Hylomorphic Escalation:

An Aristotelian Interpretation of Quantum Thermodynamics and Chemistry[1]

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Abstract

Defenders of physicalism often point to the reduction of chemistry to quantum physics as a paradigm for the reduction of the rest of reality to a microphysical foundation. This argument is based, however, on a misreading of the philosophical significance of the quantum revolution. A *hylomorphic* (from Aristotle's concepts of *hyle*, matter, and *morphe*, form) interpretation of quantum thermodynamics and chemistry, in which parts and wholes stand in a mutually determining relationship, better fits both the empirical facts and the actual practice of scientists. I argue that only a hylomorphic interpretation of QM is able to treat thermodynamic quantities, such as temperature and entropy, as genuinely real, which in turn provides grounds for the reality of the direction of time and of molecular structure.

I.

Introduction. Aristotelian philosophy of nature has always privileged substantial wholes over their microscopic parts, in contrast to the bottom-up microphysicalist paradigm that dominated physics and chemistry in the modern era. The quantum revolution has paved the way for a revival of the Aristotelian category of substantial form as a top-down factor in the structuring of physical and chemical phenomena. In this paper, I will propose that finite quantum

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systems constitute the proximate matter for thermal substances, each with its own substantial form. I will not discuss prime matter or Aquinas's signate matter in this context, although nothing that I propose would block the introduction of such entities as the ultimate substrates of material reality. In fact, by making the case for macroscopic substantial forms and microscopically constituted proximate matter, I will provide good reason for embracing a comprehensive theory of form/matter duality throughout the philosophy of nature.

In Section II, I introduce a notion of 'ontological escalation,' which corresponds to a relation of partial independence (with respect to metaphysical grounding) between different levels of scale. Ontological escalation stands in direct contradiction to any form of microphysicalism, according to which the only metaphysically fundamental entities, properties, and relations occur entirely at the microscopic scale (the scale of simple, non-composite entities).

Section III is the heart of the paper, in which I argue that quantum versions of thermodynamics and chemistry provide strong grounds for accepting ontological escalation, and thus also for making use of Aristotle's conception of formal causation. I give six reasons for this claim, drawing in each case on the indispensable role of the continuum limit (with its infinite number of degrees of freedom) in defining the relevant phase spaces.

In Section IV, I give a brief sketch of the hylomorphic interpretation of quantum theory that's required, and in Section V I respond to three objections, and I conclude in Section VI with a discussion of the relevance of hylomorphic escalation for our understanding of biology and of human agency.

II.

Hylomorphism and Ontological Escalation. The term 'emergence' has, I believe, outlived its usefulness, especially since it is now used in such a wide variety of mutually contradictory senses. Consequently, I will define a notion of *ontological escalation*, which is thoroughly metaphysical in nature, as opposed to being epistemological, pragmatic, conceptual, semantic, or logical. Escalation is realized by discrete sets of objects and their properties and relations, not by our theories or understandings of those objects. In defining escalation, I will make free use of the notion of *metaphysical ground*, as discussed recently by Kit Fine and others (Fine 1999, 2012; Rosen 2010), but which is rooted deeply in the philosophical tradition (as far back as Socrates, at the very least).

Thesis of Ontological Escalation

1. The world consists of a number of levels of compositional scale, with each scale-level consisting of certain fundamental entities with certain fundamental properties and standing in certain mutual relations.

2. Except for the very smallest scale, the entities of each scale-level are composed entirely of smaller-scale entities, and the powers of and causally relevant relations among those entities are *partly grounded in* facts about the smaller-scale entities. That is, the larger-scale entities have the causal powers they do in part *in virtue of* their smaller-scale parts and their properties. This corresponds to the hypothetical necessities of material causation.[2]

[2] In speaking of entities being 'composed entirely of' smaller-scale entities, I am referring to what Aquinas would have called the entities' *integral parts*. I am not opposed to speaking, as Aristotle did, of some composite material things' having substantial forms as "components," in some sense. However, metaphysical components (such as prime matter, substantial form, and accidents) are perhaps better thought of as *principles* of a certain kind, rather than as literal parts.

