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The Physics of Emergence (Second Edition)

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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 [21], and C D Broad [10], 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. [10, 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 not resultant in this sense are termed **emergent** (‘the whole is different than the sum of its parts’). Some property or effect might be resultant but couldn’t 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

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never implied or determined by the configuration and interactions of their constituents. These would be cases of ontological emergence seemingly of a radical type.

Emergentists, such as Broad, think most of the properties of chemistry are emergent rather than resultant. They argue the physics of atoms cannot 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 developed and made progress 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 leads to equations much too complicated to be soluble’ [12, 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 combines 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.
>
> 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. [14, 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' [14, p 3]. 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' [13, 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' [9 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 [9 p 157]). Nevertheless, ontological reduction of all domains to the most general laws of physics remained 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 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. [24, pp 128–9]

This doesn't mean Pauli thought there were no metaphysical or epistemological implications of scientific understanding. For instance, he insisted 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' [24, p 132]. The epistemological consequence? To gain knowledge through an act of observation means the loss of some other knowledge of the system. Pauli, following Bohr, emphasized 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 the failure of ontological reductionism; 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’ [23, 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 (appendix A.1); 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; it’s similarly 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 yet with a material-mental correlation we experience in our ordered world.

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. [29, 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 are organized make for a new construction operating with entirely new functions not present in the parts. Similarly, the workings of cells, organs and organisms are composed of molecules familiar to the chemist but represent an organization producing 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 make 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:
>
> 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. [29, 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' [15, 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

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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?' [29].

atoms are made out of neutrons, protons and electrons' [15, 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 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. [15, 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 appeared 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 in physics.

Anderson begins with the acknowledgment that 'the great majority of active scientists' accept reductionism [2, p 393]. He then points 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 has 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 have 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.[2] 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 (1972) never uses any language indicating constraint as the meaning of 'obeys the laws of.' Indeed, he fully accepts 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 even an 'ideal Cartesian computer' cannot use the descriptions of elementary particle physics to 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]. He emphasizes '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 calls 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 is broken so such molecules never undergo inversions and we always find such molecules in biological systems exhibiting only 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 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 maintains, 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's worth noting something about Anderson's

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[2] This is the governance metaphor for laws and forces that is quite prevalent in physics textbooks and articles. More on this metaphor later.

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 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

Conceiving of scientific disciplines as falling into a hierarchy isn't unique to Anderson but represents a very common view of the relationship of different sciences to each other (witness Feynman above). Chemical physicist Hans Primas [25] 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 consider for non-Boolean theories, such as QM, that a restriction of the theory's domain of discourse often leads to the emergence of novel properties and new phenomena [25]. Consequently, early on he 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' [25, 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 couldn't 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. [22]). 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. [25, p 290]

These 'intuitive' notions aren't part of the theory proper, but every theory is embedded in such notions (e.g. [18]). 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 [25–27] 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' [25, p 293]. This line of thinking implies 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 must meet, then, are quite stringent. Primas argued the restrictions placed on the fundamental theory to describe concrete observable contexts always generates 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 [25–27]. One reason is that the most fundamental, universal theory would lack any empirical domain because it represented 'the undivided wholeness of reality' [25, 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' [25, p 281].[3] With later reflection it was

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[3] One other limitation of approaches such as Primas' is the assumption that theories can be formalized as sets of propositions. This is rarely the case in the sciences (even in physics). As we'll see, there are other ways to maintain rigor without such an assumption (e.g. [26 pp 298–300], where Primas discusses the case of temperature referring to observables rather than sets of propositions).

recognized that these so-called weak reductions were examples of a largely unrecognized form of emergence [7, 8, 27].

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’ [30, 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’ [30, p 53]. Weinberg believed that nature is reductively structured. Epistemological reductionism may break down—biochemists may have to explain the workings of DNA in terms of biochemical concepts and principles. Nevertheless, ‘there are no autonomous principles of chemistry that are simply independent truths, not resting on deeper principles of physics’ [30, fn, p 53].

This reference to ‘autonomous principles’ and ‘independent truths’ is revealing because it’s the language characteristic of 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. Yet, 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—were the convincing reasons for his belief in ontological reductionism.

Weinberg also agreed with P W Anderson, Feynman and others that epistemological reductionism often 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 P W 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’ll 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. [30, 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' [30, p 57].

Weinberg clearly respected other fields of physics and agreed 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' [30, p 58]. The arrow of explanation points 'downward' giving elementary particle physics a privileged place in the physics pantheon.

