Physical Composition

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Abstract

Atomistic metaphysics motivated an explanatory strategy which science has pursued with great success since the scientific revolution. By decomposing matter into its atomic and subatomic parts physics gave us powerful explanations and accurate predictions as well as providing a unifying framework for the rest of science. The success of the decompositional strategy has encouraged a widespread conviction that the physical world forms a compositional hierarchy that physics and other sciences are progressively articulating. But this conviction does not stand up to a closer examination of how physics has treated composition, as a variety of case studies will show.

Keywords: composition, reduction, metaphysics, physicalism, Standard Model, condensed matter

1. Introduction

Atomistic metaphysics motivated an explanatory strategy which science has pursued with great success since the scientific revolution. By decomposing matter into its atomic and subatomic parts physics gave us powerful explanations and accurate predictions as well as providing a unifying framework for the rest of science. The success of the decompositional strategy has encouraged a widespread conviction that the physical world forms a compositional hierarchy that physics and other sciences are progressively articulating. But this conviction does not stand up to a closer examination of how physics has treated composition, as a variety of case studies will show.

Philosophers have tended to think of physical composition in spatiotemporal terms. But spatiotemporal considerations do not loom large in many varieties of composition that have proved important in modern physics. Increases in our understanding of phenomena in a given domain have often been facilitated by finding new ways of composing them out of their constituents. After a review of the philosophical as well as scientific background in section 2, section 3 examines a variety of ways in which physics has sought to decompose light into its parts in order to explain and predict its behavior. Section 4 highlights three general kinds of composition that may be abstracted from this examination, and section 5 shows how these recur in theories of matter. Section 6 highlights recent arguments as to why, contrary to popular belief, the Standard Model of elementary particles does not present us with any clear candidates for ultimate building blocks of the physical world. In section 7 I explain a fourth kind of physical composition characteristic of quantum theory. Section 8 shows how important several kinds of physical composition are to condensed matter physics, and why understanding the behavior of a sample of bulk matter at low temperatures requires one to decompose it into constituents in more than one way at once. In conclusion I draw some general morals from this examination of physical composition for the relation between physics and metaphysics.

2. Historical and philosophical background

The thought that the material world has a natural compositional structure exerted a powerful hold on the imagination of scientists and philosophers long before they were taken to be practicing separate disciplines. Among rival conceptions of this structure upheld by various pre-Socratic thinkers, it is the atomic hypothesis of Democritus and Leucippus that has had the most lasting influence on the subsequent development of science and philosophy. Atomistic ideas formed a heuristic backdrop to the seventeenth century scientific revolution, but only became integrated into the content of successful scientific theories after Dalton's explanation of regularities of chemical combination and Maxwell's kinetic theory of gases. The work of Einstein, Perrin and others early in the 20th century finally convinced scientists of the reality of atoms—ironically at around the time that Rutherford presented convincing evidence that, far from indivisible, the ατομος (atom) itself possessed an interesting internal structure. So the transformation from speculative metaphysics to experimental science deprived the atom of its fundamental status by locating atoms at an intermediate level in an emerging hierarchy.

Rutherford initially took the (neutral, gold) atom to be composed of a heavy, positively charged nucleus surrounded by much lighter negatively charged electrons: the nucleus itself turned out to be composed of an equal number of positively charged protons, together with a comparable number of neutrons. These constituents of ordinary matter were soon joined by a progressively growing collection of unstable "elementary particles" discovered in cosmic rays and then increasingly powerful particle accelerators. So by mid-century, physical science had already acknowledged a compositional hierarchy: gases and other phases of bulk matter composed of molecules; molecules composed of atoms; atoms composed of stable electrons, protons and neutrons (though free neutrons do slowly decay). These last three were then regarded as elementary particles, along with their antimatter twins (positrons, antiprotons and antineutrons), neutrinos, and a host of unstable mesons and baryons. By the 1970's, the study of these so-called elementary particles was unified by the quark hypothesis and the quantum gauge field theories of what became known as the Standard Model, though the predicative phrase "—of elementary particles" seemed no longer apt, because many baryons and mesons formerly considered elementary were now taken to be composite, including the proton and neutron, each composed of three quarks.

By extending the compositional hierarchy upward from atoms to molecules, science had connected physics to chemistry, and the advent of quantum mechanics at least promised a reduction of chemistry to physics, thereby unifying previously distinct branches of science. To many scientists and philosophers this raised the prospect of further such unification by progressive micro-reduction of still higher levels of a compositional hierarchy.

The philosophers Oppenheim and Putnam(1958) explicitly formulated such unity of science as a working hypothesis, and argued for its support from developments in molecular biology and neurology and the success of methodological individualism in the social sciences. A key premise in their argument for the unity of science was that the objects of theories in different branches of science are related by the part-whole relation: atoms are composed of elementary particles, molecules are composed of atoms, cells are composed of molecules, etc.

> When we come to branches with different universes [of discourse]—say, physics and psychology—it seems clear that the possibility of reduction depends on the existence of a structural connection between the universes by the "Pt" relation. (p.8)

They took the fact that the objects of different branches of science may be ordered by a hierarchy of levels to follow from the formal properties of the spatiotemporal composition relation.

> If the "part-whole" ("Pt") relation is understood in the wide sense, that *x* Pt *y* holds if *x* is spatially or temporally contained in *y*, then everything, continuous or discontinuous, belongs to one or another reductive level; in particular, to level 1 (at least), since it is a whole consisting of elementary particles. (p.11)

Oppenheim and Putnam also assumed that the number of levels is finite, so that level 1 designates a unique lowest level populated only by elementary particles. They thereby gave elementary particle physics a privileged status as the one branch of science capable of securing the unity of science by providing the ultimate building blocks and fundamental laws underlying the whole micro-reductive hierarchy. But microphysics could retain that privileged status even if there turned out to be an infinite descending chain of micro-reductive levels, with no *truly* ultimate building blocks or fundamental laws.

It is not surprising to find enthusiasm for micro-reduction also among such architects of the Standard Model as the physicists Weinberg(1992) and t'Hooft(1997). Weinberg has offered a qualified defense of what he calls "objective reductionism" in several places (1987,1992,1995,1998,2001). Like Oppenheim and Putnam, he sees elementary particle physics as fundamental because it occupies the place in a hierarchy to which all arrows of reductive explanation converge. In his (1995) he downplays the role of a composition relation in defining this hierarchy, emphasizing instead the role of laws or principles. In so doing he distinguishes between two kinds of reductionism–grand and petty–and undertakes to defend only the former.

> Grand reductionism is ...the view that all of nature is the way it is (with certain qualifications about initial conditions and historical accidents) because of simple universal laws, to which all other scientific laws may in some sense be reduced. (2001, p.11)

whereas

> Petty reductionism is the much less interesting doctrine that things behave the way they do because of the properties of their constituents. (*ibid*)

He continues

> Petty reductionism is not worth a fierce defense. Sometimes things can be explained by studying their constituents—sometimes not. ... In fact, petty reductionism in physics has probably run its course. Just as it doesn't make sense to talk about the hardness or temperature or intelligence of individual "elementary" particles, it is also not possible to give a precise meaning to statements about particles being composed of other particles.

But several examples he gives of "grand reductions" do involve composition relations. Newtonian theory could explain Kepler's laws only by assuming that sun and planets are composed of independently gravitating particles. Even without mentioning gravitational force, the theory of general relativity is able to explain that the motion of bodies approximately conforms to Newton's theory of motion and gravitation (e.g. in the solar system) only if those bodies are either idealized as particles or if their constituents are taken to contribute appropriately to the stress-energy tensor. Weinberg even says that the reduction of elementary particles to the principles of the Standard Model involved taking the fundamental particles themselves to be "bundles of energy" (2001, p.109), at least a metaphorical appeal to a composition relation. His difficulty in illustrating progress achieved by "grand reductionism" which did not involve appeal to a composition relation underscores Oppenheim and Putnam's point that reductive unification (of science *or* nature) by successive explanation of laws cannot occur unless these concern what are basically the same things—either strictly identical or related by composition.

Since the 1970's, physicalism has been a hotly-debated topic among philosophers of mind as well as philosophers of science. Many have tried to turn the vague slogan "everything is ultimately physical" into a precise yet substantive general thesis expressing a contemporary form of materialism. As Horgan(1993) notes

> Many philosophers were attracted by the thought that a broadly materialist metaphysics can eschew reductionism, and supervenience seemed to hold out the promise of being a non-reductive inter-level relation that could figure centrally in a non-reductive materialism.[1] (p.565)

The general idea was to acknowledge a certain explanatory/methodological autonomy of e.g. psychology from fundamental physics while insisting that the fundamental physical facts fix *all* the facts, whether or not we know the fundamental physical facts, and whether or not we know *how* they fix all the other facts. This idea may be made more concrete by connecting it to facts of a kind that contemporary physics deals in. Thus Merricks(1998) offered this formulation of what he called microphysical supervenience (MS) in order to argue *against* it:

> Necessarily, if atoms A_1 through A_n compose an object that exemplifies intrinsic qualitative properties Q_1 through Q_n, then atoms like A_1 through A_n (in all their respective intrinsic qualitative properties), related to one another by all the same restricted atom-to-atom relations as A_1 through A_n, compose an object that exemplifies Q_1 through Q_n.