3. Except for the very largest scale, the powers of and causally relevant relations among *some* entities of each scale-level are *partly grounded in* facts about certain larger-scale entities (namely, those larger-scale entities, the *substances*, of which they are proper, integral parts).

Thus, larger-scale entities *both condition and are conditioned by* smaller-scale entities, in relations of mutual metaphysical co-determination.

The thesis of ontological escalation does not require vicious circles of metaphysical grounding. The main idea is that there is a rough equality among the various scale-levels, with the entities of two successive levels constraining one another in different ways.

I will defend in particular a neo-Aristotelian or hylomorphic conception of ontological escalation, in which top-down determination corresponds to Aristotle's notion of formal causation, and bottom-determination corresponds to material causation, building on my recent paper, "Staunch vs. Fainthearted Hylomorphism" (Koons 2014).

My picture is closest to the models of emergence by fusion proposed by Paul Humphreys (1997). In Humphreys's model, the entities of the smaller-scale levels are literally destroyed in a diachronic process of fusion (the generation of the new, larger-scale entity). This kind of destructive fusion could count as an extreme case of ontological escalation, so long as we consider the "annihilated" *summands* as enjoying some kind of *virtual* or *dependent* existence within the fused entity.

As Aristotle argues in *Metaphysics* Book Eta, we cannot think of form as just another element of a composite thing. Form is the principle of unity of the elements.

Ontological escalation differs from the model of ontological *emergence* proposed by Timothy O'Connor and his collaborators (O'Connor 1994, O'Connor and Wong 2005), who, like Humphreys, postulate a diachronic process of generation of the emergent entities. In O'Connor-style emergence, the constituents *do* survive the fusion. However, O'Connor supposes that there is some kind of downward causation involving new configurational forces (as in C. D. Broad's account). This comes close to a kind of vitalism or dualism, and its plausibility is weakened by our natural reluctance to posit new fundamental forces. In addition, O'Connor assumes a kind of original or primordial *universality* of the micro-level, which must contain in a virtual way all the higher levels. With ontological escalation, in contrast, all of the levels are equally universal and primordial (at least potentially). Rather than imagining that the world began (after the Big Bang) as a cloud of autonomous particles, from which larger structures eventually emerged, I suppose that the early universe consisted entirely of large-scale substances (initially, perhaps, a single, cosmic substance), from which smaller entities gradually precipitated.

III.

Quantum Theory and Thermodynamics: Six Reasons for Escalation. In this section I will argue for ontological escalation at two levels of scale: particle physics and thermodynamics (or quantum statistical dynamics). I will posit two kinds of fundamental entities (or "substances"), along with two sets of fundamental attributes (including natures or essences): fundamental particles (quarks, leptons, etc.)[3] and substances at the level of thermodynamic systems. I will call

[3] To be honest, I am not sure that individual particles are substances at all, and so I am not really sure that there is a fundamental ontological level that corresponds to particle physics (see Koons, forthcoming and Pruss, forthcoming for details). I will assume the contrary in this paper, for the

the latter *thermal substances* for short. Thermal substances have metaphysically fundamental thermodynamic properties, including entropy, temperature, and chemical composition and potential.

In the case of thermal substances, the whole is greater than the sum of its parts—in a very literal sense (as we shall see below). Any mere collection or heap of fundamental particles has only finitely many degrees of freedom (i.e., the position and momentum of each particle), while thermal substances (corresponding to the kind of systems studied in quantum statistical mechanics) have, independently of how we model them or think about them, *infinitely many* degrees of freedom. This very bold claim is considerably stronger than is actually required for genuine ontological escalation. Although I will defend this strong thesis, there is a weaker position to which I can fall back: namely, that thermal substances do not in fact exhibit infinitely many degrees of freedom but inhabit a space of real physical possibilities that can only be *modeled* in quantum mechanics by means of the introduction of an infinity of degrees of freedom. It may be that this infinity is merely virtual, in the sense that the state of the thermal substance can always be exhaustively described using a finite amount of information. Nonetheless, the distinction between those systems that can and those that cannot be modeled successfully by finite quantum models marks a real, ontological difference between those systems (that is, between mere heaps of quantum particles and true thermal substances).