Still, 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* [30], 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. ([30, p 59])

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 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’ [20, 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 describes the everyday world of human beings—air, water, rocks, fire, people, and so forth’ [20, 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’ [19, 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’ [19, 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 [19]. 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’ [20, 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’ [20, 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’ [20, 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. [20, p 29]

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' [20, 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 neither the organizational principles nor the protectorates are deducible 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 maintains the laws of hydrodynamics would remain unchanged if the underlying laws were modified [19, 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's 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 [20, p 207]. This ambiguity will be resolved in coming chapters.

1.7 Wheeler and the foundations of physics

Inevitably with reduction-emergence debates, one worries whether we're dealing more with philosophy than physics. Yet, philosophy and physics have been joined at the hip since ancient Greek studies in natural philosophy despite modern attempts to keep them separate. And at least with the advent of QM, exploring the foundations of physics has been an important task. As John Archibald Wheeler, my physics teacher, was fond of saying, 'Philosophy is too important to leave to the philosophers' [32, p 404]!

In 'Law without Law,' Wheeler argued that observer-participancy is central to quantum measurements and the registration of quantum phenomena. For instance, in a two-slit experiment the experimenter sends an electron through the apparatus but makes a choice as to whether one slit is open or two. The experimenter's choice of apparatus configuration is determinative of whether particle-like or wave-like behavior manifests. In the case of a beam-splitter experiment, the absence of the half-silvered mirror before the photon reaches the detector determines that both detectors fire with an interference pattern and relative phase information—the photon travels 'both paths' in the apparatus—or whether the photon travels only 'one path' leading to only one detector firing. Again, the experimenter's choice of apparatus configuration is determinative of whether 'one path' or 'both paths' behavior manifests.

But for Wheeler, who was deeply influenced by Niels Boh, it is imprecise to speak of 'which path' electrons or photons take in such experiments: Until an irreversible act of amplification—a detection event—takes place, there is nothing definitive of the quantum phenomenon under investigation. As Wheeler argued, in the delayed-choice version of these experiments, the experimenter's choice now 'has an undeniable part in bringing about that which appears to have happened [in the past]' [33, p 194].[4] This is the 'participatory Universe,' though, as he rightly argued, consciousness is not relevant to quantum processes themselves; only irreversible acts of amplification—physical acts— taking place in these experiments are relevant. Somehow—and Wheeler emphasized we were far from understanding the how —'billions upon billions of acts of observer-participancy play into the Universe as we experience and study it today' [33, p 199], and he argued that this extended to the possibility that the laws of Nature were not fixed in stone but have changed over time [32].

Wheeler also insisted that the Universe and observer-participancy wouldn't be a bottom-up affair. The central principle for the existence of anything 'in the era of the quantum…[is] the necessity to draw the line between the observer-participator and the system under view' [33, p 206]. This is illustrated by his insistence that the simple first principle from which we can derive the quantum should take the role of the observer in QM as 'the most important clue we have…Except it be that observership brings the Universe into being what other way is there to understand that clue?' [31, p 28]. Even the laws of physics take shape through myriad acts of

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[4] Wheeler's predictions for such delayed-choice experiments have been confirmed (e.g., [28]).

observer-participancy stretching back eons of time, according to Wheeler [31–33]. Hence, nothing is ontologically constructed solely bottom-up for him (e.g. [34]).

1.8 Reductive methods versus reductionism

Finally, it's not uncommon for people to confuse the deployment of reductive methods in scientific investigation with ontological reductionism. Reductive methods break wholes or larger complexes down into their constituent parts to understand those parts and help explain the properties and behaviors of larger systems. There are methods in physics that are reductive in this sense, though many other methods are not.

Some, such as physical chemist Peter Atkins, characterize scientific inquiry as reductionistic confusing methods and ontological reductionism: '…science, and the tracing of phenomena to its atomic roots that epitomizes reductionism, should be regarded as supreme…Scientists, with their implicit trust in reductionism… are successfully treading the path of reductionism. They are exposing the simple essentials of the world, seeing its mechanism, seeing that they can comprehend its actions, and seeing that they can understand its origin' [4, pp 122–4].

It is beyond dispute that physicists do deploy reductive approaches as some of their explanatory tools. It is disputable that physicists, let alone other scientists, only deploy reductive methods and that scientists embrace reductionism as a group. For instance, we've seen that P W Anderson, McLaughlin, and Weinberg are ontological reductionists yet the former two pursue non-reductive methods in their condensed matter research. Meanwhile, Pauli, Primas and Wheeler aren't ontological reductionists.

