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

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Whence, then, do my errors arise? Only from the fact that the will is much more ample and far-reaching than the understanding, so that I do not restrain it within the same limits but extend it even to those things which I do not understand. Being by its nature indifferent about such matters, it very easily is turned aside from the true and the good and chooses the false and the evil. And thus it happens that I make mistakes and that I sin.

René Descartes, *Meditations on First Philosophy*, Meditation Four, "Of the True and the False"

Introduction: A Note of Caution

The task that I set for myself today 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 (Bohr 1933). Thirty years ago catastrophe theory (Thom 1975). Twenty years ago fractals (Mandelbrot 1983). Yesterday it was cellular automata (Wolfram 2002). Today it is complexity theory, cooperative phenomena, and non-linear dynamics (Scott 1999 and 2003). 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 im Innersten zusammenhält." 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 non-linear 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 proper explanation as mesoscopic manifestations of microscopic entanglement.

But I get ahead of myself. Let's slow down and begin with some of the philosopher's favorite tools or toys; let's begin with some distinctions.

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*.[1]

> *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

[1] Batterman 2002 and Silberstein 2002 are useful primers.

consequences of the postulates of T_A.[2] 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.[3]

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

[2] Nagel 1961, 345-366. Some details of Nagel’s formulation irrelevant for our purposes are suppressed.

[3] Davidson 1970 is generally regarded as first introducing this specific notion of supervenience, though it is implicit in many earlier literatures. For an overview, see Blackburn 1998.

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, the claim of what we might term *R*-emergence being a denial of reduction, and what we might terms *S*-emergence being a denial of supervenience.[4]

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

[4] Still finer distinctions among varieties of emergence are encountered in various other literatures, especially in the philosophy of mind. Silberstein 2002 is, again, a good place to start for a more comprehensive survey. The distinction between *R*-emergence and *S*-emergence suffices for present purposes.

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 in the sense of S-emergence. 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.

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 themodynamic laws that must be deriveable 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.[5] 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*

[5] 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, Ehrenfest and Ehrenfest 1911.

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, like confinement to a surface of constant energy in its phase space. 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 cases special cases or for highly idealized circumstances, the ergodic hypothesis and its kin cannot be derived from mechanical first principles. On the contrary, we can demonstrate non-ergodic behavior for a large class of more realistic models.[6]

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.

[6] For a lucid survey of the current state of opinion regarding the ergodic hypothesis, see Sklar 1993, 156-195.

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. This is what some designate as nomic emergence. 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 comfortable way of representing such 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:

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

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:

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

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 name, "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 (Einstein, Podolsky, and Rosen 1935), he drafted the papers that for the first time presented in a systematic way what is now termed the quantum mechanical interaction formalism (Schrödinger 1935a, 1935b, 1936). 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 (Einstein 1905). 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 hidden variables interpretation of quantum mechanics also required the employment of non-factorizable joint states (see Howard 1990) 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.[7] 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.[8] 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.[9]

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

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[7] d'Espagnat 1976 is only one of many good sources one can consult on the role of entanglement in the foundations of quantum mechanics.

[8] On quantum field theory, see Brown and Harré 1988; on quantum gravity, see Callender and Huggett 2001.

[9] For an accessible recent review, see Terhal, Wolf, and Doherty 2003.

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.[10] That it must be so in the quantum domain is shown by a simple and straightforward mathematical demonstration set as an exercise for every graduate student in a foundations of quantum mechanics course. Here is holism of a very deep kind, and here is emergence in the sense of a failure of supervenience.[11] 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-

[10] Healey 1989 is a helpful source on many of these issues, as are many of the papers collected in Cushing and McMullin 1989, especially Teller 1989 and Howard 1989.

[11] Silberstein and McGeever 1999 make this point about entanglement.

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 first-semester students of quantum mechanics. Nor is non-linearity involved in any obvious way, unless one simply defines non-linearity as a species of holism.[12] 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 non-linearity 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 *non-linear* variants of the Schrödinger equation. For example, in some "solutions" to the measurement problem the addition of a non-linear term to the Schrödinger equation serves to break the entanglement between instrument and object that is the basis of the measurement problem.[13] What, then, is going on in the relationship between particle physics and condensed matter physics?