He added in a footnote that

> The atoms of MS are the atoms of microphysics, not Democritus. Anyone committed to MS will probably think that the properties of both atoms and macrophysical objects supervene on the features and interrelations of yet smaller particles. My arguments against MS could easily be adapted to undermine a similar thesis about what supervenes on, for instance, quarks, leptons, and gauge bosons. (*ibid*)

Horgan(1982) had earlier advocated this localized supervenience principle:

> There do not exist any two *P*-regions which are exactly alike in all qualitative intrinsic microphysical features but different in some other qualitative intrinsic feature. (p.37)

Here a *P*-region is a space-time region of a possible world *W* in which all entities are, or are fully decomposable into, entities falling in the same specific natural kinds as those in the actual world, and where all *W*'s fundamental microphysical properties are properties mentioned in actual microphysical laws. The basic idea behind both formulations is to require that the physical facts determine all the facts about any class of objects by supposing that any object in that class be wholly composed of (sub-)atomic building blocks and that all their properties and relations be supervenient upon (i.e. wholly determined by) the microphysical properties and relations of these building blocks. Even earlier, Hellman and Thompson(1975) had explicitly separated ontological, determinationist and reductive physicalist theses in order to argue that a determinationist physicalism need not be reductive. They took ontological physicalism to be the claim that everything is exhausted by physical objects, meaning thereby that every concrete (i.e.

[1] Note the striking contrast with Weinberg's brief for reduction of laws, but dismissal of "petty reductionism".

non-abstract) object is wholly spatiotemporally composed of physical parts. They do not say exactly what spatiotemporal composition is. But there is a natural way of understanding it in the context of any classical space-time theory: *A* is a spatiotemporal component of *B* if and only if the space-time region occupied by *A* is wholly contained within that occupied by *B*.

Interest in composition among contemporary metaphysicians was further stimulated by van Inwagen(1990) and Lewis(1991). Lewis took an extremely liberal attitude toward composition, holding it to be necessarily true that *any* arbitrary collection of particulars composes a unique particular—their mereological fusion, without regard to spatiotemporal or other considerations. By contrast, van Inwagen held composition to require a peculiarly intimate relation among the parts of a whole. In the preface to his (1990) he stated ten convictions that functioned as constraints on his theorizing, including this one:

> I assume in this book that matter is ultimately particulate. I assume that every material thing is composed of things that have no proper parts: "elementary particles" or "mereological atoms" or "metaphysical simples".

In the rest of the book he struggles with the question "What else do such ultimate parts compose?", and concludes that the *only* acceptable answer is "living organisms"—no arms, legs, shoes, cell-phones, blood cells, the water and DNA molecules they contain, the bases guanine, adenosine, cytosine and thymine of the DNA or the hydrogen and oxygen atoms in the water. Few of his colleagues accepted this answer, and many alternatives have been proposed. Some vied with each other in their attempts to make the world safe for the many familiar and unfamiliar composite objects with which scientists and laymen confidently populate it. Others have advocated other exotic ontologies, including nihilists who reject even living organisms, as well as mereological essentialists like Lewis. But contemporary philosophical discussions proceed against some widely shared (though disputed) assumptions:

1) The physical world does have some kind of compositional structure.
2) It is the business of physics to investigate this structure, and specifically to seek out its lowest level, if any.
3) Available candidates for mereological atoms include elementary particles and fundamental field values.
4) "A good metaphysical or scientific theory should avoid positing a plethora of quite specific, disconnected, *sui generis*, compositional facts". (Horgan and Potrč, 2008)

How well do these assumptions comport with the way contemporary physics treats composition?

3. The decomposition of light

As a first example of the use of the decompositional strategy, consider how physics has approached the nature of light. Descartes already considered light itself an object worthy of scientific study, and in his first publication Newton(1671) proposed a powerful theory of light and colors. Newton took his experiments to have proved that sunlight consists of a mixture of rays "of divers refrangibilities." This mixture may be separated into its component types of ray, e.g. by passing sunlight through a prism. While rays of different types traced different paths through the prism, no individual ray was modified thereby. Newton tells us that "By the Rays of Light I understand its least Parts, and these as well Successive in the same Lines as Contemporary in several Lines." So Newton's rays are not straight geometric lines, but physical objects–corpuscles–that travel along them. He believed that sunlight is an aggregate of corpuscles, differentiated into types by some shared intrinsic property like size that accounted for their "divers refrangibilities". If he were right, sunlight would be composed of particles in much the same way that a beach is composed of sand grains. In each case, composition is simply a matter of aggregation. But, unlike a beach, each part of sunlight would be constantly moving, at a speed that depends on what it moves through and (in general) what type of particle it is.

Newton's theory decomposes light into its corpuscular constituents—his "rays". The experiments he describes in which the "divers rays" are separated out from white light by a prism or other means, and then selectively recombined by another prism or a lens, make vivid the nature of the composition relation in this case. On Newton's theory, light is an *aggregate* of its constituent corpuscles.[2] No "glue" or any kind of force is required to hold it together. Though not spatial, the composition relation remains purely spatiotemporal: a beam of light is unified solely by the closely similar spatiotemporal trajectories of its component corpuscles. This is true whether the corpuscles are of similar or different kinds. Decomposition of an aggregate into its component parts gives a first kind of physical decomposition. But a secondary notion of composition of *types* of light is naturally abstracted from this, as when Newton says that compound light that appears of one color (such as white) is composed of a variety of different "original and simple" sorts of light, each of which appears of a distinct primary color and is uniquely composed of rays of the same fixed "refrangibility" (refractive index).

In the 19th century, experimental investigations of the interference, diffraction and polarization of light resulted in Newton's particles being abandoned in favor of Young's and Fresnel's waves. Following Maxwell and Hertz, these waves were understood to be electric and magnetic, and after Einstein's relativity, light came to be thought of as constituted by the spatial and temporal variation of electromagnetic fields. While passage through a medium such as air affected this variation by slowing their passage, light waves could propagate freely through empty space. Newton's prism produced a spectrum not by sieving particles of light, but by performing a physical Fourier decomposition of the incoming sunlight into components of well-defined wavelength.

Maxwell's theory decomposes light into its constituent waves, each of definite wavelength and polarization. The wavelength decomposition is natural because of the linearity of the wave equation for electromagnetic fields in a vacuum or non-dispersive medium that is a consequence of Maxwell's equations. Each wave of fixed wavelength satisfying given boundary conditions is a solution, and so, therefore, is any linear sum (or integral) of such waves. Such *superposition* gives a second, non-spatiotemporal, kind of physical decomposition. The mathematics of Fourier decomposition applies much more widely: not only solutions to the linear wave equation, but *any* function from a very wide class has a Fourier decomposition into complex exponentials, each corresponding to a wave of definite wavelength and phase. The very mathematical promiscuity of such decomposition may prompt one to question its physical significance when one notes that a Ptolemaic analysis of geocentric motion by a system of epicycles and deferents can reproduce any observed planetary motion with arbitrary accuracy.[3] But I think the enormous utility of the technique in diverse applications throughout physics

[2] He calls (ordinary) light a "heterogeneous mixture", a "heterogeneous aggregate" and a "confused aggregate".

[3] Hanson(1960), http://videosift.com/video/Ptolemy-s-epicycles-can-trace-out-ANY-orbit-Doh

should at least prompt a more critical examination of the very notion of physical significance.

According to the classical theory, light of fixed wavelength may have any of a continuous range of polarizations that includes linear, circular and elliptical polarizations. Every such polarization may be decomposed into a linear superposition of just two basic polarizations with complex coefficients. But this decomposition is not unique, since the basis for the decomposition may itself be arbitrarily selected from a continuous range of candidates, including linearly polarized light along any pair of orthogonal axes transverse to its direction of propagation as well as right- and left-circularly polarized light. Since there is no natural basis for this decomposition, light has no privileged "polarization parts". Right-circularly polarized light may be considered a superposition of vertically and horizontally polarized light, or of light polarized at 45 and 135 degrees: but equally vertically polarized light is a superposition of right- and left-circularly polarized light

So what are the *parts* of sunlight, on this classical electromagnetic wave conception? Several answers seem possible.

1. Each electromagnetic wave of definite wavelength and polarization appearing with non-zero coefficient in a Fourier decomposition of the electromagnetic field corresponding to sunlight.
2. Each point/tiny region of space with non-zero electromagnetic field strength associated with the sunlight.
3. Each point/tiny region of space-time with non-zero electromagnetic field strength associated with the sunlight.
4. The sunlight in a region of space/space-time *has* no proper parts—the electromagnetic field that constitutes it is wholly present everywhere in that region.

As far as physics is concerned, the first answer is the most *useful*, predictively and explanatorily, since the mathematics of Fourier decomposition facilitates analysis of the effects of sunlight, including its effects on experimental apparatus such as prisms, diffraction gratings, polarizing filters, etc. Unlike on Newton's conception, sunlight has no "thing-like" parts on a classical wave conception, and this seems to drain the question of any metaphysical significance. Classical electromagnetic theory gives the pragmatist answer that sunlight has whatever parts it is most useful to regard it as being composed of.

But haven't we known since Einstein's Nobel-prize winning 1905 paper that light is actually made up of particles—now called photons? Feynman(1985) said:

> I want to emphasize that light comes in this form: particles. (p.15)

and

> Newton thought light was made up of particles—he called them 'corpuscles'—and he was right (but the reasoning that he used to come to that decision was erroneous). (p.14)

But another Nobel-prize winning expert on quantum optics, Lamb(1995) argued strongly that talk of photons is liable so dangerously to mislead the uninitiated that it should be permitted only among licensed users like Feynman. Do not try this at home! Contemporary quantum theory treats light, including sunlight, as a quantized electromagnetic field, whose field quanta are called photons. In the lowest energy state of this field—the vacuum state—no photons are present, though the field still has measurable effects (Lamb won his Nobel prize for detecting one such effect, now known as the Lamb shift). But there is no sunlight in the vacuum state.