The commitment to an infinite number of degrees of freedom is compatible with the Aristotelian thesis that all infinities are merely potential and not actual. To ascribe a degree of

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sake of simplifying the discussion somewhat. If particles are not substances, the case for the substantiality of thermal substances will be just that much stronger.

freedom to a system is to describe that system's potentialities. Aristotle was committed to the real *continuity* of matter (see Brentano 1988), which entails an infinite number of degrees of freedom, since each of the *potentially* infinite number of material parts of the continuous body *could* take on accidental property (like velocity or chemical composition) distinct from the corresponding property of the body's remainder. It is important to distinguish two senses of potential infinity: (1) there are an infinite number of different ways in which a substance can be finitely decomposed, and (2) the substance can be decomposed into an infinite number of parts. Aristotle accepts the first and rejects the second. Similarly, we can postulate that thermal substances have an infinite number of degrees of freedom while insisting that any actual state of the system can be exhaustively described with a finite amount of information. The infinity of the degrees of freedom simply represents an infinite number of alternative, potential states of the substance.

This infinite inflation of the degrees of freedom would have been extremely implausible in *classical* statistical mechanics, where we know that there can be, in any actual system, only finitely many degrees of freedom, since the particles (atoms, molecules) survive as discrete, individual entities. In quantum mechanics, individual particles (and finite ensembles of particles, like atoms and molecules) seem to lose their individual identity, merging into a kind of quantum goo or gunk. For the quantum hylomorphist, when particles participate in a thermal substance, the fundamental physical attributes are possessed at the level of the thermal substance as a whole, and only derivatively and dependently by the individual molecules. Hence, there is no absurdity in supposing that the whole has more degrees of freedom (even infinitely more) than are possessed by the individual molecules, treated as an ordinary multitude or heap.

From the 1950's onward, quantum theory moved from what the chemist Hans Primas called "the pioneer period" to that of *generalized* quantum mechanics. Generalized QM moved away from the Hilbert-space representation of quantum systems[4] to that of an algebra, in which both quantum and classical observables could be combined in a single formal representation. The algebras of generalized QM can have non-trivial *cores*, consisting of the classical properties that *commute* with every other property, representing exceptions to the mutual complementarity of the quantum properties.[5] In practice, this means representing the classical properties of complex systems (like molecules or experimental instruments) as ontologically fundamental, on par with the quantum properties of the smallest particles.

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[4] A Hilbert space is a space with an infinite number of dimensions. The state of the system can be represented by a single unit vector in this space. Each physical parameter (like a particle's position or momentum) is represented by an operator of a certain kind on this space. A vector in the Hilbert space is called an 'eigenvector' of a parameter when it is a fixed point of the corresponding operator. To get the probability of a parameter's taking a certain value, we project the system's unit vector onto the corresponding eigenvector. The result is a value between 0 and 1. In the Hilbert-space representation of dynamics, it is not the vector that "moves" in the space: instead, it is the correspondence between physical parameters and operators that evolves over time.

[5] The fact that quantum properties (modeled as operators) do not commute with each other or with the classical properties is the formal counterpart of Heisenberg's uncertainty principle and of Bohr's complementarity principle.

This emergence of non-trivial cores of classical observables comes about quite naturally as we move from finite to infinite models. In applied physics, it is common to take some parameter to infinity: that is, to replace the original model having some finite parameter with a new model in which that parameter takes the value of infinity. For example, in the so-called "thermodynamic" limit, a system containing *n* molecules and a fixed volume *V* is replaced by one in which both the number of molecules and the volume go to infinity, while keeping the density n/V constant. As Compagner explains (Compagner 1987), this thermodynamic limit is mathematically equivalent to the *continuum limit*: keeping the volume constant and letting the number of molecules go to infinity, while the size of each molecule shrinks to zero.[6] In many applications, such as the understanding of capillary action or the formation of droplets, the continuum limit is the right way to conceptualize the problem, since infinite volumes have no external surfaces and cannot interact with their containers.

