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Reduction and Emergence in the Physical Sciences: Some Lessons from the Particle Physics and Condensed Matter Debate

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6.1. Introduction: A Note of Caution

The task that I set myself is a mundane philosophical one—getting clear about fundamental concepts, developing a taxonomy of viewpoints, assessing the validity of arguments for those views, and handicapping the odds for one or another of them to emerge triumphant. The arena is the much contested one of questions about reduction and emergence in the physical sciences, more specifically the relationship between particle physics and condensed matter physics. The main point that I wish to make is that we know so little about that relationship, and that what we do know strongly suggests that condensed matter phenomena are *not* emergent with respect to particle physics, that we should be wary of venturing hasty generalizations and of making premature extrapolations from physics to the biosciences, the neurosciences, and beyond.

Caution is the byword. Caution is called for because the academy is yet again seized by an enthusiasm. Seventy years ago, it was complementarity.[1] Thirty years ago, catastrophe theory.[2] Twenty years ago,

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[1] Niels Bohr, 'Light and Life,' *Nature* 131 (1933): 421–423, 457–459. Reprinted in *Atomic Physics and Human Knowledge* (New York: John Wiley & Sons, 1961), 3–12.

[2] René Thom, *Structural Stability and Morphogenesis: An Outline of a General Theory of Models*, trans. D. H. Fowler (Reading, MA: W. A. Benjamin, 1975).

fractals.[3] Yesterday it was cellular automata.[4] Today it is complexity theory, cooperative phenomena, and nonlinear dynamics.[5] Enthusiasm is good. It promotes creativity. It stimulates imagination. It gives one strength to carry on in the face of dogmatic opposition. But, Descartes—himself no intellectual wallflower—taught us in the *Meditations* that error is a consequence of the will outrunning the understanding. Like Faust, many of us want to know 'was die Welt am innersten zusammnehält.' Let's just be sure that our desire to solve the riddle of the universe doesn't get too far out in front of what we actually understand.

As mentioned, the specific place where I want today to make the case for caution is at the interface between particle physics and solid state or condensed matter physics. Here is where we find some of the boldest assertions that physics has demonstrated emergence. Various salient physical properties of the *mesorealm*, properties such as superconductivity and superfluidity, are held to be emergent with respect to particle physics. Such properties are said to exemplify coherent states of matter or long-range cooperative phenomena of a kind often associated with systems obeying a nonlinear dynamics. Such coherent states are said not to be explicable in terms of the properties of the molecular, atomic, or still more elementary constituents of superconductors or superfluids. I urge caution here for two reasons: (1) the physics of the mesorealm is not well enough established to license any inferences about the *essential* and *distinguishing* properties of matter at this intermediate scale. (2) That coherent states of matter are not to be explained at the level of particle physics has simply not been demonstrated. On the contrary, it is precisely at the level of particle physics that we *do* find compelling physical arguments and empirical evidence of the holism said—wrongly, I think—to be *distinctive* of mesophysics. We've had a name for such microphysical holism since 1935. That name is *entanglement*. And at least superconductivity and superfluidity, if not also various other phenomena in the realm of condensed matter physics, find their

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[3] Benoit Mandelbrot, *The Fractal Geometry of Nature* (New York: W. H. Freeman, 1983).

[4] Stephen Wolfram, *A New Kind of Science* (Champaign, IL: Wolfram Media, 2002).

[5] Alwyn Scott, *Nonlinear Science: Emergence and Dynamics of Coherent Structures* (Oxford: Oxford University Press, 1999); see also Chapter 8 in this volume.

proper explanation as mesoscopic manifestations of microscopic entanglement.

6.2. Some Conceptual Preliminaries: Reduction, Supervenience, and Emergence

Contemporary discussions of emergent phenomena often start with a helpful distinction between two different relationships that might obtain between two different levels of description, *intertheoretic reduction* and *supervenience*.[6]

Intertheoretic reduction is a logical relationship between theories. In the classic formulation owing to Ernest Nagel, theory T_B, assumed correctly to describe or explain phenomena at level B, reduces to theory T_A, assumed correctly to describe or explain phenomena at level A, if and only if the primitive terms in the vocabulary of T_B are definable via the primitive terms of T_A and the postulates of T_B are deductive consequences of the postulates of T_A.[7] As normally formulated, this definition of reduction assumes a *syntactic* view of theories as sets of statements or propositions.