Laser light (not sunlight) can be described by a so-called *coherent state* of the quantized field. For several reasons, this is the closest quantum analog to a classical electromagnetic wave. While the field is not assigned a definite (vector) magnitude anywhere, the expected result of measuring it varies from point to point in the same way as the magnitude of a classical field, while individual measurement results are subject to random fluctuations that decrease in relative proportion to this expected magnitude. Measurements would also reveal a pretty well-defined phase at each point. But it then follows that no determinate number of photons is present in a coherent state: repeated measurements of the number of photons present would give a statistical spread of results about a mean photon number (that need not be an integer). There are states corresponding to definite photon number, but in all these states the expectation value of the electric field is everywhere zero! The coherent light produced by a laser corresponds most closely to a classical electromagnetic wave of a precise wavelength.

In the quantum theory, each classical mode of light is quantized, where a mode corresponds to definite wavelength λ and polarization ε: one usually thinks of each mode as occupied by any number n=0,1,... of polarized photons, each of frequency $\nu = c/\lambda$, energy $h\nu$, and polarization ε. A general (pure) state of the quantized electromagnetic field is then a superposition of such states, represented as a vector in a Fock space with basis states of the form $|n_{\lambda,\varepsilon}, n_{\lambda',\varepsilon'}, \ldots\rangle$ – representing a photon number eigenstate with $n_{\lambda,\varepsilon}$ photons each of wavelength λ and polarization ε, $n_{\lambda',\varepsilon'}$ photons each of wavelength λ′ and polarization ε′, etc. Any vector in this space has a decomposition as a superposition of such basis states, and so a typical state vector is associated with an indefinite number of photons. One such vector represents a coherent state—a particular superposition of every integral number of photons in a single mode. A coherent state of light in a single mode may be decomposed in a basis of Fock states as follows

$$|\alpha\rangle = \exp(-|\alpha|^2/2)\, \sum_0^\infty \{\alpha^n/(n!)^{1/2}\}\, |n\rangle \qquad (1)$$

where $\alpha = |\alpha|\exp i\varphi$. The set of all coherent states forms an overcomplete basis of approximately orthogonal states in Fock space. So an arbitrary (pure) state also has a decomposition as a superposition of coherent states, each of which approximates a classical electromagnetic wave. It may therefore be thought of either as composed of a (typically indefinite) number of photons from various modes, or as partially constituted by each of a continuous range of distinct, approximately classical, electromagnetic waves. Since neither decomposition has priority, neither tells one what light represented by such a state is *really* composed of: a photon-number basis state may be decomposed into coherent states just as a coherent state can be decomposed into photon-number basis states.

There are other sources of roughly monochromatic light that is *not* coherent, some involving gas discharges: such light is sometimes called chaotic. It is produced in individual pulses, with random phase relations between pulses. According to both classical and quantum theory, the result is a broadening of the distribution of wavelengths and corresponding indefiniteness in phase of chaotic light as compared to coherent light. Sunlight has even less well-defined wavelength and phase than chaotic light from a gas discharge tube, because of the way it has been produced and transmitted through the atmosphere. Its quantum mechanical representation would not be as a superposition (in a basis of Fock states or coherent states, for example) but by a so-called mixed density operator.

This illustrates a third, distinctively quantum, kind of decomposition, namely *mixture*. A key role of the quantum state of a system is to yield probabilities for possible outcomes of measurements on that system. A measurable magnitude ("observable") is represented by a linear operator on the vector space associated with the system. Suppose the state of the system is represented by a vector. If the eigenvalues of this operator are all non-degenerate, with eigenvectors that span the space, then a measurement of the observable will yield an eigenvalue, and the probability that a measurement of the observable will yield a particular eigenvalue is basically just the square of the length of the projection of the vector representing the state onto the corresponding eigenvector. Now suppose that although one is ignorant of which of several pure states represents the state of a system, for each state one knows the probability that it correctly represents the system. Then one can calculate an overall probability for each possible outcome of a measurement of an observable on the system by first calculating the probability conditional on each possible pure state and then forming an average weighted by the probability one associates with these different possible states. Alternatively, one can proceed more directly by representing the state of the system not by a vector in its space, but by a *density operator* acting on that space. The probability of measuring a particular eigenvalue is then given by the trace of the product of this density operator with an operator that projects onto the corresponding eigenvector (more generally, eigenspace). This more general mathematical framework encompasses the original representation of states by vectors: a state is *pure* just in case its density operator projects onto a one-dimensional subspace spanned by the vector originally taken to represent it, otherwise it is *mixed*.[4] The generalization is not merely mathematical but conceptual. Section 7 will illustrate how one can also represent the state of a system by a density operator not in ignorance of its pure state vector, but knowing that its state cannot be represented by *any* vector.

An alternative representation of the (pure) coherent state (1) is as a density operator $W_\varphi \equiv |\alpha\rangle\langle\alpha|$. One can then express a maximally mixed state of this mode as a uniform phase average over coherent states with the same amplitude $|\alpha|$ but different phases φ as follows:

$$W_M = 1/2\pi \int_0^{2\pi} W_\varphi \, d\varphi \qquad (2)$$

or alternatively as a Poissonian mixture of Fock states:

$$W_M = \ni^{\infty}_0 \{\exp(-\langle n\rangle)\langle n\rangle^n/n!\} \, |n\rangle\langle n|. \qquad (3)$$

Ordinary sunlight would then be represented as a *further* mixture of states W_M from different modes. While it would therefore contain no definite number of photons, and have no definite wavelength, phase or polarization, it could still be thought of as composed of a mixture (not superposition) of states each corresponding to a definite photon number in each mode, or equally as a mixture (not superposition) of states each corresponding to a reasonably definite electromagnetic field intensity, phase and polarization.

The question "Is sunlight composed of photons or of electromagnetic fields?" has no context-independent answer according to contemporary quantum theories of light. In one context (for example, when considering discrete processes that respond to individual photons, such as photo-detectors) it may be appropriate to treat sunlight as a mixture expressed in a photon-number basis, in which case one can regard it as composed of an unknown number of photons of various energies and polarizations. In another context (for example, when considering continuous processes sensitive to the values of electric or magnetic fields) it may be appropriate

[4] An equivalent condition for a state represented by density operator ρ to be pure is $\rho^2 = \rho$.

to treat sunlight as the same mixture expressed in a coherent-state basis, in which case one might regard it as composed of electromagnetic waves of different wavelengths, albeit each with indeterminate amplitude, phase and polarization. In yet other contexts (e.g. when considering processes producing "squeezed light") some third expression may be preferable to thinking of light as composed of photons or of electromagnetic fields. The quantum theory of light repeats and expands on the *same* kind of pragmatist answer as the classical wave theory—that sunlight has whatever parts it is most useful to regard it as being composed of.

Since the quantum theory of light does not appear explicitly in the Standard Model it cannot be taken to represent physics's latest word on the composition of light. According to that Model, the quantized electromagnetic field emerges as a result of the spontaneous symmetry-breaking of the electro-weak interaction. In the canonical version of the Model, the photon then appears as a massless Goldstone boson through the Higgs mechanism associated with the Higgs field and associated Higgs particle that the Large Hadron Collider is currently attempting to detect. There is therefore a sense in which neither the quantized electromagnetic field nor its quanta (photons) can be considered fundamental: this field is a definite linear superposition of fields of *un*broken $SU(2)\mathrm{x}U(1)$ symmetry. Of course, since any such quantum superposition is invertible, this would not justify the conclusion that the fundamental parts of photons are other particles—the quanta of fields with unbroken symmetry: for it would be equally true that each of *these* fields is itself a superposition of electromagnetic and weak broken-symmetry fields. Such symmetry of a potential composition relation may be one consideration behind Weinberg's remark that it is not possible to give a precise meaning to statements about particles being composed of other particles.

But what is light *really* composed of? Isn't it the very business of physics to return a straight answer to this question? If Newton, Maxwell, Einstein, Feynman, Lamb and Weinberg can't tell us, don't we have to keep physicists' noses to the grindstone until they come up with a true theory that *does* tell us what light is composed of?

No. Physics neither does, nor should, try definitively to answer such questions about how the physical world is composed. But this should not be understood to leave these questions open for the die-hard metaphysician to pursue until she discovers their true answers. Rather, the physicist's pragmatic attitude toward composition should serve as a model to a metaphysician interested in the way the world is composed. How one answers the question as to whether *A*'s are composed of *B*'s depends on the context of inquiry in which one is engaged, and the criterion for correctness of the answer is whether it works—whether it helps one further that inquiry.

4. Three kinds of decomposition

I think we should learn two more lessons from these different accounts of the nature of light offered by successive physical theories. While the accounts differ radically, with little indication of convergence on an underlying ontology, there is a sense in which each proposes to decompose light into its constituent parts in order to understand its behavior. Each thereby provides an additional illustration of the scientific efficacy of the decompositional strategy in physics. This first lesson derives from a common feature of the accounts. But we can learn a second lesson from their diversity.

The previous section outlined three different ways in which physics has decomposed light into parts: aggregation, superposition and mixture. Newton took light to be a heterogeneous aggregate of corpuscles. Classical wave theory took light to be a superposition of waves of various wavelengths and polarizations. The quantum theory takes light to be either a superposition or a mixture of different components, where these components may be chosen either from a set each of whose members correspond to a definite number of photons, or from a set each of whose members corresponds (roughly) to a definite wavelength, or from any one of an infinity of other possible sets. Of these three decompositions, only the first is spatiotemporal, and even that is neither purely spatial nor purely temporal: the parts of a beam of Newtonian light are corpuscles, each of which has a similar spatiotemporal trajectory. One can also think of corpuscles of each particular type in such a beam as themselves composing a whole within the beam, thus introducing an intermediate compositional level. But the resulting three-level spatiotemporal compositional hierarchy still portrays light as what Newton appropriately termed a confused and heterogeneous aggregate.