Atkins clearly is enamored of reductionism, thinking that scientific investigation 'shows that the world is simple.' Critiquing scientists who think otherwise, he writes,

> Scientists are often overawed by the complexity of detecting simplicity. They look at the latest fundamental particle experiment, see that it involves a thousand kilograms of apparatus and a discernible percentage of a gross national product, and become thunderstruck. They see the complexity of the apparatus and the intensity of the effort needed to construct and operate it, and confuse that with the simplicity that the experiment, if successful, will expose. [4, p 126]

This critique is as problematic as it is revealing. The complexities of the standard model of particle physics, quantum electrodynamics and chromodynamics, among other features, are, well, very complicated! There is nothing simple about our theories of elementary particle physics or the constituents of such theories. Nor is it plausible that scientists get 'thunderstruck' by complex apparatus and thereby become convinced nature is complex. Atkins follows a reductionist philosophy that building blocks must somehow be simpler than the structures they take part in as illustrated by his oversimplified account of how macroscopic phenomena described by classical mechanics arises from the wave-like nature of particles [5, pp 53–4]. Is this the pattern physics reveals to us or is this the result of an underlying metaphysical commitment to ontological reductionism? A similar question arises for how he discusses laws and their origins. As with P W Anderson, Atkins relies on the governance metaphor [e.g. 5, 6] typically deployed by those who endorse ontological reductionism.[5]

Like Atkins, elementary particle physicist Sabine Hossenfelder endorses epistemic emergence and ontological reductionism [16, pp 44–5]. She likewise confuses reduction as method with reductionism as metaphysics. ‘As a physicist, I am often accused of reductionism, as if that were an optional position to hold. But this isn’t philosophy—it’s a property of nature, revealed by experiments’ [16, p 45]. What Hossenfelder means is that our experimental methods have uncovered ‘levels’—objects such as tables are made of molecules, molecules are made of atoms, atoms are made of electrons, protons, and neutrons, nucleons are made of quarks and gluons. ‘Effective field theory tells us we can, in principle, derive the theory for large scales from the theory for small scales, but not the other way round’ [16, p 46]. This is ontological reductionism with epistemic emergence, not unlike P W Anderson and Laughlin, though as we saw with Primas, it’s not possible to derive theories for large scales without drawing on factors from those scales. Only a metaphysical commitment to ontological reductionism would lead one to think that we can do this ‘in principle.’

Hossenfelder also believes the complex behavior we see in Nature is the result of simple laws. For example, ‘atoms follow remarkably simple laws—so simple that atoms can be neatly classified in the periodic table based solely on the electrons’ shell structure,’ and ‘Large things are made of smaller things, and the laws for the larger things follow from the laws for the smaller things. The surprise is that the laws for the large things are so simple’ [16, pp 43–4]. Though she qualifies this belief by raising questions about whether beauty and simplicity are guides to finding true laws of Nature and theories in *Lost in Math: How Beauty Leads Physics Astray* [16]. Similarly, she also adopts the governance metaphor for laws [16 pp xi, 4, 17, 132] as any good reductionist would.

Hossenfelder regularly confuses ontological reductionism with methods of scientific investigation. Although she believes ‘the properties of the constituents of a system determine how the system works’ [17], this isn’t a scientific claim; it’s a metaphysical belief about how nature is structured.[6] Whether the beauty of this belief is substantiated by the patterns in physics and research methods is a question explored in the succeeding chapters of this book.

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[5] It is worth noting that Atkins eschews ‘the vexed question of interpretation’ of the laws of Nature [6, p 40], but his discussion of laws is deeply shaped by interpretation such as the deployment of the governance metaphor. Although claiming ‘interpretation is secondary to the laws that govern the behavior of entities’ [6, p 40], Atkins doesn’t realize we cannot understand laws apart from interpreting their meaning and implications. Laws and their interpretation go hand in hand.

[6] Hossenfelder believes ‘the whole history of science until now has been a success story of reductionism. Biology can be reduced to chemistry, chemistry can be reduced to atomic physics, and atoms are made of elementary particles’ [17]. Joining Atkins, only someone wedded to ontological reductionism would misinterpret the history of scientific investigation this way and repeat the oversimplified levels picture of Nature.