Supervenience is an ontic relationship between structures. A structure, S_x, is a set of entities, E_x, together with their properties and relations, PR_x. A structure, S_B, characteristic of one level, B, supervenes on a structure, S_A, characteristic of another level, A, if and only if the entities of S_B are composed out of the entities of S_A and the properties and relations, PR_B, of S_B are wholly determined by the properties and relations, PR_A, of S_A. One way to understand the relevant sense of 'determination' is as requiring that there be no differences at level B, say different values of a parameter such as the temperature of a gas, without there being a corresponding difference at level A, say in the mean kinetic energy of the molecules constituting the gas.[8]

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[6] Robert Batterman, *The Devil in the Details: Asymptotic Reasoning in Explanation, Reduction and Emergence* (Oxford: Oxford University Press, 2002); and Michael Silberstein, 'Reduction, Emergence, and Explanation,' in *The Blackwell Guide to the Philosophy of Science*, eds. Peter Machamer and Michael Silberstein (Oxford: Blackwell, 2002), 182–223.

[7] Ernst Nagel, *The Structure of Science: Problems in the Logic of Scientific Explanation* (New York: Harcourt, Brace & World, 1961).

[8] Donald Davidson is generally regarded as introducing this specific notion of supervenience, though it is implicit in earlier literature. Donald Davidson, 'Mental Events,' in *Experience and Theory*, eds. Lawrence Foster and J. W. Swanson (Amherst, MA: University of Massachusetts Press, 1970), 79–101.

There is no straightforward relationship between reduction and supervenience. One might think that reduction implies supervenience, in the sense that, if theory T_B reduces to theory T_A, then the structures, S_B, assumed correctly to be described or explained by T_B, supervene on the structures, S_A, assumed correctly to be described or explained by T_A. This need not be the case, however, if some of the properties and relations constitutive of S_B depend on boundary conditions. Not all structure is nomic. Think of global metrical structure in big-bang cosmology or 'edge state' excitations in the fractional quantum Hall effect. That supervenience does not imply reduction should be even clearer, for the properties and relations, PR_B, constitutive of structure S_B can be wholly determined by the properties and relations, PR_A, of S_A without there being laws governing PR_B that are deductive consequences of laws governing PR_A, perhaps because there are no exceptionless laws governing PR_B.

Emergence can be asserted either as a denial of intertheoretic reduction or as a denial of supervenience. There being no necessary relationship between reduction and supervenience, there will, in consequence, be no necessary relationship between the corresponding varieties of emergence, which must, therefore, be distinguished. What we might term R-emergence is a denial of reduction, and what we might term S-emergence is a denial of supervenience.

Thinking about the relationship between different levels of description in terms of intertheoretic reduction has the advantage of clarity, for while it might prove difficult actually to determine whether a postulate at level B is derivable from the postulates of level A—as is the case with the ergodic hypothesis, which is to be discussed shortly—we at least know what we mean by derivability and definability as relationships between syntactic objects like terms and statements, since we know by what rules we are to judge. The chief disadvantage of this way of thinking about interlevel relationships is that one is hard-pressed to find a genuine example of intertheoretic reduction outside of mathematics, so to assert emergence as a denial of reduction is to assert something trivial and uninteresting. Yet, another disadvantage is the restriction to theories represented syntactically as sets of statements or propositions, central among which are statements of laws, for there is reason to think that many important scientific theories—evolution is an often cited example—are not best understood in this way. Later on I will say a word or two about the possible advantages of a *semantic* view of theories, whereupon a theory is conceived as a set of models.

The chief advantage of thinking about interlevel relationships from the point of view of supervenience is that it seems to many to capture well our pre-analytic intuitions, such as those about the relationship between heat and agitated molecular motion. The chief disadvantage of so posing the question of interlevel relationships is that it is not always clear by what general rules we are to assess claims about supervenience and its denial, so in asserting emergence as a denial of supervenience one risks asserting something validated by little more than intuition. There are, however, some reasonably clear paradigm cases of emergence as a failure of supervenience, the most important for our purposes being quantum mechanical entanglement, which is shortly to be addressed.