Neither a superposition nor a mixture decomposes light into *spatiotemporal* parts of any kind. Superposition is not a standard part-whole relation, since the relation *being a component of* is not antisymmetric but symmetric. Corresponding to each state is a set containing all and only vectors that may appear as a component (with non-zero coefficient) in some way of expressing that state as a superposition: trivially, that includes the state itself. So the relation of being a component of is also reflexive. If the components of a superposition are required to be linearly independent but not necessarily pairwise orthogonal, then this relation is also transitive, in which case it is an equivalence relation whose equivalence classes correspond to superselection sectors of the vector state-space. Nonstandard symmetric but transitive part-whole relations have not been much explored, though they have been discussed as a way of understanding material constitution (Thomson(1998)), non-well-founded sets (Barwise and Moss(1996)) and Borgesian fiction (Sanford(1993)). But a single symmetric composition relation cannot found a compositional hierarchy of more than one level, and so would be of no help in Oppenheim and Putnam's(1958) projected unification of science.

What are the components of a mixed state? Several answers are possible. Any density operator may be diagonalized and then expressed in block-diagonal form, corresponding to a decomposition of the form

$$\rho = \sum_i (w_i/d_i)P_i$$

where $\sum_i w_i = 1$ and distinct P_i project onto distinct d_i-dimensional eigenspaces of the state space. One could take the components of ρ to be (typically mixed) states represented by the density operators P_i/d_i . Or one could regard the set of pure states represented by vectors in the image space of ρ as the components of ρ. Equation (3) of the previous section corresponds to the first kind of decomposition (with $d_i = 1$), while equation (2) is a decomposition into components of the second kind. On either choice, the resulting composition relation would be antisymmetric, making it a standard part-whole relation. But on neither choice could this relation be naturally extended to more than two levels of a putative hierarchy: transitivity would only hold trivially.

Contemporary physical theories of light do offer ways of wholly decomposing it into parts in order to explain and predict its behavior. But the composition relations they employ do not involve spatiotemporal relations, and their formal properties exclude an extension to higher levels of a putative compositional hierarchy. One is led to very similar conclusions by an examination of contemporary physical theories of matter, as the next section will show.

5. The decomposition of matter

Here is a popular account of the ultimate building blocks of matter. Some 80 years ago physicists took the protons, neutrons and electrons of which atoms are composed to be the ultimate constituents of matter. But after further investigation physicists have now discovered that electrons are just one of four kinds of lepton, while each proton and neutron is itself composed of three quarks of two kinds, and more exotic matter is composed of two or three of these and/or quarks of four more kinds. That leaves out the photons we were just talking about, but they don't really count as material anyway, since each has zero mass and so cannot be brought to rest to enter into composition with anything.

Kaons are among the more exotic unstable forms of matter. Each is composed of two quarks. There are two kinds of electrically charged kaon, one with the same (negative) charge as the electron, the other with an equal and opposite electric charge: and there are two different kinds of kaon, each of which has zero charge—dubbed K_0 and $\overline{K}_0$. Neutral kaons of each type have the same mass as well as charge, but the types are distinguished from each other by their opposite values of a further magnitude called (for obvious historical reasons) *strangeness*, a distinction revealed by the different circumstances in which kaons of each type were first detected as well as how the different types interact with other matter. For each constituent of matter there is a corresponding constituent of so-called *antimatter* with opposite values of charge and other similar intrinsic magnitudes. Just as the positron is the antiparticle of the electron, K_0 and $\overline{K}_0$ are each other's antiparticles. This is accounted for by the extension of the notion of antimatter to their constituent quarks: while a K_0 is composed of a down quark and a strange antiquark, a $\overline{K}_0$ is composed of a down antiquark and a strange quark: we can write these compositional facts as follows $K_0 = d\overline{s}$, $\overline{K}_0 = \overline{d}s$. So we seem to have a perfectly straightforward answer to the question "What are neutral kaons composed of?"

But now it is time to dig deeper to reveal the limitations of the popular account! Kaons are *hadrons*—just as a proton or neutron is said to be composed of three quarks, a kaon is said to be composed of a quark-antiquark pair—so they are subject to the same strong interquark interaction that holds atomic nuclei together despite the electrical repulsion of the protons they contain. I will say more about this interaction shortly. The strong interactions that produce kaons in cosmic ray collisions or high energy accelerators like the LHC conserve net strangeness as well as net electric charge. So even though kaons are not stable, a kaon cannot decay by itself through a process mediated by the strong interaction. But just as a neutron outside the nucleus can decay into a proton (plus an electron and antineutrino) through the weak interaction associated with certain kinds of radioactivity, so too a kaon can decay through the weak interaction since that need not conserve strangeness. But while a free neutron has a half-life of about ten minutes, a free neutral kaon has a much shorter half-life before it decays through the weak interaction.

Neutral kaons have two decay modes through the weak interaction: a neutral kaon can decay either into two pions or into three pions: the half-life for 2-pion decay is just less than 10^{-10} seconds, while that for 3-pion decay is over 500 times longer. So after a billionth of a second or so, any remaining neutral kaons in a beam will almost certainly decay by emitting three, rather than two, pions. But if the beam is then passed through a thin sample of ordinary matter, most kaons in the emerging beam decay quickly into *two*, not three pions. It is as if the longer-lived kaons have been regenerated by passage through the target! This disappearance and "regeneration" of the 2-pion decay mode can be repeated by passage through a sequence of thin samples until the beam gets too weak to be observed. It is explained as follows. Any $\overline{K}_0$'s in the beam will be removed when it passes through the sample because they will interact strongly with the protons and neutrons it contains. But most K_0's will pass right through, since conservation of strangeness in strong interactions prevents any similar reaction with ordinary nuclear matter. So the emerging beam will consist almost exclusively of K_0's, which can go on to decay only through the weak interaction. But the weak interaction (very nearly!) obeys a symmetry principle (CP-invariance) governing such weak decays: 3-pion decays are possible only from states of one kind of symmetry, while 2-pion decays are allowed only from states with a different symmetry. And *neither* K_0's *nor* $\bar{K}_0$'s have *either* of these two symmetries! Now we have a puzzle, since neutral kaons do indeed decay. The solution to the puzzle teaches us something important about composition in physics.

Instead of thinking of neutral kaons as coming in two kinds—K_0's and $\bar{K}_0$'s—think of a neutral kaon as having a symmetry permitting it to decay into two pions if and only if it is of one kind (K_0^s, "s" for short) and having a symmetry permitting it to decay into three pions if and only if it is of another kind (K_0^l, "l" for long). What is the relation between these two ways of classifying neutral kaons into kinds? K_0^s and K_0^l can't be viewed as forming subcategories of K_0's and $\bar{K}_0$'s (or *vice versa*) because of the phenomenon of K_0^s "regeneration". Rather, each individual K_0 or $\bar{K}_0$ must be considered to be partly K_0^s and partly K_0^l; symmetrically, each individual K_0^s or K_0^l must be considered to be partly K_0 and partly $\bar{K}_0$. This idea is better expressed in mathematics than ordinary language, as follows

$$|K_0^s\rangle = 1/\sqrt{2}(|K_0\rangle + |\bar{K}_0\rangle), \qquad |K_0^l\rangle = 1/\sqrt{2}(|K_0\rangle - |\bar{K}_0\rangle) \qquad (4)$$

$$|K_0\rangle = 1/\sqrt{2}(|K_0^s\rangle + |K_0^l\rangle), \qquad |\bar{K}_0\rangle = 1/\sqrt{2}(|K_0^s\rangle - |K_0^l\rangle) \qquad (5)$$

The mathematics implies that any individual neutral kaon state can be expressed as a *superposition* of its component K_0 and $\bar{K}_0$, and also as a *superposition* of its component K_0^s and K_0^l. These superpositions express not only what percentage each component contributes, but also how these contributions are related in composing the whole. (The coefficients in a superposition are complex numbers, the squares of whose moduli give their relative percentages, while their complex arguments give their relative phase. The relative phase in a beam of neutral Kaons *changes* in a regular way, producing *oscillations* between K_0 and $\bar{K}_0$ even in empty space!) One might continue to think that the K_0, $\bar{K}_0$ decomposition is somehow fundamental, based on the popular account I began with. For this specified the quark composition of K_0 and $\bar{K}_0$, not that of K_0^s and K_0^l. But quarks can also superpose! We can just as well write:

$$|K_0^s\rangle = 1/\sqrt{2}(|d\bar{s}\rangle + |\bar{d}s\rangle), \qquad |K_0^l\rangle = 1/\sqrt{2}(|d\bar{s}\rangle - |\bar{d}s\rangle) \qquad (6)$$

where the two quark states on the right of each equation are now expressed as superpositions. These superficially incompatible but actually equivalent ways of regarding neutral kaons as composed of parts may remind you of the different but equivalent ways of decomposing light according to current quantum theory. Of course this is no coincidence. Notation such as $|d\bar{s}\rangle$ represents a quantum state of a quantized quark field that may be thought of as containing one down quark and one strange antiquark in just the same way that the quantum state $|n\rangle$ may be thought to contain exactly *n* photons. Regarded as quanta of the quark field of quantum chromodynamics, quarks are no more substantial than photons (despite their nonzero rest mass and the fact that they are fermions rather than bosons—a distinction whose importance will become clear in section 8).