By contrast, cosmologist Sean Carroll is vague about distinctions between ontological reductionism and reductive methods. A typical statement of his reductionism is

> The reason why we are all born young and die older; the reason why we can make choices about what to do next but not about things we've already done; the reason why we remember the past and not the future—all of these can ultimately be traced to the evolution of the wider universe, and in particular to conditions near its very beginning, 14 billion years ago at the Big Bang…We look at the world around us and describe it in terms of causes and effects, reasons why, purposes and goals. None of those concepts exists as part of the fundamental furniture of reality at its deepest. They emerge as we zoom out from the microscopic level to the level of the everyday. [11, p 54]

He defines a fundamental category as anything 'playing an essential role in our deepest, most comprehensive picture of reality' [11, p 17]. What exists at this deepest, fundamental level? The elementary laws, fields or particles forming the configuration of the initial Universe. Carrol explicates this in a 'principle of conservation of information': 'each moment contains precisely the right amount of information to determine every other moment.' By information, he means a microscopic specification of the state, 'the complete specification of the state of the system, everything you could possibly know about it. When speaking of information being conserved, we mean literally all of it' [11, p 34]. Carroll treats this principle as a conservation law: 'Information about the precise state of the Universe is conserved over time; there is no fundamental difference between past and future' [11, p 60]. What accounts for the difference between past and future that we experience? '[T]he fact that the Universe runs according to time-symmetric laws [and] by the additional fact that the past had a lower entropy than the future' [11, p 61].[7]

This kind of metaphysical view leads Carroll to claims such as '"memories" and "causes"' aren't pieces of our fundamental ontology describing our world that we discover through careful research' [11, p 66]. But what kind or research? He describes what he calls the 'scientific method' as 'methodological empiricism,' meaning 'knowledge is derived from our experience of the world, rather than by thought alone. Science is a technique, not a set of conclusions. The technique consists of imagining as many different ways the world could be (theories, models, ways of talking) as we possibly can, and then observing the world as carefully as possible' [11, pp 133–4]. Yet this is all very abstract and vague like the term 'scientific method' itself in his book. Scientists avail themselves of many methods, but Carroll

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[7] K-systems—systems where the current state is independent of information in past states—are counter-examples to Carroll's law of conservation of information. There are quantum K-systems, hence even at the microscopic scale, information isn't conserved as he imagines. More on K-systems later.

never gives any detailed discussion of what he has in mind. It is hard to resist the conclusion that his reductionist commitments color his understanding of scientific research.[8]

Carroll clearly presupposes the governance metaphor for laws (e.g. [11 pp 5, 13, 20, 43, 61, 66]), consistent with ontological reductionism. And he advocates ontological reductionism along with epistemic emergence—there are useful concepts and descriptions at larger-scale viewpoints of reality: 'A property of a system is 'emergent' if it is not part of a detailed 'fundamental' description of the system, but it becomes useful or even inevitable when we look at the system more broadly' [11, p 94]. The implication is that our macroscopic theories are pragmatic and useful because they give us practical purchase on the world of our experience, not because they involve anything approaching fundamentality (similar to P W Anderson). Fundamentality is reserved for the base entities, laws, and their description, whatever that turns out to be. But one can raise a question here: If we're practicing methodological empiricism and empirical investigation confirms our larger-scale models and theories, doesn't this imply that such models and theories are more than merely pragmatic?

We want to keep clear that there is a distinction between ontological reductionism—a metaphysical view of nature—and reductive methods which some subdisciplines practice. In physics, for example, condensed matter, chaos and complexity studies typically pursue nonreductionistic methods. We also should be cautious of the idea that nature is neatly organized into levels and question whether laws govern or only constrain behavior. Perhaps nature is structured differently and exhibits more nuanced and interesting behavior. Atkins, Hossenfelder and Carroll illustrate how metaphysical commitments to ontological reductionism can color one's interpretation of laws, particles, scientific methodology…Everything.