Distinguishing intertheoretic reduction and supervenience along with the respective notions of emergence is a big step in the direction of clarity and understanding. For example, I will argue that while condensed matter physics does not obviously reduce to particle physics, phenomena characteristic of condensed matter physics such as superfluidity and superconductivity do supervene on physical properties at the particle physics level and hence are not emergent with respect to particle physics. But, we might also find, as I think we do find in the case of condensed matter physics, that neither reduction nor supervenience is the most helpful analytical tool for explicating the truly important and interesting features—both structural and methodological—of interlevel relationships in the physical sciences.

6.3. Ergodicity and Entanglement: Two Challenges to Our Presuppositions

That intertheoretic reduction might not be a helpful way to think about interlevel relationships is perhaps best shown by pointing out that everyone's favorite example of a putatively successful reduction—that of macroscopic thermodynamics to classical statistical mechanics—simply does not work. Recall what is required for reduction: the definability of terms and the derivability of laws.

Concede the former in this instance—as with the definition of temperature via mean kinetic energy—and focus on the latter. Foremost among the thermodynamic laws that must be derivable from statistical mechanical postulates is the second law, which asserts the exceptionless evolution of closed non-equilibrium systems from states of lower to states of higher entropy. Providing a statistical mechanical grounding of the second law was Boltzmann's paramount aim in the latter part of the nineteenth century.[9] Did he succeed?

The answer is no. For one thing, what Boltzmann derived was not the deterministic second law of thermodynamics but a statistical simulacrum of that law, according to which closed non-equilibrium systems are at best highly likely to evolve from states of lower to states of higher entropy. More importantly, even this statistical simulacrum of the second law is derived not from mechanical first principles alone but from those conjoined to what was early termed the *ergodic hypothesis*, which asserts that, regardless of its initial state, an isolated system will eventually visit every one of its microstates compatible with relevant macroscopic constraints. The ergodic hypothesis can be given comparably opaque equivalent formulations, such as the assertion of the equality of time and ensemble averages, but the work that it does in the foundations of statistical mechanics is clear: The theory being a statistical one, it must work with averages. The ergodic hypothesis makes the averages come out right. The crucial fact is, however, that for all but a few special cases or for highly idealized circumstances, the ergodic hypothesis and its kin cannot be derived from mechanical first principles. On the contrary, we demonstrate non-ergodic behavior for a large class of more realistic models.[10]

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[9] Still one of the most illuminating studies of the conceptual foundations of Boltzmann's program is to be found in the Ehrenfests's splendid monograph of 1911. Paul Ehrenfest and Tatiana Ehrenfest, 'Begriffliche Grundlagen der statistischen Auffassung in der Mechanik', in *Encyklopädie der mathematischen Wissenschaften, mit Einschluss ihrer Anwendungen*, Vol. 4. *Mechanik*, part 4, eds. Felix Klein and Conrad Müller (Leipzig: Teubner, 1907–1914), 1–90. English translation: *The Conceptual Foundations of the Statistical Approach in Mechanics*, trans. Michael J. Moravcsik (Ithaca: Cornell University Press, 1959).

[10] For a survey of the current state of opinion regarding the ergodic hypothesis, see Lawrence Sklar, *Physics and Chance: Philosophical Issues in the Foundations of Statistical Mechanics* (Cambridge: Cambridge University Press, 1993), 156–195.

Are macroscopic thermodynamic phenomena, therefore, emergent with respect to the mechanical behavior of the individual molecular and atomic constituents of the systems of interest? Yes, if emergence means the failure of intertheoretic reduction. Is that an important fact? Yes, if our aim is to undermine dogmatic reductionist prejudices or to unsettle the presupposition that physics, generally, is a paradigmatically reductionist science. Otherwise, the significance of there not being a reduction of thermodynamics to statistical mechanics is not so clear. Does the lesson of the ergodic hypothesis generalize to other cases of interlevel relationships? I know of no reason to think that it does, though one should also not be surprised to encounter analogous situations elsewhere. Whether the relationship between particle physics and condensed matter physics is thus analogous will be discussed in a moment.