How do quarks compose protons and neutrons (stable constituents of the nucleus) as well as kaons and many other unstable particles? The composition relation in this case is certainly not simply spatiotemporal. In the Standard Model, the strong interactions among quarks that bind them into hadrons are the subject of quantum chromodynamics. Just as photons are the massless quanta of the quantized electromagnetic field, so-called gluons are the massless quanta of the "color" field responsible for the strong interaction. As their name suggests, physicists think of them (at least informally) as gluing together quarks into hadrons. Although its anomalous fractional electric charge (−1/3 or +2/3 that of the magnitude of the charge of the electron) would make an isolated quark stand out, none have been detected, despite at least one unconfirmed claim. The "glue" appears so strong as to permanently confine quark constituents within hadrons: it is as if the attractive force between isolated quarks *increases* with the distance between them, though talk of force here must be understood metaphorically, since quantum chromodynamics does not treat interactions in terms of anything like Newtonian forces.

In popular expositions, physicists often appeal to a different metaphor to explain how the strong interactions between quarks bind them into hadrons: the metaphor of exchange of gluons. Taking this metaphor seriously would lead one to conclude that a proton (say) is composed not only of three quarks, but also of the gluons whose exchange holds it together. But it becomes clear that it should *not* be taken so seriously when one realizes that any gluons involved in any such exchange would be *virtual* rather than real—the existence of a real particle with the relevant momentum and energy within a proton would be incompatible with the relativistic energy-momentum relation for massless particles. The metaphor of exchange of virtual gluons is further elaborated by considering a proton to be surrounded by a "sea" of virtual quarks as well as gluons.[5] I think that it is because he was aware that the metaphor cannot be cashed out literally within quantum chromodynamics that Weinberg acknowledged that it is not possible to give a precise meaning to statements about particles being composed of other particles. We shall now see that it is hard to understand a fundamental quantum field theory such as quantum chromodynamics as talking about particles at all.

6. The ontology of quantum fields

The leptons, quarks, gluons, photons, and the *W* and *Z* bosons that are associated with the weak interaction responsible for such radioactive decays as those of neutral Kaons and the free neutron are all viewed in the Standard Model as quanta of associated fundamental quantized fields. Quanta associated with a fermionic field (leptons, quarks) are sometimes considered material particles, while quanta associated with a bosonic field (gluons, photons and *W* and *Z* bosons) are thought of as responsible for the fundamental interactions mediated by that field—strong or electroweak. All these Standard Model quanta have been detected in high energy accelerators: the LHC is currently attempting to detect a final Standard Model "particle", the Higgs boson, the

[5] "Protons and neutrons are comprised of three valence quarks held together by the exchange of gluons, along with a quark-gluon sea of particles that are constantly popping into and out of existence." http://www.jlab.org/visitors/science/study.html

quantum of the Higgs field believed to be responsible for electroweak symmetry breaking as well as the mass of all massive Standard Model particles.

Despite the enormous amount of research that has gone into developing string theories, supersymmetry, loop quantum gravity and other attempts to go beyond it, the Standard Model is currently physics's best bet for a fundamental theory of all matter and forces (other than gravity which is still best understood in terms of Einstein's theory of general relativity). So anyone looking for ultimate building blocks of the physical world may expect to find candidates for that status in the ontology of the Standard Model. Since that Model itself rests on the quantum field theories of quantum chromodynamics and the unified electroweak theory that has absorbed quantum electrodynamics, one naturally looks to those theories to provide the ontology underlying the Standard Model. So it is important to ask what a quantum field theory is ultimately about—what are the objects in its universe of discourse, to use Oppenheim and Putnam's terminology. In so far as a string theory (or *M*-theory) is also a form of quantum field theory, this question will retain its relevance even if the Standard Model comes to be superseded by such a theory.

An obvious answer is that a quantum field theory is about particles—the quanta of the field—photons, in the case of the quantized electromagnetic field. As I noted earlier, Feynman(1985), himself a creator of quantum electrodynamics, gave this answer.

> I want to emphasize that light comes in this form: particles. (p.15)
>
> Newton thought light was made up of particles—he called them 'corpuscles'—and he was right… (p.14)

But section 4 already suggested an alternative answer—fields—by showing how the quantum theory of light permitted a decomposition of the quantum state of light in a basis of coherent states of the field. Here was Wald's(1994) answer:

> Quantum field theory is a theory of *fields*, not particles. Although in appropriate circumstances a particle interpretation of the theory may be available, the notion of "particles" plays no fundamental role, either in the formulation or interpretation of the theory. (p.2)

Davies(1984) apparently rejected both these answers by adopting an instrumentalist approach to the question.

> There are quantum states and there are particle detectors. Quantum field theory enables us to predict probabilistically how a particular detector will respond to that state. That is all. That is all there can ever be in physics, because physics is about the observations and measurements that we can make in the world. We can't talk meaningfully about whether such-and-such a state contains particles except in the context of a specified particle detector measurement. (p.69)

This is an instrumentalist approach (in the Bohrian tradition) in so far as it treats a quantum state merely as an intellectual tool used for calculating probabilities of detector responses rather than representing any "element of physical reality".

Several philosophers of physics have now produced powerful arguments against both particles and fields as providing a fundamental ontology for a quantum field theory— as elements of its physical universe of discourse, thought of as a domain over which its quantifiers would range in some hypothetical Quinean regimentation in first-order logic.[6] Teller(1995) peeled off familiar particle-like features such as spatial localizability, following continuous spatiotemporal trajectories and labelability, leaving a core notion of quanta that may be aggregated but not counted. But Fraser(2008) argued that interacting quantum field theories do not admit even such entities into their fundamental ontology.

> Quantum field theory (QFT) is the basis of the branch of physics known as 'particle physics'. However the philosophical question of whether quantum field theories genuinely describe particles is not straightforward to answer. What is at stake is whether QFT, one of our current best physical theories, supports the inclusion of particles in our ontology. (p.841)
> ...because systems which interact cannot be given a particle interpretation, QFT does not describe particles. (p.842)

If quantum field theory cannot be understood as positing a particle, or even quanta, ontology, a natural reaction is to revert to a field ontology as the default option. But Baker(2009) has shown that this option also faces formidable obstacles.

> The notion that QFT can be understood as describing systems of point particles has been all but refuted by recent work in the philosophy of physics. (p.585)

however

> the most popular extant proposal for fleshing out a field interpretation is problematic. ..two of the most powerful arguments against particles are also arguments against such a field interpretation. … If the particle concept cannot be applied to QFT, it seems that the field concept must break down as well. (*ibid*, pp.585-6)

While I believe it would be a mistake to conclude with Davies that particles (and also fields) don't exist, these arguments at least seriously undermine the assumption that contemporary theories of fundamental physics present us with candidates for ultimate building blocks from which the physical world might be composed. They rather suggest that while talk of fundamental fields and Weinberg's elementary particles as bundles of energy play an essential heuristic role in applications of the Standard Model, the decompositional strategy has indeed "probably run its course" here.

7. Subsystem Decomposition and Entanglement

There is another kind of composition that figures importantly in quantum theory, associated with entanglement. The idea of entanglement is often illustrated by considering a pair of spin ½ particles: for example, an electron-positron pair emerging from the decay of a neutral pion. The pair is naturally taken to be composed of the electron and positron as it parts. Considered in isolation, the spin-state of the electron could be represented by a vector in one two-dimensional vector space, and that of the positron by a vector in another two-dimensional vector space. The spin-state of the pair is also represented, this time by a vector in a space whose dimensionality is the *product* of those two vector spaces—in this case a four-dimensional space.

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[6] For some influential arguments against a particle ontology, see in particular Malament(1996), Halvorson and Clifton (2002).

$$|\psi_S\rangle = 1/\sqrt{2}(|\uparrow_e \downarrow_p\rangle - |\downarrow_e \uparrow_p\rangle) \quad (7)$$

But now there is *no* vector representing the spin state of either electron or positron in its own 2-dimensional space: they were born with their spin-states entangled.

Schrödinger, who introduced the term ‘entangled’ (‘verschränkt’ in the original German), called it not one, but *the* characteristic of quantum mechanics—the one that forces its entire departure from classical ways of thinking. When one has more than one quantum system, whose collective state is represented by a vector in a suitable product space, it is typically not possible to represent the state of any of them by a vector in its own state space. The basic reason for this is that, unlike in classical physics, the state spaces of component quantum systems combine to form the state space of the whole not by *addition* of their individual dimensions, but by *multiplication* of their individual dimensions. One can still represent the quantum state of each component of an entangled system (the electron and positron in the example) separately—not by a vector but by a density operator. These states are known as improper mixtures, since their mixed density operators cannot be understood as devices for representing the epistemic probability that the particle is in a definite but unknown pure (vector) state.

In giving a general explanation of entanglement I used the expression ‘quantum system’. In the example, it is natural to think that the electron and positron are the subsystems that compose the quantum system that is the pair. But the mathematics underlying quantum entanglement allow for a more liberal understanding of ‘quantum system’, even in this example. For example, an electron’s spin is only one of its features: other features (independent degrees of freedom) may be represented in a different vector space—an infinite-dimensional wave-function space used to represent its spatial state. The electron’s *total* state is then represented by a vector in the (tensor) product of these two spaces.[7] If one follows the lead of the mathematics, then the electron should now be thought to be composed of not one but *two* quantum systems—a spin system and a spatial system. Explicit statements of this view of quantum systems may be found in well-respected texts, such as that by Peres(1993). He uses the example of a Stern-Gerlach device, which entangles a silver atom’s position state with its spin state, so that the atom is neither here nor there but in an entangled superposition of states corresponding to being here with spin up along some direction, and being there with spin down.