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

[12] This is how I read Scott 2003.

[13] Helpful surveys of this approach to the measurement problem can be found in Ghirardi and Rimini 1990 and Pearle 1990.

to the future than inherently reductionistic particle physics (see, for example, Anderson 1972, Laughlin and Pines 2000, Laughlin et al. 2000). How sound is the prophecy?

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 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.[14]

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. There are, to be sure, strong family resemblances among some of the techniques employed in different areas of condensed matter physics, effective Hamiltonian techniques being foremost among them.

[14] Hoddeson et al. 1992 is a good historical introduction to the development of solid state and condensed matter physics.

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 non-linear systems one encounters striking coherent structures not obviously explicable in microphysical terms. We have all seen long-lived eddies on the surface of a 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 non-linear systems, though similar structures can emerge in a non-linear 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 non-linear 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.[15] Indeed, it was Einstein's discovery of this phenomenon in 1925 (Einstein 1925) that set off the chain of events leading to his above-mentioned repudiation of quantum mechanics in 1927 after he discovered that his own hidden variables interpretation evinced the same entanglement that was central to Schrödinger's wave mechanics. The

[15] For helpful recent discussions of the physics of superfluidity and superconductivity, see Guénault 2003and Pitaevskii and Stringari 2003. An interesting recent discussion of the place of entanglement in quantum statistics will be found in Massimi 2001.

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 at an explanation 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. When Einstein introduced the photon hypothesis in 1905 he said exactly that about the relevant respect in which light quanta were corpuscular or particle-like. Indeed, he wrote explicitly that what he meant by the claim that light quanta behaved as if they were “mutually independent” corpuscles was that the joint probability for two such quanta to occupy specific cells of phase space factorizes:

$$W_{12} = W_1 \cdot W_2.$$

But Einstein was a smart guy, and he understood that photons would evince such quintessentially particle-like behavior, such mutual independence, only in what is termed the Wien regime, where the ratio of frequency to temperature is high: $\nu/T \gg 1$. Otherwise, and in general, photons would not behave as mutually independent particle-like quanta of electromagnetic energy. Otherwise, and in general, as Einstein recognized from the start, photons would have to interfere with one another, which is to say that they would not behave like particles. Once de Broglie taught us to associate a similar wave-like aspect with material particles like electrons we understood that they too would not, in general, behave like particles. What this all means is that what we, today, call particle physics is, the name notwithstanding, not really a theory of particles.[16] 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.

A complete genealogy of the confusions rampant in the particle physics–condensed matter physics debate would also have to note that the entire argument was anyway just a proxy war, the

[16] Footnote on other problems such as indefinite particle number.

real issue being not philosophical but monetary. Condensed matter physics was something of a backwater in the 1970s and the early 1980s, before the days of high-temperature superconductivity and Ronald Reagan's infusion of star wars money into the field. The condensed matter community was especially resentful of the fact that oceans of money were to be spent on building the superconducting supercollider. If particle physics could legitimately promise to be a theory of everything, then, in the eyes of particle physicists like Steven Weinberg, solid state physicists should gratefully have served as mere underlaborers, designing the superconducting magnets necessary for generating the supercollider's high-energy particle beams. But if condensed matter physics were truly emergent with respect to particle physics, then a dollar spent on the supercollider would be a dollar not spent on learning how the everyday world of the mesorealm really works. But I digress.

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 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-a-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 (see, for example, Kitcher 1981, but also Longino 1990 in the dissent), the *methodological unity of science thesis* finds rather less support today, the dominant tendency now being to emphasize the features distinctive of scientific practice in different domains (see, for example, Cartwright 1999). 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. My own main interest is in trying to understand how one does physics with effective Hamiltonians. But, time being short, let me talk instead about two other projects, both more relevant than mine to general questions about interlevel relations.