What about emergence in the sense of a failure of supervenience? Does the irreducibility of thermodynamics to statistical mechanics show that thermodynamic phenomena do not supervene on mechanical phenomena? Hard to say. The intuitions of many of us point in the opposite direction, to the conclusion that thermodynamic phenomena do supervene on mechanical ones. On the other hand, if we regard satisfaction of the ergodic hypothesis as a property of systems like a gas, perhaps we should regard that as emergent with respect to more narrowly mechanical properties of the molecular constituents of the gas. But, recall my noting that the chief disadvantage of supervenience as a perspective on interlevel relations is precisely that, in the generic case, it is hard to know how to judge whether supervenience obtains.

One case where it is, however, not at all hard to make a judgment about supervenience, or rather its failure, is the case of quantum mechanical entanglement. Start with ordinary (non-relativistic) quantum mechanics. We represent the state of a system by means of a quantum mechanical state function, ψ, corresponding, technically, to a ray in some Hilbert space, which is a complex vector space. For many of us, a more comfortable way of representing a state function is as a Schrödinger wave function. The question now is how to represent the joint state, ψ_{12}, of a composite system consisting of two (or more) previously interacting systems. Had the two systems not interacted, then quantum mechanics would represent the joint state just as, in effect, all 'classical' theories do (think of Newtonian mechanics and Maxwellian electrodynamics), namely, as the product of two separate states:

$$\psi_{12} = \psi_1 \times \psi_2$$

If, however, systems 1 and 2 have interacted, then, in general, quantum mechanics describes their joint state in such a way as to make it not equivalent to any product of separate states:

$$\psi_{12} \neq \psi_1 \times \psi_2$$

Such joint states are said to be *entangled* joint states, and it is an easy bit of mathematics to show how these entangled states necessarily yield different predictions than do factorizable joint states especially for certain types of correlations between two entangled systems, such as spin correlations.

The term 'entanglement' has been around since Erwin Schrödinger coined it in 1935 when, in the wake of the famous Einstein, Podolsky, and Rosen argument for the incompleteness of quantum mechanics,[11] he drafted the papers that for the first time presented in a systematic way what is now termed the quantum mechanical interaction formalism.[12] That some such departure from classical assumptions about the mutual independence of interacting systems would be part of the full story of the quantum realm was already clear as early as Einstein's first paper on the photon hypothesis in 1905.[13] That entanglement is, in fact, an essential part of the quantum mechanical formalism and the most important distinguishing feature of the quantum mechanical description of nature was clear by 1927, when Einstein ceased being a contributor to the further development of quantum mechanics after discovering that his own attempt at a

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[11] Albert Einstein, Boris Podolsky, and Nathan Rosen, 'Can Quantum-mechanical Description of Physical Reality Be Considered Complete?' *Physical Review* 47 (1935): 777–780.

[12] Erwin Schrödinger, 'Die gegenwärtige Situation in der Quantenmechanik,' *Die Naturwissenschaften* 23 (1935): 807–812, 823–828, 844–849; *idem,* 'Discussion of Probability Relations Between Separated Systems,' *Proceedings of the Cambridge Philosophical Society* 31 (1935): 555–662; *idem*, 'Probability Relations Between Separated Systems,' *Proceedings of the Cambridge Philosophical Society* 32 (1936): 446–452.

[13] Albert Einstein, 'Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt,' *Annalen der Physik* 17 (1905): 132–148.

hidden variables interpretation of quantum mechanics also required the employment of non-factorizable joint states[14] and when Niels Bohr made entanglement the centerpiece of his complementarity interpretation of quantum mechanics (see Howard 1994, 2004). It was entanglement, which Einstein could not abide, about which Einstein and Bohr (Bohr 1935) were really arguing at the time of the Einstein, Podolsky, and Rosen paper (see Howard 1985).