Now, in general, a product vector space does not have a unique factorization. This is true also for the tensor product Hilbert space H used to represent the state of a quantum system, the state of each of whose subsystems is represented in a Hilbert space that is a factor of H. Consider the electron and proton in a hydrogen atom. As far as position and momentum are concerned, the atom’s state may be represented in a Hilbert space that is a product of a space for the electron and a space for the proton. But that is *not* how one decomposes the product space before solving the Schrödinger equation to understand the structure of the hydrogen atom. To do that, one decomposes it into a product, one of whose elements is used to represent the position/momentum of the electron *relative to* the proton, while the other is used to represent the center of mass position/momentum of the atom as a whole.

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[7] This is the natural representation when the electron is treated within non-relativistic quantum mechanics. Dirac’s relativistic theory of the electron reveals a more intimate connection between its spin and spatial states.

We may call the phenomenon described in the last paragraph the *ambiguity* of subsystem decomposition. In general, subsystems of a quantum system may be selected in more than one way, and the resulting subsystem structure does not form a linear but only a partial order. This is very different from the hierarchical structure described by Oppenheim and Putnam(1958). While the subsystem relation provides an extremely fine compositional structure within the set of systems studied by physics, many of the systems within this structure will likely strike non-physicists as somewhat gerrymandered, even though the division into such systems may be just what is needed for the predictive and explanatory purposes of physics itself. It is worth looking more closely at one such division.

Recent experiments have succeeded in coupling optical and mechanical systems with the goal of producing entanglement between their quantum states. In one such experiment, directed by Markus Aspelmeyer at the University of Vienna, an optical cavity was constructed with a tiny mirror at one end, mounted in such a way that it is free to vibrate, approximately as a simple harmonic oscillator. Strong coupling has already been demonstrated between this mechanical mode of the mirror and an optical mode of the cavity. The aim is now to cool the apparatus down until the mirror is in its quantum mechanical ground state, and then to entangle this with the state of the electromagnetic field in the cavity. Here is how Markus described what he is studying in an interview.

> We can generate this bipartite system where it doesn't make sense at first to talk about optics or mechanics, because it is just one opto-mechanical big mess—a quantum lump, or whatever you want to call it.

What are the parts of this "quantum lump"?

Someone might say "The mirror and the field". Someone else (a contemporary metaphysician?) might say "Since the mirror is composed of atoms, which are composed of quarks and electrons; while the field in the cavity is composed either of photons or of basic field-elements; these are the *ultimate* parts of the quantum lump."

But both of these answers miss the point of the experiment, which is designed to couple two quantum systems. One of these systems is *the center of mass* of the mirror. What is the other system? It is *not* simply the field in the cavity. That would not be experimentally feasible, since the cavity field's natural frequency is many orders of magnitude greater than the mirror's natural frequency of vibration. But the cavity field is produced and maintained by an external laser beam tuned to a frequency that differs very slightly from its own natural frequency. This produces *beats* in the cavity field at a much lower frequency that can be tuned to the mirror's center of mass natural vibration frequency. It is *this* "mode" of the quantized electromagnetic field in the cavity that constitutes the second part of the bipartite quantum system the experiment is designed to study!

The part-whole relation *QS*: *being a quantum subsystem of* defined by factorization of the Hilbert space tensor product has interesting formal properties, and so does its state-dependent sub-relation *being an entangled subsystem of*. I shall denote the latter relation *Th* to abbreviate the more memorable name '*is a thread of*'.

QS is a standard part-whole relation in so far as it is reflexive, transitive and antisymmetric, provided we admit a system as an (improper) subsystem of itself. *QS* also satisfies a condition Varzi(2010) calls *Strong Supplementation*. In words, if a quantum system *t* is not a subsystem of a system *s*, then there must be a remainder---a (proper or improper) subsystem of *t* that shares no common subsystem with *s*. But *QS* fails to meet a further condition

of *Complementation* (Varzi, p.23): in words, the condition that if *t* is not a subsystem of *s* then there is a system whose subsystems are exactly the subsystems of *t* that have no subsystems in common with *s* – i.e. are disjoint from *s*. This is shown by the example of the hydrogen atom, the solution to whose Schrödinger equation depends on a decomposition into subsystems corresponding to relative and center-of-mass coordinates. The hydrogen atom is not a subsystem of the proton, but there is no subsystem of the hydrogen atom whose subsystems are just the electron, the center-of-mass position subsystem and the electron-proton relative-position subsystem. All three of these subsystems are disjoint from the proton subsystem, since none of them share any subsystems with it (or indeed with each other). But it is still natural to single out the electron subsystem as the unique relative complement of the proton subsystem, since the electron is the only subsystem which composes with the proton to form the hydrogen atom.
The same example shows that *QS* violates an important mereological principle Varzi(p.39) calls *Unrestricted Sum*. Applied here, that principle says that every collection of subsystems of a system composes some system of which they are also subsystems but which has no other subsystems disjoint from all of them. The electron, proton and center-of-mass subsystems of a hydrogen atom compose no such system as their "mereological sum". Consequently *QS* does not satisfy all the axioms of systems of mereology like that of Lewis(1991), in which it violates the principle of Unrestricted Composition.

In all these respects *QS* has the same formal properties as the classical subsystem relation *CS* derived from the Cartesian product construction for composing the state spaces of classical systems to get the state space of the system they compose. This is true despite the important formal difference that classical state spaces compose by Cartesian product (direct sum) while quantum mechanical state spaces compose by direct (tensor) *product*. (That is why the dimension of the classical mechanical state space for a system is the sum of the dimensions of its subsystems' state spaces, while the quantum mechanical state space of the analogous system is the product of the dimensions of its subsystems' state spaces.)

A *partition* of an object is a set of non-null, non-overlapping parts that together compose that object. Because of the ambiguity of subsystem decomposition, a quantum(classical) system may be partitioned into subsystems by *QS* (*CS*) in more than one way. Such a partition may admit further refinement as some of its parts are themselves partitioned. One way to refine partitions is to intersect them. An intersection Χ of two partitions Π, Ξ is a partition such that every element of either Π or Ξ is composed of elements of Χ: this definition has a natural generalization to the intersection of an arbitrary set of partitions of a system. Not every set of partitions of a system has an intersection: partitions with an intersection are compatible, otherwise they are incompatible. Partitions of an object by a part-whole relation that violates Complementation may or may not be compatible: distinct partitions of a hydrogen atom into electron/proton subsystems, and into center of mass/relative motion subsystems are not compatible.

Appeal to incompatible partitions of a system may be required to explain different aspects of its behavior. If these are considered equally natural, the system cannot be taken to be composed of a privileged set of basic or ultimate component parts corresponding to an intersection of all partitions of that system. Classically, a partition of a mechanical system into subsystems associated with each of its constituent particles may be considered more natural than a partition into centre-of-mass and relative-motion subsystems. The quantum mechanical treatment of systems like the hydrogen atom may suggest that this is true also in quantum theory.

But our most fundamental quantum theories are quantum field theories and, as noted in the previous section, these do not describe particles.

Interesting features of *QS* with no classical analog appear when one considers its sub-relation *Th*, a part-whole relation which has no classical analog. *Th* has many properties of a composition relation, even though it is state-dependent. Since no system is ever a thread of itself, *Th* is not reflexive, so it is best thought of as a *proper* part relation. It is asymmetric, and the following argument shows it to be transitive.

A state of a system *S* is *bipartite separable* if and only if its density operator satisfies

$$\rho_S = \ni_{\mathrm{i}}\, p_{\mathrm{i}}\, (\rho^i_a \otimes \rho^i_b) \qquad (8)$$

for some subsystems *a*,*b* of *S*, where *i* ranges over a denumerable set and $\ni_{\mathrm{i}}\, p_{\mathrm{i}} = 1$. A system *a is a thread of S* (*aThS*) if and only if both *a* and its relative complement *b* are subsystems of *S* and the state of *S* is not in this way bipartite separable into states of *a* and *b*. Suppose that *a* is a thread of some system *S* because its relative complement is a subsystem *bc* composed of disjoint subsystems *b*,*c* satisfying

$$\rho_S = \ni_{\mathrm{i}}\, p_{\mathrm{i}}\, (\rho^i_a \otimes \rho^i_{bc}) \qquad (9)$$

It follows that

$$\rho_{ab} = Trace_c\, \rho_S \qquad (10)$$
$$= \ni_{\mathrm{i}}\, p_{\mathrm{i}}\, (\rho^i_a \otimes Trace_c \rho^i_{bc}) \qquad (11)$$
$$= \ni_{\mathrm{i}}\, p_{\mathrm{i}}\, (\rho^i_a \otimes \rho^i_b) \qquad (12)$$

for some ρ^i_b. Hence ρ_{ab} is bipartite separable with subsystems *a*,*b*. Conversely, if *a* is a thread of *b*, then it is also a thread of any system *S* of which *a*,*b* are both subsystems. *A fortiori*, if *a* is a thread of *b*, and *b* is a thread of *S*, then *a* is a thread of *S*. So *Th* is a transitive relation. But it still fails to define a robust compositional hierarchy, because it is state dependent. Call part of an object a *component part* if and only if it is freely available to act as an independent unit in other compositional contexts.[8] Threads of a system are not its components parts.