Margaret Morrison is a philosopher of physics at Toronto long interested in questions about unification. In earlier work she has argued that while unified theories are an appropriate ideal one should separate unification as a virtue from explanatory power (see Morrison 2000). Her central idea is that unification is to be found mainly in the employment of common mathematical tools or structures, but that the pieces of theoretical structure facilitating unification need not be and often are not themselves thereby explained. With respect to the wide employment of Lagrangian techniques, she notes that "it becomes easy to see how explanatory detail is sacrificed for the kind of generality and abstraction that facilitate unification" (Morrison 2000, p. 5). Of late Morrison has turned her eye toward condensed matter physics, being especially interested in the role that models play in areas like the BCS theory of low-temperature superconductivity (Morrison 2003).

I noted above that a chief disadvantage of intertheoretic reduction as a perspective on emergence was a restriction to theories understood syntactically as sets of statements or propositions. This is not the only reason why many philosophers of science today regard the syntactic view of theories as being less helpful than what is termed the *semantic* view, wherein theories are regarded as sets of models (see van Fraassen 1980 for a now classic formulation of the semantic view). Morrison deploys a version of the semantic view in now representing the relations among different theories in condensed matter physics as one of partial isomorphism. Where explanatory structures coincide there is unification, but the parts of the models where isomorphism is found typically do not, by themselves, carry the explanatory burden. This is an interesting suggestion, one worth pursuing. But it does little, by itself, to illumine the relationship between condensed matter physics and particle physics.

Illuminating that relationship is, however, one of principle aims of Ang Wook Yi, a recent Ph.D. from the London School of Economics, who, like Morrison, finds the semantic view of theories more helpful in thinking about condensed matter physics. Yi suggests that we distinguish "global theories" from "substantial theories" (Yi 2001). 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, as on Morrison's view, 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.

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 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.[17]

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.

[17] One among the authors whom I would thus caution is Nancey Murphey; see, for example, Murphy 1999.

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Habe nun, ach! Philosophie[23],
Juristerei und Medizin,
Und leider auch Theologie
Durchaus studiert, mit heißem Bemühn.
Da steh ich nun, ich armer Tor!
Und bin so klug als wie zuvor;
Heiße Magister, heiße Doktor gar
Und ziehe schon an die zehen Jahr
Herauf, herab und quer und krumm
Meine Schüler an der Nase herum-
Und sehe, daß wir nichts wissen können!
Das will mir schier das Herz verbrennen.
Zwar bin ich gescheiter als all die Laffen,
Doktoren, Magister, Schreiber und Pfaffen;
Mich plagen keine Skrupel noch Zweifel,
Fürchte mich weder vor Hölle noch Teufel-
Dafür ist mir auch alle Freud entrissen,
Bilde mir nicht ein, was Rechts zu wissen,
Bilde mir nicht ein, ich könnte was lehren,
Die Menschen zu bessern und zu bekehren.
Auch hab ich weder Gut noch Geld,
Noch Ehr und Herrlichkeit der Welt;
Es möchte kein Hund so länger leben!
Drum hab ich mich der Magie ergeben,
Ob mir durch Geistes Kraft und Mund
Nicht manch Geheimnis würde kund;
Daß ich nicht mehr mit saurem Schweiß
Zu sagen brauche, was ich nicht weiß;
Daß ich erkenne, was die Welt
Im Innersten zusammenhält,
Schau alle Wirkenskraft und Samen,
Und tu nicht mehr in Worten kramen.
O sähst du, voller Mondenschein,
Zum letzenmal auf meine Pein,
Den ich so manche Mitternacht
An diesem Pult herangewacht:
Dann über Büchern und Papier,
Trübsel'ger Freund, erschienst du mir!
Ach! könnt ich doch auf Bergeshöhn
In deinem lieben Lichte gehn,
Um Bergeshöhle mit Geistern schweben,