The fundamental significance of quantum mechanical entanglement has long been understood and appreciated by philosophers working on the foundations of quantum mechanics.[15] Entanglement is a fact not only about non-relativistic quantum mechanics, but about any quantum theory. Entanglement is ineluctably and deeply woven into the fabric of quantum electrodynamics, quantum chromodynamics, and all of the good candidates for a quantum theory of gravity, including string theory and loop quantum gravity.[16] That its fundamental significance has not been so widely appreciated by the mainstream physics community is a historical puzzle that I won't attempt to solve right now, though it is a fact pregnant with implications for the current debate over reduction and emergence in physics. One is cheered by the fact that recent interest in topics such as quantum computing, quantum cryptography, and quantum information theory has finally put entanglement on the mainstream agenda, for now, in effect, we find physicists doing engineering with entanglement.[17]

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[14] Don Howard, ' "Nicht sein kann was nicht sein darf," or the Prehistory of EPR, 1909–1935: Einstein's Early Worries about the Quantum Mechanics of Composite Systems,' in *Sixty-two Years of Uncertainty: Historical, Philosophical, and Physical Inquiries into the Foundations of Quantum Mechanics*, ed. Arthur Miller (New York and London: Plenum, 1990), 61–111.

[15] See Bernard d'Espagnat, *Conceptual Foundations of Quantum Mechanics*, 2nd edn. (Reading, MA: W. A. Benjamin, 1976) on the role of entanglement in quantum mechanics.

[16] On quantum field theory, see Harvey Brown and Rom Harré, eds., *Philosophical Foundations of Quantum Field Theory* (Oxford: Clarendon Press, 1988); on quantum gravity, see Craig Callender and Nick Huggett, *Physics Meets Philosophy at the Planck Scale: Contemporary Theories in Quantum Gravity* (Cambridge: Cambridge University Press, 2001).

[17] For an accessible recent review, see Barbara Terhal, Michael Wolf, and Andrew Doherty, 'Quantum Entanglement: A Modern Perspective,' *Physics Today* 56/4 (April 2003): 46–52.

For our purposes, entanglement is important because it is the clearest example known to me from any domain of investigation of a failure of supervenience. How and why the properties of a pair of previously interacting and, therefore, entangled quantum systems fail to supervene on the properties of the two individual systems taken separately is perfectly well understood and today routinely demonstrated in the laboratory, as in experimental tests of Bell's theorem. Even with perfect, complete knowledge of the states of the separate systems, one cannot account for the correlations between those systems characteristic of entangled joint states.[18] That it must be so in the quantum domain is shown by a simple and straightforward mathematical demonstration. Here is holism of a very deep kind, and here is emergence in the sense of a failure of supervenience. By my lights, the quantum correlations characteristic of entangled joint states have a better claim to the status of emergent properties than do any of the other properties elsewhere in nature so far nominated for the prize.

Savor the significance of this point. It is at the most fundamental level of description in nature that the clearest instance of emergence is found. Emergence in the guise of entanglement is the most basic fact about the quantum realm. We will speak in a moment about the relationship between particle physics and condensed matter physics. Particle physics is quantum field theory. Entanglement is a fundamental fact about quantum field theory and, therefore, a fundamental fact about particle physics. It is, therefore, simply not true that holism, coherent states of matter, and long-range correlations occur first at the mesoscopic level of condensed matter physics. Nor is complexity the key. It's hard to imagine anything simpler than two charged particles like a proton and an electron interacting electromagnetically, which is to say, the hydrogen atom, or a positron-electron pair resulting from pair creation, or two correlated optical photons. Generating an analytic solution of the Schrödinger equation for the hydrogen atom is so simple that it has long been a homework problem for

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[18] Richard Healey, *The Philosophy of Quantum Mechanics: An Interactive Interpretation* (Cambridge: Cambridge University Press, 1989) is a helpful source on many of these issues, as are many of the papers collected in James Cushing and Ernan McMullin, *Philosophical Consequences of Quantum Theory: Reflections on Bell's Theorem* (Notre Dame, IN: University of Notre Dame Press, 1989).

first-semester students of quantum mechanics. Nor is nonlinearity involved in any obvious way, unless one simply defines nonlinearity as a species of holism.[19] For the Schrödinger equation that governs the dynamics of these entangled quantum systems is a linear partial differential equation. It is linear Schrödinger evolution that carries the non-entangled pre-interaction joint state into the entangled post-interaction joint state. Far from nonlinearity engendering the kind of holism evinced as entanglement, some famous attempts to *evade* puzzling consequences of the quantum theory associated with entanglement take the form of proposed *nonlinear* variants of the Schrödinger equation. For example, in some 'solutions' to the measurement problem the addition of a nonlinear term to the Schrödinger equation serves to break the entanglement between instrument and object that is the basis of the measurement problem.[20] What, then, is going on in the relationship between particle physics and condensed matter physics?

