences from these kinds of examples of symmetry breaking. First, symmetry is important in physics. Second, there is no requirement that the internal structure of some piece of matter be symmetrical even if the total state is. This inference is an example of why he thinks that epistemological emergence is unavoidable: Starting with a quantum first principles description, there is no way to derive such a case. Symmetry breaking is as fundamental as the most elementary laws.

Third, ‘the state of a really big system does not at all have to have the symmetry of the laws which govern it; in fact, it usually has less symmetry’ [2, p 395]. As the size scale increases, there are many opportunities for systems to lose the full set of symmetries the underlying laws exhibit. Such symmetry breakings, Anderson maintained, aren’t violations of the underlying laws. These symmetry breakings lead to the whole becoming ‘not only more than but very different from the sum of its parts’ [2, p 395]. Nevertheless, it is worth noting something about Anderson’s cases of broken symmetry that will be important later—the role of *context*. The example of sugars, their formation in larger-scale organic systems, and the case of inverting crystalline cell organization of dipoles from pyroelectric to ferroelectric are both instances where crucial symmetries are broken by the context in which the molecules or dipoles find themselves.

1.4 Questioning the hierarchy

Anderson speaking of the scientific disciplines as falling into a hierarchy isn’t unique to him, but represents a very common view of the relationship of different sciences to each other (witness Feynman above). Hans Primas [19] raised questions about this kind of hierarchical ordering and its implications for reductionism.

Regarding epistemological reductionism—one version of which Primas cashed out as the deduction of higher-level laws from lower-level laws—he argued that one had to take into account the fact that for non-Boolean theories, such as QM, a restriction of the theory's domain of discourse often leads to the emergence of novel properties and new phenomena [19]. Consequently, early on Primas argued that epistemological reductions succeed in cases where 'The meaningful patterns and the function of a complex system (e.g. a flower) are intrinsically contained in the fundamental description but they manifest themselves only in a theoretical description having a very restricted domain of discourse. By restricting the domain of the fundamental theory, these phenomena can be derived' [19, p 283]. There are as many different possible restrictions as there are contexts of investigation, and the subtheories generated by these different restrictions can only be partially ordered if the fundamental theory is non-Boolean. If QM is fundamental, the special sciences would represent particular restrictions on the quantum domain of discourse; hence, these sciences could not be totally ordered in contrast to the oft-assumed hierarchy.

A further assumption for epistemological reductionism is that the fundamental theory's 'Universe of discourse' must be valid for all the domains of experience we wish to analyze. Only if the domain of discourse for the fundamental theory is adequate for these domains of experience (e.g. all the domains associated with the special sciences) can epistemological reductions be successful (again, witness Feynman above).

Assuming that states in the fundamental theory evolve under a one-parameter group, any subtheory generated by restricting the domain of discourse would inherit the states, s_t, and the time evolution of the universal theory. Generally s_t in the fundamental theory will not be an element of the theoretical domain of a subtheory. This depends on the specifics of the restriction in question, but has the implication that it isn't possible to fully order subtheories that are restrictions of the fundamental theory into a hierarchy. For instance, the reduction of biology to the fundamental theory isn't guaranteed to pass through chemistry (i.e. there is no reason biology should be reducible to chemistry to be reducible to the fundamental theory).

Note that the restrictions are never given by the fundamental theory, so this isn't the usual deductive reductionist scheme (e.g. [16]). Moreover, Primas explicitly acknowledged constraints on reduction that usually remain implicit:

> We cannot avoid that a scientific theory presupposes a more primitive metalanguage, makes implicit assumptions, and relies on tacit assumptions that are 'obvious and natural' to scientists but which nevertheless only reflect the investigator's cultural background. It is neither compulsory nor possible that all these rules are recognized as tentative working hypotheses but it is important that they are not changed in theory reduction [19, p 21].

These 'intuitive' notions aren't part of the theory proper, but every theory is embedded in such notions (e.g. [12]). Here, we see a hint that successful reductions are more delicate than normally discussed. More importantly, we will see that implicit conditions are a key to understanding the physics of emergence.