As Hans Primas has pointed out (Primas 1983), there are three reasons for taking infinite limits in physics: (1) for mathematical convenience, (2) in order to isolate some factors from others, and (3) in order to introduce new structure into the representation. The continuum limit in generalized quantum mechanics is an example of the third reason. In 1931, John von Neumann and Marshall Stone proved that finite systems admit of only one irreducible Hilbert-space

[6] Compagner has in mind the Aristotelian conception of the *continuum* (as discussed in Brentano 1988) rather than the mathematical conception developed by Karl Weiestraus and Richard Dedekind in the 19th century. An Aristotelian continuum is simply a body that lacks actual internal boundaries, which will certainly be true of the collection of molecules at the continuum limit, since molecules with zero volume do not have finite surfaces.

representation (von Neumann 1931).[7] Infinite systems, in contrast, admit of infinitely many inequivalent Hilbert-space representations.[8] This apparent embarrassment of riches in the infinite case turns out to be crucial for the representation of phase transitions, entropy, and thermodynamic phenomena. As Geoffrey Sewell explains:

> For infinite systems, the algebraic picture [with its infinite number of subsystems] is richer than that provided by any irreducible [single Hilbert-space] representation of observables…. Furthermore, the wealth of inequivalent representations of the observables permits a natural classification of the states in

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[7] An algebraic representation is *irreducible* if and only if it does not have any proper sub-representations that are closed under the relevant functions. Stone and von Neumann proved that any two irreducible groups of the appropriate kind (one-parameter unitary groups) are *unitarily equivalent*. Two representations or groups are unitarily equivalent when there is a unitary transformation of one into the other (a transformation involving a *unitary*—that is, a linear, bounded, and surjective—operator). In this case, the two representations can be treated as simply two different ways of representing the same physical situation, analogous to the way that changes in units of measurement or the location of the axes of space produce physically equivalent representations.

[8] As Kronz and Lupher (2005, 1242-3) point out, an infinite system is one that has infinitely many particles or sub-systems, resulting in a *non-separable* Hilbert space. (A separable space has a countable "dense" subset: a set that contains at least one element of every nonempty open subset of the space.) It is necessary but not sufficient for the system to have infinitely many degrees of freedom.

> both microscopic and macroscopic terms. To be specific, the vectors in a [single Hilbert] representation space correspond to states that are macroscopically equivalent but microscopically different, while those carried by different [inequivalent] representations are macroscopically distinct. Hence, the macrostate corresponds to a representation [space] and the microstate to a vector in the representation space. (Sewell 2002, pp. 4-5)

In addition, by moving to the thermodynamic or *continuum* limit, which involves treating a system with apparently finitely many particles as though there were infinitely many, algebraic QM enabled theorists to introduce *superselection rules*,[9] which could be used to distinguish the different *phases* of matter that can co-exist under the same conditions (such as gas, liquid, solid, ferromagnetized, superconducting). I will argue that the use of the continuum limit can best be interpreted as representing an ontological difference between two irreducibly macroscopic conditions, providing strong evidence against microphysicalism.

If these infinite models are to be genuinely explanatory, then the use of the continuum limit has to be justified in ontological terms, and not merely as a useful fiction. We don't have to suppose that there is literally an infinite number (whether countable or uncountable) of infinitesimal molecules (and so, to that extent, the model may indeed be fictional), but we must suppose that the molecules *really cooperate in such a way that they fuse into a dynamic*

[9] In algebraic QM, a superselection "rule" is actually a property of a system that cannot change through local, microscopic perturbations. The different, mutually incompatible values of this quantity are called superselection sectors. Such distinct sectors can never be found in quantum superpositions, unlike quantum observables.