6.4. Cooper Pairs and ^{4}He: Evidence for Emergence in Condensed Matter Physics

With prophetic mien, prominent solid state physicists like Philip Anderson, Robert Laughlin, and David Pines have been heralding the appearance of a new paradigm of emergence in the physics of the mesorealm and arguing that, precisely because condensed matter physics has the conceptual tools for thinking about emergent properties, it is a way of doing physics more likely to hold the key to a future theory of everything than inherently reductionistic particle physics.[21] How sound is the prophecy?

[19] This is how I read Scott in Chapter 8 of this volume.

[20] Helpful surveys of this approach can be found in Gian Carlo Ghirardi, and Alberto Rimini, 'Old and New Ideas in the Theory of Quantum Measurement'; and in Philip Pearle, 'Toward a Relativistic Theory of Statevector Reduction,' in *Sixty-two Years of Uncertainty: Historical, Philosophical, and Physical Inquiries into the Foundations of Quantum Mechanics*, ed. Arthur Miller (New York and London: Plenum, 1990), 167–191, 193–214.

[21] P. W. Anderson, 'More is Different,' *Science* 177 (1972): 393–396; Robert B. Laughlin and David Pines, 'The Theory of Everything,' *Proceedings of the National Academy of Sciences* 97 (2000): 28–31; Robert B. Laughlin *et al.*, 'The Middle Way,' *Proceedings of the National Academy of Sciences* 97 (2000): 28–31.

If thermodynamics does not reduce to classical statistical mechanics, then we should not expect condensed matter physics to reduce to particle physics. If emergence is a failure of reduction, then condensed matter physics would be emergent with respect to particle physics. But, I have argued that the question of intertheoretic reduction is not the right question. The right question is the question of supervenience, and what I now want to argue is that there is good reason to think that condensed matter physics supervenes on particle physics, once the latter is understood properly as assuming quantum entanglement as the most fundamental physical property of microphysical systems.

Consider three more or less incontestable facts and consequences thereof.[22]

Fact 1 (*incontestable*): There is no unified, general theory of condensed matter physics. Some areas are in reasonably good shape, among them superfluidity and low-temperature superconductivity. Elsewhere the picture is spotty. In some important areas, most notably high-temperature superconductivity, few are so bold as to claim any adequate theoretical understanding.

Consequences: In the absence a more unified, general theoretical framework for condensed matter physics and a better understanding of how and when effective Hamiltonian techniques work, it is hard to see how one can draw any general conclusion about emergence as a pervasive, essential, and distinctive feature of the mesorealm. Here the contrast with the microrealm as described by quantum mechanics and quantum field theory is striking, for it is precisely the fact that there we do have a unified, general theoretical framework that makes possible a strong conclusion about the pervasive, essential, and distinctive character of quantum entanglement.

Fact 2 (*incontestable*): In many nonlinear systems, one encounters striking coherent structures not obviously explicable in microphysical terms. We have all seen long-lived eddies on the surface of a

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[22] For a good historical introduction to the development of solid state and condensed matter physics see, Lillian Hoddeson *et al.*, eds., *Out of the Crystal Maze: Chapters from the History of Solid-State Physics* (New York: Oxford University Press, 1992).

fast-moving and in other respects seemingly turbulent stream. The generic term for such stable structures is 'solitons.'