References

[1] Alexander S 1920 *Space, Time and Deity* (London: Macmillan)

[2] Anderson P W 1972 More is different: broken symmetry and the nature of the hierarchical structure of science *Science* **177** 393–6

[3] Anderson P W 2011 *More and Different: Notes from a Thoughtful Curmudgeon* (Singapore: World Scientific)

[4] Atkins P 1995 The limitless power of science *Nature's Imagination: The Frontiers of Scientific Vision* ed J Cornwell (Oxford: Oxford University Press) pp 122–32

[5] Atkins P 2007 *Four Laws That Drive the Universe* (Oxford: Oxford University Press)

[6] Atkins P 2018 *Conjuring of the Universe: The Origins of the Laws of Nature* (Oxford: Oxford University Press)

[7] Bishop R C 2005 Patching physics and chemistry together *Philos. Sci.* **72** 710–22

[8] Bishop R C and Atmanspacher H 2006 Contextual emergence in the description of properties *Found. Phys.* **36** 1753–77

[9] Born M 1969 *Physics in My Generation* (New York: Springer)

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[8] Carroll's blogs are similarly as vague and abstract as *The Big Picture: On the Origins of Life, Meaning, and the Universe Itself* [11], so one cannot get much insight there.

[10] Broad C D 1925 *Mind and Its Place in Nature* (London: Routledge and Kegan Paul)

[11] Carroll Sean 2016 *The Big Picture: On the Origins of Life, Meaning, and the Universe Itself* (New York: Dutton)

[12] Dirac P A M 1929 Quantum mechanics of many-electron systems *Proc. R. Soc. Lond.* A **123** 714–33

[13] Einstein A 1934 On the method of theoretical physics *Essays in Science* (New York: Philosophical Library) pp 12–21

[14] Einstein A 1934 Principles of research *Essays in Science* (New York: Philosophical Library) pp 1–5

[15] Feynman R 1965 *The Character of Physical Law* (Cambridge, MA: MIT Press)

[16] Hossenfelder S 2018 *Lost in Math: How Beauty Leads Physics Astray* (New York: Basic Books)

[17] Hossenfelder S 2020 What is reductionism? https://backreaction.blogspot.com/2020/04/what-is-reductionism.html (accessed 4 March 2024)

[18] Kuhn T S 2012 *The Structure of Scientific Revolutions* 4th edn (Chicago: University of Chicago Press)

[19] Laughlin R B 2005 *A Different Universe: Reinventing Physics from the Bottom Down* (New York: Basic Books)

[20] Laughlin R B and Pines D 2000 The theory of everything *Proc. Natl Acad. Sci.* **97** 28–31

[21] Morgan C L 1923 *Emergent Evolution* (London: Williams and Norgate))

[22] Nagel E 1961 *The Structure of Science: Problems in the Logic of Scientific Explanation* (New York: Harcourt, Brace, and World)

[23] Pauli W 1994 The influence of archetypal ideas on the scientific theories of Kepler *Writings on Physics and Physics and Philosophy* ed C P Enz and K von Meyenn (Berlin: Springer) pp 219–79

[24] Pauli W 1994 Phenomenon and physical reality *Writings on Physics and Physics and Philosophy* ed C P Enz and K von Meyenn (Berlin: Springer) pp 127–35

[25] Primas H 1977 Theory reduction and non-Boolean theories *J. Math. Biol.* **4** 281–301

[26] Primas H 1983 *Chemistry, Quantum Mechanics and Reductionism: Perspectives in Theoretical Chemistry* (Lecture Notes in Chemistry vol 24) 2nd corrected edn (Berlin: Springer)

[27] Primas H 1998 Emergence in exact natural sciences *Acta Polytech. Scand. Ma.* **91** 83–98

[28] Roch J-F *et al* 2007 Experimental realization of Wheeler's delayed-choice gedanken experiment *Science* **315** 996–8

[29] Schrödinger E 1967 *What Is Life? The Physical Aspect of the Living Cell* (Cambridge: Cambridge University Press)

[30] Weinberg S 1993 *Dreams of a Final Theory* (New York: Pantheon Books)

[31] Wheeler J A 1977 Genesis and observership *Foundational Problems in the Special Sciences: Part Two of the Proc. 5th Int. Congress of Logic, Methodology and Philosophy of Science* ed R E Butts and J Hintikka (Dordrecht: D. Reidel) pp 3–33

[32] Wheeler J A 1983 On recognizing 'law without law' Oersted medal response at the joint APS-AAPT meeting, New York, 25 January 1983 *Am. J. Phys.* **51** 398–404

[33] Wheeler J A 1983 *Law Without Law Quantum Theory and Measurement* ed J A Wheeler and W Zurek (Princeton, NJ: Princeton University Press) pp 182–213

[34] Wheeler J A 1986 Physics as meaning circuit: three problems *Frontiers of Nonequilibrium Statistical Physics* ed G T Moore and M O Sully (New York: Springer) pp 25–32