Aristotelian continuum in space. This means that another kind of ontological fusion (a chemical or thermodynamic fusion) must take place in these cases, distinct from but analogous to the quantum fusion posited by Paul Humphreys. (See Woolley 1988, pp. 58-60, 72-78, and 86 for a defense of this interpretation.) As a result of this thermodynamic fusion, the molecules form a continuous *field* of matter, with literally an infinite number of distinct sub-systems, each sub-system corresponding to a different finite spatial *region* (not to a fictional molecule of zero volume), and each with its corresponding degrees of freedom.

Their fusion into such a material continuum is a different way for the quantum particles to relate to our three-dimensional space: not as discrete, separate units but as a single, cooperating mass, resulting in an entirely new dynamical situation, with a new Hamiltonian function, in violation of the metaphysical requirements of Democritean microphysicalism.

This escalation does not require any new fundamental force, but the reorganization of mass and charge in space alters the framework (the boundary conditions) within which the usual forces can act. There are six phenomena each of which can only be explained (given the current state of the field) in terms of the ontological escalation of the thermal level from the microscopic: (1) the objective irreversibility of time, (2) rigorous definitions of entropy, temperature, and chemical potential, (3) the low entropy of the early universe, (4) spontaneous symmetry breaking, (5) phase transitions, and (6) the persistence of chemical form. I will take up each of these phenomena in turn.

First, as Ilya Prigogine (1996, 49) explains, the *objective irreversibility of time* is essential to the very idea of observation or measurement, and without observation and measurement, science is of course impossible:

> If the arrow of time existed only because our human consciousness interfered with a world otherwise ruled by time-symmetrical laws, the very acquisition of knowledge would become paradoxical, since any measure already implies an irreversible process. If we wish to learn anything at all about a time-reversible object, we cannot avoid the irreversible processes involved in measurement, whether at the level of an apparatus or of our own sensory mechanisms.

R. G. Woolley (1988, 56) argues that true irreversibility is possible only at the continuum limit, when the number of degrees of freedom is infinite:

> [The work of] Ilya Prigogine and his collaborators…highlights the fact that irreversible processes in quantum mechanics are only possible in the limit of a continuous spectrum; an immediate consequence of this restriction is that no finite quantum system, for example a molecule or finite collection of *N* molecules with intermolecular interactions, can show irreversible behavior, and the Second Law of Thermodynamics cannot be applied to such systems.

The continuum limit is needed to ground true thermodynamic irreversibility, as noted by Compagner 1989, 115: "The relative measure in phase space occupied by exceptional microstates vanishes in the continuum limit." Geoffrey Sewell (1986, 30) explains why: "The dynamics of a finite system is quasi-periodic, due to the discreteness of its Hamiltonian."

Second, the infinite algebraic models of generalized QM provide, for the first time, the possibility of rigorous and non-arbitrary *definitions of the basic thermodynamic properties* of entropy, temperature, and chemical potential (see Sewell 2002).

Contrary to what many philosophers believe, science does *not* suppose that temperature is the mean kinetic energy of molecules! Vemulapalli and Byerly 1999, pp. 28-32 explain:

If the system is not at equilibrium, temperature is not well-defined, though the mean kinetic energy is…. Temperature is a characteristic of equilibrium distribution and not of either individual molecules or their kinetic energy. When there is no equilibrium between different kinds of motion (translations, rotations, and vibrations), as in the case of molecular beams, temperature is an artificial construct. (Vemulapalli and Byerly 1999, pp. 31-32; See also Primas 1983, pp. 312-3)

Robert Bishop and Harald Atmanspacher agree:

> Since thermal equilibrium is not defined at the level of [finite] statistical mechanics, temperature is not a mechanical property but, rather, emerges as a novel property at the level of thermodynamics. (Bishop & Atmanspacher 2006, p. 1769)

Third, we can explain the *low entropy of the early universe*. Roger Penrose has made the plausible suggestion that it either is a law of nature or follows from some law of nature that the universe began to exist in a state of extremely low entropy. The universe began in a state of extremely low entropy. According to Penrose, the odds of such a low state of entropy occurring by chance are in the order of 1 in 10 to the 10 to the 123rd power (a number which, when written out fully, would require more zeros than there are particles in the universe). The only possible scientific explanation and the only possible ground for the objectivity of the arrow of time would be that there is some sort of law of nature requiring the absolute beginning of the universe to be in a state of extreme low entropy. If the observed beginning of our universe were merely a transition from some earlier state, then there would be no possible explanation for its low-entropy state.