Note finally that a quantum system *S* with incompatible partitions Π, Ξ by *QS* may be in a state that is bipartite separable with respect to Π even though each of its parts with respect to Ξ is a thread of S.[9]

8. Parts of condensed matter

Even before the development of quantum theory in 1925-6 it was realized that both electrons and (the then still controversial) photons displayed behavior not to be expected from candidates for ultimate building blocks of a compositional hierarchy. Rather than acting as a set of independent individuals, each with distinct existence, a collection of photons or of electrons displays collective behavior not mediated by forces or other influences between them. Atomic electrons obey Pauli's exclusion principle—that no two of them can have the same set of quantum

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[8] Compare Varzi(2010, pp.3-4).

[9] Seevinck(2008, p.38) gives an example of a pure state in a 6-dimensional Hilbert space that is separable in one tensor product decomposition $H_6 = H_2 \otimes H_3$ but not in a distinct decomposition $H_6 = H'_3 \otimes H'_2$.

numbers: while even when introducing the "heuristic point of view" now known as his light quantum, or photon, hypothesis Einstein was well aware that any such particles could not always be regarded as wholly independent of one another.

Electrons, quarks and other half-integral elementary particles are called fermions because they obey Fermi-Dirac statistics as a consequence of the fact that the (pure) quantum state of any collection of fermions of the same kind must change sign when all degrees of freedom associated with any two of them are exchanged. Photons, gluons and other integral spin particles are called bosons because they obey Bose-Einstein statistics as a consequence of the fact that the (pure) quantum state of any collection of bosons of the same kind must remain unchanged when all degrees of freedom associated with any two of them are exchanged. Equivalently, the Fock space of states for a bosonic (fermionic) quantum field is an infinite direct sum over n = 0,1,2,... of symmetrized (anti-symmetrized) n-fold tensor products of the space in which the states of a single particle may be represented. It follows that the state of any collection of fermions of the same kind (what physicists confusingly call 'identical' fermions) is always entangled, while that of any collection of "identical" bosons is almost always entangled—the exception being the simple product state. But a collection of bosons represented by a product state displays striking collective behavior of its own.

Following an idea of Bose, Einstein in 1925 predicted that if a gas of non-interacting bosons were cooled to a sufficiently low temperature many or even all of its constituent bosons would enter their lowest energy state—a process now known as Bose condensation. Complete Bose condensation would be represented by the product of the ground states of all the bosons. It was not until 70 years later that Bose condensation was achieved experimentally in a dilute gas of rubidium.[10] But striking phenomena observed much earlier in other condensed matter systems are also now attributed to similar quantum behavior involving Bose-Einstein statistics. This includes low temperature superconductivity in metals like tin and superfluidity in liquid helium.

Alert readers will have noticed a *non sequitur* between the last two paragraphs. The first concerned only elementary bosons and fermions of the Standard Model, while the second assumed that atoms of rubidium, and perhaps(?) also of tin and helium, are themselves bosons. This raises an important issue: what determines whether an atom or other non-elementary "particle" is a boson, a fermion or neither? Answering this question requires a careful examination of how a composite "particle" is composed out of more elementary parts. This will reveal a rich variety of different physical part-whole relations, none of them purely spatiotemporal.

Hydrogen is a diatomic molecular gas (H_2) under normal conditions of temperature and pressure. But Fried *et al*.(1998) cooled and trapped a dilute gas of monatomic spin-polarized hydrogen (H) and, after further cooling to a temperature of about 50μ , about 5% of the gas formed a Bose-Einstein condensate (BEC). Clearly the hydrogen atoms were acting as bosons, even though each contained a single unpaired electron bound to a single proton. This raises the question "Under what circumstances can a pair of fermions be treated as an elementary boson?", to quote the first sentence of Chudzicki *et al*.(2010).[11] BECs have now been formed from several

[10] Anderson *et al*. (1995)

[11] It does so at least if one assumes that a proton can be treated as an elementary fermion, even though it is in some sense composed of three elementary fermionic quarks. Of course this assumption raises the analogous question "Under what circumstances can a collection of

other dilute gases besides rubidium and hydrogen, so the question must be generalized to multi-electron atoms whose nuclei contain many neutrons as well as protons. But it may be best to begin by considering hydrogen as the simplest case.

The spin of all the electrons in spin-polarized H are aligned, and in the ground state in a high magnetic field at very low temperatures essentially all their nuclear spins are also aligned. Consider hypothetical processes that would involve exchanging the electrons, protons or both between two H atoms. Since the gas is dilute, physically exchanging only electrons would involve a great deal of energy to overcome the Coulomb barriers of the atoms: the same would apply to an exchange of only the protons. According to Leggett(2006)

> the relative sign of two quantum states can matter only if there is a nonzero probability amplitude for a physical transition between them to take place (we do not expect the "exchange" of an electron on Sirius with one on Earth to have physical consequences!). Whether it can or not is, of course, a question of energetics. (p.6)

In this case energetic considerations dictate that the only physical exchange process relevant to determining the sign of the overall quantum state of a dilute gas of H is a process in which *entire atoms* are exchanged—electron and proton together. Since both electrons and protons are fermions, the total quantum state must be antisymmetric under exchange of any two electrons, and separately under exchange of any two protons. So it must be *symmetric* under exchange of any two entire H atoms. This appeal to energetics is one way to justify treating composite H atoms in a dilute spin-polarized gas as bosons that extends naturally to more complex atoms like rubidium that have been shown to undergo Bose condensation.

Chudzicki *et al*.(2010) offer an interestingly different justification that enables one to estimate the degree of approximation involved in a treatment of spin-polarized atomic hydrogen as a boson. Following on earlier work by Law(2005) they show that the entanglement between two non-identical fermions largely determines the extent to which the pair behaves like an elementary boson. They define a measure P of the degree of entanglement of such a pair and a measure B of its bosonic character, and establish upper as well as lower bounds on B in a collection of N such pairs of the form

$$1-NP \leq B \leq 1-P \qquad (8)$$

P is called the purity of a pair's quantum state since it takes its maximum value of 1 for a pure state, with a lower bound of 0 as the state becomes progressively more entangled. On this measure, the composite pairs act as ideal bosons if and only if $B = 1$: a pair may be treated as a boson in a collection of N pairs if and only if its quantum state is sufficiently entangled. Notice that this criterion refers neither to the spatiotemporal relation between the fermions in a pair nor to any forces acting to bind its elementary fermions to each other. Chudzicki *et al*.(2010) comment:

> two particles can be highly entangled even if they are far apart. Could we treat such a pair of fermions as a composite boson? The above analysis suggests that we can do so. However, we would have to regard the pair as a very fragile boson in the absence of an interaction that would preserve the pair's entanglement in the face of external

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fermions be treated as an elementary fermion?"—a question likely answered more easily for electrons and nucleons in an atom than for quarks in a baryon.

disturbances. On this view, the role of interaction in creating a composite boson is not fundamentally to keep the two particles close to each other, but to keep them entangled.

A dilute gas atomic BEC has two natural decompositions: into atoms that act as composite bosons, and (further) into the electrons and nucleons within each atom, which may be thought of as elementary fermions (at least if one ignores the Standard Model quark structure of the nucleons). Here, at least, we seem to have three levels of a compositional hierarchy. But this simple structure faces a potential complication arising from the need to explain the interference observed between separately prepared atomic BECs.[12] Bose condensation is a kind of phase transition—from the normal gas phase to the Bose condensate. An influential general approach to the explanation of phase transitions appeals to the idea that a symmetry is broken as the temperature of a sample of bulk matter is lowered and a parameter characterizing its order takes on one out of a range of possible values. The order parameter characterizing a dilute gas BEC is often taken to be a complex-valued function—the expectation value of a Bose field operator in the given quantum state.

$$\Psi(\mathbf{r}, t) = \langle \hat{\psi}(\mathbf{r}, t) \rangle \qquad (9)$$

If this is written as

$$\Psi(\mathbf{r}, t) = |\Psi(\mathbf{r}, t)| \exp i\varphi(\mathbf{r}, t) \qquad (10)$$

then the phase $\varphi(\mathbf{r}, t)$ parametrizes an element of the group U(1), corresponding to a transformation that sets the complex argument of Ψ to φ at point $(\mathbf{r}, t)$. If the equations describing the field of the condensate are symmetric under global U(1) transformations, then changing the order parameter by addition of an arbitrary constant to the phase will take one solution into a distinct solution. Global U(1) symmetry will be broken by choice of one such value.

On this approach, if each of two separately prepared samples of the same dilute gas underwent such a phase transition on Bose condensation, one would expect each then to be described by an order parameter with a different (randomly chosen) phase. The resulting phase difference between the two samples could then give a simple explanation of the interference observed between them. But the phase of a sample is conjugate to an operator $\hat{N}$ representing the number of bosons condensed in that sample. So a definite phase implies an *indefinite* number of condensed bosons. So accepting this broken symmetry explanation of the observed interference between separately prepared dilute gas BECs commits one to maintaining that even though such a BEC is composed only of atoms, it is not composed of any definite *number* of them. Fortunately, there are good reasons instead to accept an alternative explanation of the observed interference, based on the contrary assumption that each BEC is indeed composed of some definite number of atoms. A careful quantum analysis shows that when they come together, the bosonic character of their states implies exactly the correlations among multiple measurements on atoms from the combined BEC that would be expected on the rival hypothesis that its state displays a definite relative phase between the two component BECs.[13]

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[12] Andrews *et al*.(1997) were among the first to report observations of interference fringes formed by absorption of light shone through such BECs when they overlapped after being released from their traps.

[13] See my(2010) commentary on work by Javanainen and Yoo(1996), Castin and Dalibard(1997), Laloë(2005), etc.