One example of restrictions on the fundamental theory, according to Primas, represents abstracting away from properties considered inessential for the particular experimental situation. This is a consistent theme for Primas [19–21] and connects the idea of epistemological reduction with the context- or interest-relative focus of scientists. Every experimental situation or operationalization implies a classification or grouping of phenomena 'into disjoint [equivalence] classes on the basis of certain attributes they have in common.' Consequently, 'Different points of view correspond to different abstractions, different lists of experimental procedures, hence different pattern recognition methods and different empirical domains' [19, p 293]. This line of thinking implies that a particular experimental situation corresponds to a specific restriction of the empirical domain of discourse of the fundamental theory. Concrete contexts, then, play a crucial role in the formulation of any restrictions and consequent subtheories.

The conditions theory reduction has to meet, then, are quite stringent. Primas argued that the restrictions placed on the fundamental theory to describe concrete observable contexts always generated new phenomena, not properly part of the empirical domain of the fundamental theory, as well as involving novel concepts not part of the apparatus of the fundamental theory [19–21]. One reason is that the most fundamental, universal theory would lack any empirical domain because it represented 'the undivided wholeness of reality' [19, p 297]. To derive specific empirical properties and novel concepts associated with a particular level of description requires information from that level to generate the relevant abstraction from the holism of the universal theory. Early on, Primas called this *weak reductionism*: 'The weak form of reductionism does not require that the laws in the more complex field can be deduced from the fundamental laws of physics but only that they do not violate them. It allows constraints which do not belong to the reducing theory but nevertheless are compatible with it' [19, p 281].[2] With later reflection it was recognized that these so-called weak reductions were actually examples of a largely unrecognized form of emergence [4, 5, 21].

1.5 Weinberg and the response to P W Anderson

For Stephen Weinberg, reductionism is an 'attitude toward nature itself.' What kind of attitude? 'It is nothing more or less than the perception that scientific principles are the way they are because of deeper scientific principles (and, in some cases, historical accidents) and that all these principles can be traced to one simple connected set of laws' [23, p 52]. As for ontological reductionism, he is honest about its implications: 'The reductionist worldview is chilling and impersonal. It has to be accepted as it is, not because we like it, but because that is the way the world works' [23, p 53]. And Weinberg believes that nature is reductively structured. Epistemological reductionism may break down—chemists may have to explain the

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[2] One other limitation of approaches such as Primas' is the assumption that theories can be formalized as sets of proposition. This is rarely the case in the sciences (even in physics). As we will see, there are other ways to maintain rigor without such an assumption (e.g. [18, pp 298–300], where Primas discusses the case of temperature referring to observables rather than sets of propositions).

workings of DNA in terms of chemical concepts and principles. Nevertheless, 'there are no autonomous principles of chemistry that are simply independent truths, not resting on deeper principles of physics' [23, fn, p 53].

This reference to 'autonomous principles' and 'independent truths' is revealing because this is the kind of language that describes the radical emergentist view. As indicated earlier, the radical view is the usual contrast class in reduction/emergence debates, and it serves as the foil for Weinberg's defense of ontological reductionism. This observation is significant because he never offers an argument or evidence supporting ontological reductionism. It is possible that the sheer implausibility of radical emergence along with an intuition that the sciences are hierarchically ordered—even if that intuition isn't well founded—are the convincing reasons for his belief in ontological reductionism.

Weinberg also agrees with P W Anderson, Feynman and others that epistemological reductionism fails, hence his view that we will always need other branches of physics than just elementary particle physics along with the other sciences. So what was the fuss with Anderson about? Research funding and priorities. Anderson was leading the charge in the 1990s against the Superconducting Super Collider in favor of prioritizing condensed matter and other fields of physics. The arguments turned on 'fundamentality', a vexed concept as we will see. Weinberg argued that elementary particle physics was fundamental, hence deserving a privileged place in research funding priorities, while Anderson was arguing that other fields of physics were just as important to both understanding nature and discovering applications, hence were equally worthy of funding rather than being squeezed out by elementary particle physics.