Auf Wiesen in deinem Dämmer weben,
Von allem Wissensqualm entladen,
In deinem Tau gesund mich baden!
Weh! steck ich in dem Kerker noch?
Verfluchtes dumpfes Mauerloch,
Wo selbst das liebe Himmelslicht
Trüb durch gemalte Scheiben bricht!
Beschränkt mit diesem Bücherhauf,
den Würme nagen, Staub bedeckt,
Den bis ans hohe Gewölb hinauf
Ein angeraucht Papier umsteckt;
Mit Gläsern, Büchsen rings umstellt,
Mit Instrumenten vollgepfropft,
Urväter Hausrat drein gestopft-
Das ist deine Welt! das heißt eine Welt!
Und fragst du noch, warum dein Herz
Sich bang in deinem Busen klemmt?
Warum ein unerklärter Schmerz
Dir alle Lebensregung hemmt?
Statt der lebendigen Natur,
Da Gott die Menschen schuf hinein,
Umgibt in Rauch und Moder nur
Dich Tiergeripp und Totenbein.
Flieh! auf! hinaus ins weite Land!
Und dies geheimnisvolle Buch,
Von Nostradamus' eigner Hand,
Ist dir es nicht Geleit genug?
Erkennest dann der Sterne Lauf,
Und wenn Natur dich Unterweist,
Dann geht die Seelenkraft dir auf,
Wie spricht ein Geist zum andren Geist.
Umsonst, daß trocknes Sinnen hier
Die heil'gen Zeichen dir erklärt:
Ihr schwebt, ihr Geister, neben mir;
Antwortet mir, wenn ihr mich hört!
(Er schlägt das Buch auf und erblickt das Zeichen des Makrokosmus.)
Ha! welche Wonne fließt in diesem Blick
Auf einmal mir durch alle meine Sinnen!
Ich fühle junges, heil'ges Lebensglück
Neuglühend mir durch Nerv' und Adern rinnen.
War es ein Gott, der diese Zeichen schrieb,

Die mir das innre Toben stillen,
Das arme Herz mit Freude füllen,
Und mit geheimnisvollem Trieb
Die Kräfte der Natur rings um mich her enthüllen?
Bin ich ein Gott? Mir wird so licht!
Ich schau in diesen reinen Zügen
Die wirkende Natur vor meiner Seele liegen.
Jetzt erst erkenn ich, was der Weise spricht:
"Die Geisterwelt ist nicht verschlossen;
Dein Sinn ist zu, dein Herz ist tot!
Auf, bade, Schüler, unverdrossen
Die ird'sche Brust im Morgenrot!"
(er beschaut das Zeichen.)
Wie alles sich zum Ganzen webt,
Eins in dem andern wirkt und lebt!
Wie Himmelskräfte auf und nieder steigen
Und sich die goldnen Eimer reichen!
Mit segenduftenden Schwingen
Vom Himmel durch die Erde dringen,
Harmonisch all das All durchklingen!
Welch Schauspiel! Aber ach! ein Schauspiel nur!
Wo fass ich dich, unendliche Natur?
Euch Brüste, wo? Ihr Quellen alles Lebens,
An denen Himmel und Erde hängt,
Dahin die welke Brust sich drängt-
Ihr quellt, ihr tränkt, und schmacht ich so vergebens?
(er schlägt unwillig das Buch um und erblickt das Zeichen des Erdgeistes.)
Wie anders wirkt dies Zeichen auf mich ein!
Du, Geist der Erde, bist mir näher;
Schon fühl ich meine Kräfte höher,
Schon glüh ich wie von neuem Wein.
Ich fühle Mut, mich in die Welt zu wagen,
Der Erde Weh, der Erde Glück zu tragen,
Mit Stürmen mich herumzuschlagen
Und in des Schiffbruchs Knirschen nicht zu zagen.
Es wölkt sich über mir-
Der Mond verbirgt sein Licht-
Die Lampe schwindet!
Es dampft! Es zucken rote Strahlen
Mir um das Haupt- Es weht
Ein Schauer vom Gewölb herab

Und faßt mich an!
Ich fühl's, du schwebst um mich, erflehter Geist
Enthülle dich!
Ha! wie's in meinem Herzen reißt!
Zu neuen Gefühlen
All meine Sinnen sich erwühlen!
Ich fühle ganz mein Herz dir hingegeben!
Du mußt! du mußt! und kostet es mein Leben!
(Er faßt das Buch und spricht das Zeichen des Geistes geheimnisvoll aus. Es zuckt eine rötliche Flamme, der Geist erscheint in der Flamme.)