Condensed matter displays phase transitions in other systems. Ordinary liquid helium (^4He—the isotope whose nucleus contains two neutrons as well as two protons) becomes superfluid (at normal pressures) at a temperature of about 2°K. This is not a simple case of Bose condensation because interactions between the atoms in the liquid state are significant. But the compositional structure is still similar: the superfluid component of the liquid helium is composed of ordinary helium atoms, which act like bosons because of the way each is itself composed of an even number (6) of elementary fermions.

Tin, mercury and other metals undergo a phase transition to the superconducting phase at low temperatures. The BCS theory explains this as a case of condensation of Cooper pairs of electrons, which then constitute a current able to flow through the metal without any resistance. The electrons in the metal are elementary fermions even in the context of the Standard Model. They pair up despite their mutual electrical repulsion because of subtle mediating effects of the ionic lattice surrounding them. Pairing and condensation occur together: there are no uncondensed pairs. It is perhaps a semantic decision whether or not to call a Cooper pair a boson within the BCS theory, but the preceding discussion already makes it clear that the substantive point behind this decision is the extent to which it is useful to treat a composite of elementary fermions or bosons as a boson. The superconducting component of a metal like tin is composed of Cooper pairs, each of which is in turn composed of two electrons. The bulk matter containing the Cooper pairs also contains an ionic lattice of tin nuclei surrounded by bound electrons that do not contribute to the superconducting current, as well as ordinary unpaired conduction electrons.

One phenomenon displayed by metallic superconductors like tin is the Josephson effect: superfluid ^4He displays an analogous effect. A spontaneous alternating current will appear across a narrow insulating junction between two metals when they are cooled until they become superconducting. The quantum explanation of this effect assigns a macroscopic wave-function to the superconducting electrons with a well-defined phase difference across the junction. This implies that at any time no definite number of Cooper pairs is to be found on a given side of the junction. It does not follow that the system as a whole contains no definite number of Cooper pairs at that time, but only that not all pairs have definite locations within the system. This is perhaps not surprising when one remembers that the junction is extremely thin and the electrons in a Cooper pair are not closely bound to one another: (roughly speaking) the electrons in a pair may be separated by over a million other electrons, each part of its own pair. Clearly the compositional structure of a superconductor is far more intricate than would be suggested by the levels picture of Oppenheim and Putnam(1958).

A further complication occurs when one introduces the idea of *quasiparticles*. The pairing mechanism in a metallic superconductor is often described in terms of exchange of phonons—lattice vibrations that may be thought of as the quanta of sound waves. Phonons are just one kind of quasiparticle that features in condensed matter physics. There are also excitons, magnons, rotons, plasmons, polarons, polaritons, etc. A quasiparticle is not composed of atoms or their constituent particles. Indeed

> It must be emphasized right away that the elementary excitations arise as a result of collective interactions between the particles of the system, so that they relate to the system as a whole, and not to individual particles. In particular, their number is by no means the same as the total number of particles in the system. (Abrikosov *et al.*(1965, p.4).

Such quasiparticles do not fit neatly into a compositional hierarchy. They cannot be taken to consist of any definite number of constituent particles, though they arise out of the collective behavior of many particles. But nor are they wholly "epiphenomenal" entities, since appeal to them plays an essential role in explanations of the properties of bulk matter. We shall shortly see an example of this.

There are dilute gas BECs and superfluids that display a richer compositional structure than those considered so far. While the first BECs to be experimentally realized in dilute gases were all monatomic, molecular BECs have also now been formed, including diatomic ^{6}Li and ^{40}K. In these cases the single atoms act as composite fermions, and so cannot condense. But the diatomic molecules they form when bound together act as bosons, thus permitting Bose condensation. ^{3}He atoms behave as composite fermions, so liquid ^{3}He might not be expected to form a superfluid by condensation. In fact it does so, but at much lower tempera) than ^{4}He. Here the mechanism is analogous to that involved in the BCS theory of superconductivity. ^{3}He atoms form pairs with characteristics of bosons, permitting the formation of a condensed superfluid component within the ordinary liquid. But the pairing mechanism is different in this case, as it must be since there is no surrounding ionic lattice to form binding phonons—just more ^{3}He atoms. The mechanism is usually explained as involving a further intermediate compositional step: the condensate is formed by paired *quasiparticles* rather than simply paired ^{3}He atoms. Each quasiparticle may be thought of as a single ^{3}He atom surrounded by a "cloud" of neighboring ^{3}He atoms in such a way that its total mass is several times that of a single atom. But the binding into quasiparticles is not a case of chemical composition: this quasiparticle is a more tenuous and indeterminate structure than a molecule, and does not consist of a fixed integral number of ^{3}He atoms. Indeed, one can also think of talk of quasiparticles here as a metaphoric gloss on the mathematics involved in treating the ^{3}He as a Fermi liquid.

But, here as elsewhere, others appear to have taken the metaphor more literally, as in this description of a sample of ^{3}He as containing a number of quasiparticles that

> move along (straight) trajectories, but along each trajectory there is quantum mechanical interference between particles flying in opposite directions.[14]

Indeed, some have at least been tempted to reject any ontological distinction between particles like atoms and electrons and quasiparticles generally:

> The more one studies the mathematical descriptions of cold phases, the more accustomed one gets to using the parallel terminologies of matter and space interchangeably. Thus instead of a phase of matter we speak of a vacuum. Instead of particles we speak of excitations. Instead of collective motions we speak of quasiparticles. The prefix "quasi" turns out to be a vestige of historical battles over the physical meaning of these objects and conveys no meaning. In private conversations one drops the pretense and refers to the objects as particles.[15]

The treatments of a "fundamental" boson such as a gluon and a "quasiparticle" boson such as a phonon as in each case a quantum of a quantized field are sufficiently formally analogous as to prompt one to question whether there is any significant difference in their ontological status.

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[14] Posted on 19.8.2003 by Erkki Thuneberg at http://ltl.tkk.fi/research/theory/quasiclassical3he.html.

[15] Laughlin(2005, p.105).

One topic of intense recent interest is the BCS-BEC crossover in a gas of atomic fermions such as ^{40}K.[16] Besides forming a BEC as the atoms combine into diatomic molecules, such a fermionic gas is capable of forming a superfluid as its atoms combine into pairs in a different way analogous to the formation of Cooper pairs in a BCS superconductor or quasiparticle pairs in superfluid ^{3}He. In fact, theory predicts a continuous transition between these two modes of composition, which experimentalists are exploring by "sweeping across a Feshbach resonance".[17] Clearly, the compositional structures involved in condensed matter physics are much more complex and interesting than the simple compositional hierarchy of elementary particles–atoms–molecules described by Oppenheim and Putnam(1958). None of them are simply spatiotemporal.

9. Conclusion

Decomposing a physical system into constituent (i.e. non-overlapping) parts to account for its behavior in terms of their properties and relations has repeatedly proved to be a successful explanatory and predictive strategy within physics as well as the rest of science. But so have several other strategies that are relatively independent of composition, including thermodynamic reasoning, universality and the renormalization group, geometrical/topological methods, and abstract methods based on symmetry considerations. It is a mistake to suppose that pursuit of any one explanatory/predictive strategy defines or constrains the goal of physics.

The success of the decompositional strategy need not require that constituent parts exhaust a system to which it is applied. The system may contain other distinct parts to whose properties and relations its behavior is insensitive, and which therefore need not be mentioned when explaining that behavior ("inert ingredients").

Physicists continue to develop a surprising variety of different ways of decomposing a system into parts, each corresponding to a different part-whole relation. Spatiotemporal composition alone rarely has explanatory or predictive value, and to speak of forces holding parts together is at best a metaphoric gloss on some (but not other) kinds of composition relation that figure prominently in contemporary physics.

The search for ultimate building blocks of the physical world in elementary particle physics appears to have run its course: the quantum field theories of the Standard Model present us with no clear candidates for ultimate building blocks—neither particles nor fields. As illustrated by the history of theories of light, progress in physics has not always been accompanied by ontological continuity at the fundamental level, so this verdict may turn out to be premature. Perhaps string theory and *M*-theory will present us with strings and branes as new candidates for ultimate building blocks. But today that conclusion is doubly premature. Not only is evidence for such theories currently severely lacking, but in so far as they are variants on more traditional quantum field theories they may be expected to inherit the ontological opacity of their predecessors.

A system may have more than one incompatible partition into constituent parts. Even if a system does have a unique or natural partition into basic parts, to explain its behavior it may be necessary also to advert to parts of a different kind—parts formed from basic parts through (one

[16] See Regal (2005).

[17] See Leggett(2006, pp.364-71)

or more) *different* composition relations, and/or parts that supervene on basic parts without being composed of them. The intricate webs of physical composition relations in theories of condensed matter physics stand as beautiful testimony to the creativity of the physicists who have woven them.

Metaphysicians and philosophers of science can learn a more general lesson from the treatment of composition in modern physics. There is no single relation of physical composition, but an open-ended variety of different kinds of physical composition (though these do *not* ground a plethora of quite specific, disconnected, *sui generis*, compositional facts). Many different kinds of composition relation may be appealed to in accounting for the behavior of a single physical system, in different circumstances, or even in a given situation. But no physical composition relation is introduced merely to resolve an apparent paradox or to provide a satisfying analysis of some puzzling concept. A physical composition relation must prove its worth in the empirical arena, by facilitating novel predictions or at least powerful explanations of experimental and/or observational findings. But even if it does prove its worth in this way, a physical composition relation does not thereby further the metaphysical project begun by the ancient atomists and still pursued by some philosophers—the project of discovering the ultimate building blocks of the world and demonstrating how they compose it. Physics neither does, nor could, convince us that our world has the structure of a compositional hierarchy.

Acknowledgments

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