Weinberg's defense of elementary particle physics being fundamental was explicitly rooted in epistemological reductionism (though a commitment to ontological reductionism leads to the same conclusion):

> The reason we [elementary particle physicists] give the impression that we think that elementary particle physics is more fundamental than other branches of physics is because it is. I do not know how to defend the amounts being spent on particle physics without being frank about this. But by elementary particle physics being more fundamental I do not mean that it is more mathematically profound or that it is more needed for progress in other fields or anything else but only that it is closer to the point of convergence of all our arrows of explanation [23, p 55].

This is an interesting motivation because Weinberg clearly admits that epistemological reductionism often fails: We usually cannot explain phenomena such as molecular shape, chemical reactions, biological function, plate tectonics, and so forth, from elementary particle physics. As he notes, 'whether or not the discoveries of elementary particle physics are useful to all other scientists, the principles of elementary particle physics are fundamental to all nature' [23, p 57].

Weinberg clearly respects other fields of physics and agrees that several, such as condensed matter physics, were underfunded in the 1980s and 1990s. But the explanatory arrow is revealed to be crucial to his sense of fundamentality. Weinberg moves from 'the properties of any molecule are what they are because of the properties of electrons and atomic nuclei and electric forces' to 'This has been *partly explained* by the standard model of elementary particles, and now we want to take the next step and explain the standard model and the principles of relativity and other symmetries on which it is based' ([23, p 58], emphasis added). The arrow of explanation points 'downward' giving elementary particle physics a privileged place in the physics pantheon.

Yet, there are limits to this privileged position, according to Weinberg. On the one hand, condensed matter physicists are seeking to understand the phenomenon of high-temperature superconductivity; meanwhile, at the time he was writing *Dreams of a Final Theory*, particle physicists were seeking to understand the origin of elementary particle masses. A comparison of these two projects brings out the sense of privilege Weinberg thinks elementary particle physics has:

> The difference between these two problems is that, when condensed matter physicists finally explain high-temperature super-conductivity—whatever brilliant new ideas have to be invented along the way—in the end the explanation will take the form of a mathematical demonstration that *deduces the existence of this phenomenon from known properties of electrons, photons, and atomic nuclei*; in contrast, when particle physicists finally understand the origin of mass in the standard model the explanation will be based on aspects of the standard model about which we are today quite uncertain, and which we cannot learn (though we may guess) without new data from facilities like the Super Collider ([23, p 59], emphasis added).

There are two interesting things to note about what Weinberg says here. First, the explanatory arrow for high-temperature superconductivity points 'downward' towards elementary particle physics. Second, there is a statement of certainty that the properties of elementary particles and nuclei will be the exhaustive base from which the explanation will come; no allowance is made for any other factors than these to be relevant. Both of these points will be questioned for physics in subsequent chapters.

1.6 Universality and independence

In a much-discussed paper Robert Laughlin and David Pines also support a hierarchical view of theories, with each theory in the hierarchy 'emerging from its parent and evolving into its children as the energy scale is lowered' [14, p 30]. This hierarchy, nevertheless, isn't fully ordered as the relations involve renormalization and asymptotic singularities. This parallels Primas' case against the fully ordered hierarchy of theories. Moreover, Laughlin, as with P W Anderson before him, isn't convinced that the explanatory arrow points towards elementary particle physics with the same confidence as Weinberg.

Yet, Laughlin also holds to a form of ontological reductionism coupled with epistemic emergence. For instance, he endorses the view that 'the equation of conventional nonrelativistic quantum mechanics' [Schrödinger's equation] 'describes the everyday world of human beings—air, water, rocks, fire, people, and so forth' [14, p 28]. For him, 'All physicists are reductionists at heart, myself included. I do not wish to impugn reductionism so much as establish its proper place in the grand scheme of things' [13, p xv]. Indeed, in his 2005 book he claims, 'I prefer the more physical view that politics, and human society generally, grow out of nature and are really sophisticated high-level versions of primitive physical phenomena. In other words, politics is an allegory of physics, not the reverse' [13, p 210]. This is ontological reductionism at its boldest.