Consequences: Decidedly unclear. Don't be misled by the suffix '-on,' which suggests a likeness in kind to leptons, baryons, and other elementary particles, for solitons are features mainly of classical, not quantum nonlinear systems, though similar structures can emerge in a nonlinear quantum setting. That such stable structures are emergent (in either sense of the term) with respect to classical particle mechanics is not worthy of dispute. But so what? Classical particle mechanics is not true of the microworld; quantum mechanics is. Whether classical nonlinear phenomena supervene on microstructure as described quantum mechanically is, perhaps, not even a well-posed question, given that we have no good story to tell about the relationship between quantum and classical descriptions. Glib talk of the correspondence principle or of taking a classical limit by letting Planck's constant, h, go to zero just obscures the fact that, from a first principles conceptual point of view quantum mechanics does not go over continuously to classical mechanics in the limit of small h. However small we let h become, the difference between quantum and classical descriptions is still the difference between non-commutative and a commutative algebraic structure, which is a big difference.

Don't be misled either by the fact that stability of structure is a hallmark of the quantum realm, as in the existence of stable stationary atomic states. The kind of stability characteristic of the quantum realm, the stability of electron orbits and, therefore, the stability of chemical bonds and molecular structures, is a consequence of the fundamental linearity of quantum dynamics, deeply associated with entanglement. The hydrogen atom is a stable structure because the proton and the electron form an entangled pair.

Fact 3 (*more or less incontestable*): In those areas of condensed matter physics where we do have a reasonably satisfactory theory–I have in mind mainly superfluidity and low-temperature superconductivity—there is also a reasonably clear connection to microphysical entanglement. This is especially so in the case of superfluidity, where the mechanism long thought to be in play, what is known as Bose-Einstein condensation, is a famous instance of entanglement, the atoms of a ^{4}He superfluid, for example, being in an entangled joint state.[23] The connection to entanglement is only a little less straightforward in the case of low-temperature superconductivity, where sets of fermion pairs like the electrons designated Cooper pairs in the BCS (Bardeen-Cooper-Schrieffer) theory are described by coherent macroscopic wave functions, the bosonic fermion pairs in effect forming a condensate.

Consequences: The examples of superfluidity and superconductivity suggest that success in explaining phenomena in condensed matter physics will typically depend upon our making clear precisely the connection to quantum mechanical entanglement. That means that, far from such phenomena being emergent with respect to particle physics, they are proven to supervene on particle physics. The properties of entangled composite systems do not supervene on the properties of the individual components, but the molar properties of mesoscopic condensed matter systems, properties like superfluidity and superconductivity, do supervene on the most basic property of the quantum mechanical microrealm, namely, entanglement. The only emergence is, ironically, that found at the particle physics level itself.

The connection of superfluidity and superconductivity to Bose-Einstein condensation and the connection of the latter to entanglement is no secret. I'm not here asserting a radically heterodox point of view. How, then, could the idea that condensed matter physics is emergent with respect to particle physics have become so deeply entrenched in the community of condensed matter physicists? Frankly, I'm puzzled by this phenomenon. My best guess is that folks have been misled by the particle analogy. Intuitively, we regard particles as inherently mutually independent structures of a kind that cannot be entangled with one another. But, Einstein recognized that, in general, photons would not behave as mutually independent particles, and de Broglie taught us to associate a similar wave-like

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[23] For recent discussions of the physics of superfluidity and superconductivity, see Tony Guénault, *Basic Superfluids* (London: Taylor & Francis, 2003); and Lev Pitaevskii and Sandro Stringari, *Bose-Einstein Condensation* (Oxford: Clarendon Press, 2003). An interesting recent discussion of the place of entanglement in quantum statistics can be found in Michela Massimi, 'Exclusion Principle and the Identity of Indiscernibles: A Response to Margenau's Argument,' *British Journal for the Philosophy of Science* 52 (2001): 303–330.

aspect to massive particles like electrons. Thus, what we, today, call particle physics is, the name notwithstanding, not really a theory of particles. Were we all clear about the fact that particle physics takes entanglement as the most basic attribute of the systems it describes, then we would be unlikely to regard the phenomena of condensed matter physics as emergent with respect to particle physics.