Epistemological emergence turns on the failure of epistemological reductionism, the failure to be able to trace out all the 'deductive links' from QM to the phase diagram of liquid ^{3}He, the entire phenomenology of high-temperature superconductors, the low-energy excitations of conventional superconductors and crystalline insulators, the electron mass and charge, the value of Planck's constant and much more [13]. For the specific example of high-temperature superconductivity, 'deduction from microscopics has not explained, and probably cannot explain as a matter of principle, the wealth of crossover behavior discovered in the normal state of the underdoped systems, much less the remarkably high superconducting transition temperatures measured at optimal doping' [14, p 30].

The failure of epistemological reduction leads to epistemologically emergent phenomena: 'The emergent physical phenomena regulated by higher organizing principles have a property, namely their insensitivity to microscopics, that is directly relevant to the broad question of what is knowable in the deepest sense of the term' [14, p 29]. These higher organizing principles and the phenomena they engender are *protectorates*: 'The crystalline state is the simplest known example of a quantum protectorate, a stable state of matter whose generic low-energy properties are determined by a higher organizing principle and nothing else' [14, p 29]. Low-energy excited quantum states in such systems as quantum Hall states, superconductors, band insulators, ferromagnets, superfluids in Bose liquids, and atomic condensates, are

> particles in exactly the same sense that the electron in the vacuum of quantum electrodynamics is a particle: They carry momentum, energy, spin, and charge, scatter off one another according to simple rules, obey Fermi or Bose statistics depending on their nature, and in some cases are even 'relativistic,' in the sense of being described quantitatively by Dirac or Klein–Gordon equations at low energy scales. *Yet they are not elementary, and, as in the case of sound, simply do not exist outside the context of the stable state of matter in which they live.* These quantum protectorates, with their associated emergent behavior, provide us with explicit demonstrations that the underlying microscopic theory can easily have no measurable consequences whatsoever at low energies. The nature of the underlying theory is unknowable until one raises the energy scale sufficiently to escape protection ([14, p 29], emphasis added).

Laughlin and Pines go on to note that ‘self-organization and protection are not inherently quantum phenomena,’ and that ‘quantum and classical protectorates… are governed by emergent rules ’ [14, p 29].

These protectorates can only exist in a particular, concrete context, where the higher organizing principles operate in a way that is independent of the microdetails even though these principles arise out of the lower-level laws on Laughlin’s view. And there is no way to deduce either the organizational principles nor the protectorates from lower-level laws. Even the hierarchy of theories referred to above likely cannot be deduced from first principles without knowledge gained from experiments in the different energy regimes.

Similar to P W Anderson, Laughlin argues for ontological reductionism and epistemological emergence. Yet, a fundamental ambiguity remains in Laughlin’s account. There is interplay between the basic physics entities and laws, on the one hand, and the emergent organizational principles on the other. The higher ordering principles arise spontaneously out of these underlying laws, yet are independent of those laws. These organizing principles have universality in that a subsequent change in the lower laws would not affect the higher ordering principles. For example, Laughlin thinks the laws of hydrodynamics would remain unchanged if the underlying laws were modified [13, p 207]. And clearly this universality and independence of the ordering principles with respect to the underlying laws is epistemological emergence for Laughlin. But he also seems to treat it as if it is ontological, in other words, a violation of ontological reductionism. Indeed, Laughlin claims that there is both an ‘epistemological barrier’ to understanding how the ordering principles emerge from underlying laws as well as for understanding whether the latter are more fundamental than the former. He suggests this latter barrier is physical [14, p 207]. This ambiguity will be resolved in coming chapters.

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