6.5. Other Ways to Model Interlevel and Intertheory Relationships

In denying that condensed matter phenomena like superfluidity and superconductivity are emergent with respect to particle physics, I don't mean to deny that there are interesting and important questions about the relationship between the two theoretical realms. On the contrary, that relationship is, and should be even more so, a fertile area of investigation in the foundations of physics. Moreover, I also don't want to disparage the view that condensed matter physics enjoys a measure of explanatory autonomy vis-à-vis particle physics, this for two reasons. First, recall my noting above that supervenience does not imply reduction. Superfluidity can supervene on the entanglement fundamental to particle physics without condensed matter physics reducing to particle physics. Second, and more importantly, the manner in which condensed matter physics explains phenomena like superfluidity and superconductivity is thought by some to differ in crucial respects from the way explanation proceeds in particle physics. Explanatory autonomy of this kind is, to me, far more interesting than dubious claims about emergence.

Philosophers of physics have overcome the logical empiricist prejudice according to which there is one and only one right method for all scientific domains. While the provision of unified explanations of disparate phenomena is still widely prized as a worthy epistemic ideal,[24] the *methodological unity of science thesis* finds rather less support today, the dominant tendency now being to emphasize the

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[24] Philip Kitcher, 'Explanatory Unification,' *Philosophy of Science* 48 (1981): 507–531. For a dissenting view see Helen Longino, *Science as Social Knowledge* (Princeton, NJ: Princeton University Press, 1990).

features distinctive of scientific practice in different domains.[25] In that spirit, a small but growing number of philosophers of physics are studying carefully condensed matter physics as well as its relationship to particle physics, trying hard to make clear methodological sense out of the explanatory strategies characteristic of the former.

Illuminating that relationship is one of principle aims of Ang Wook Yi, who finds the semantic view of theories (wherein they are regarded as sets of models[26]) more helpful in thinking about condensed matter physics. Yi suggests that we distinguish 'global theories' from 'substantial theories.'[27] The former—global theories—model structure common to systems in a wide phenomenal domain; the latter—substantial theories—fill in the structural details for specific phenomenal domains. In sharing the structure encoded in the relevant global theory, different substantial theories would be related to one another by partial isomorphism. But that global theory can and typically will be a theory at a deeper level of description, in which case it is not obvious that emergence is the most felicitous way to characterize the relationship between the substantial theories and the associated global theory. Think of my story about entanglement in particle physics and take entanglement—a fact about the microdomain—to be the global structure incorporated in the substantial theories that condensed matter physics proposes for different mesoscopic phenomena like superfluidity and superconductivity.

6.6. In Conclusion: Extrapolations beyond Physics

I have argued that the case for emergence in condensed matter physics has not been made, partly because of confusion over what is being claimed, different meanings of the term, 'emergence,' not always being clearly distinguished, and partly because of the lack of

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[25] Nancy Cartwright, *The Dappled World: A Study of the Boundaries of Science* (Cambridge: Cambridge University Press, 1999).

[26] See Bas van Fraassen for a now classic formulation of the semantic view. Bas C. van Fraassen, *The Scientific Image* (Oxford: Clarendon Press, 1980).

[27] Ang Wook Yi, 'How to Model Macroscopic Worlds: Towards the Philosophy of Condensed Matter Physics' (Ph.D. diss., London School of Economics/University of London, 2000).

any overall theory of condensed matter physics upon which to base general assertions about distinctive features of the mesorealm. But, my main argument is that the physical structure that seems actually to do the explaining in condensed matter physics—in those cases where we have good explanations—is the very structure, entanglement, that is the defining trait of the quantum microworld described by particle physics, the microworld upon which condensed matter physics is said not to supervene.

What does any of this have to do with the science/theology dialogue? I think that it has important implications. I warned at the outset that, in the current enthusiasm for viewing emergence as the hallmark of interlevel relations, the will might be outrunning the understanding. Claims for emergence in condensed matter physics constitute one of the most important premises in the argument. But, if the case has not been made here, where we have a modicum of theoretical control over the relevant phenomena, then one should be wary of extrapolations to levels of description—to organic life, to the mind, to the soul, perhaps—where our theoretical control of the phenomena is orders of magnitude less secure.

Patience, modesty, and humility are intellectual virtues as well as moral ones. Let us be patient, modest, and humble. Don't let wishful thinking and vague analogies take the place of clear understanding. Let the science lead us where it will.