Penrose's suggestion is a plausible constraint on the phase space of quantum mechanics that can only be formulated in a natural way on a macroscopic scale, suggesting that the true structure of the space of microscopic possibilities is in fact grounded in a natural constraint on the space of macroscopic possibilities. As we have seen, thermodynamic properties can be given a rigorous definition only in the continuum limit. If entropy enters into the fundamental laws of nature, it must be a fundamental property of natural things, leading directly to the ontological escalation of thermal substances over fundamental particles.

Fourth, Strocchi (1985) explains that the continuum limit is needed to explain any *spontaneous symmetry breaking* in quantum-mechanical terms:

> In the past, the description of physical system exhibiting approximate symmetries was reduced to the problem of identifying explicit "forces" or "perturbations" responsible for such asymmetric effects…. The progress of the last years has shown that the above strategy is not only unconvenient from a practical point of view, since the existence of asymmetric terms complicates the equations of motion and their identification is somewhat arbitrary, but *it is actually unacceptable on general grounds*, because it is often impossible to reduce symmetry breaking effects to asymmetric terms in the Hamiltonian…. The result is that the dynamics must be defined in terms of a symmetric Hamiltonian and that the symmetry breaking is due to a dynamic instability according to which symmetric equations of motion may nevertheless lead to an asymmetric physical description… As we have seen, *such phenomena are possible only for infinite quantum mechanical systems*. (Strocchi 1985, pp 117-8; emphases mine)

Fifth, *phase transitions*, such as those between the solid, liquid, gas states, and between conditions before and after the onset of coherent ferromagnetism or superconductivity in metals, require the use of infinite models (models involving the continuum limit): see Liu 1999, Ruetsche 2006, and Bangu 2009. Phase transitions are an important case of spontaneous symmetry breaking. Geoffrey Sewell provides a clear explanation of this:

> Thus we have a spontaneous symmetry breakdown, as each phase lacks the rotational symmetry of the interactions in the system. This is a situation which typifies a class of phase transitions. We emphasize here that this situation could not be covered by a model of a finite system, since that would admit only one representation of its observables and therefore would not present the phase structure we have just described….
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> We have seen in the preceding Sections that the idealization, whereby a macroscopic system is represented as infinite, provides new structures, which form a natural framework for theories of collective phenomena. (Sewell 1986, p. 19, 34)

As Laura Ruetsche has explained recently:

> Only in the thermodynamic limit can one introduce a notion of equilibrium that allows what the Gibbs notion of equilibrium for finite systems disallows: the multiplicity of equilibrium states at a finite temperature implicated in phase structure. (Ruetsche 2006, p. 474)

Microphysicalists must insist that the models of phase transitions and other thermodynamic phenomena are misrepresentations of the fundamental dynamics: that what is really going on is nothing more than the standard interaction of a finite number of particles according to the Schrödinger equation of pioneer quantum mechanics. In light of the indispensability of the continuum model, microphysicalists have only two options: (1) they can deny that transitions between phases really happens, insisting that it is merely an illusion generated by situations whose complexity exceeds our understanding, or (2) they can try to argue that the infinite model is somehow a useful approximation of what could, in principle, be explained using a finite, elementary quantum mechanical model.

Leo Kadanoff seems to take the first option, arguing that the different phases of matter are not really there in the world but only in our scientific and folksy models of the world: "Since a phase transition only happens in an infinite system, we cannot say that any phase transitions actually occur in the finite objects that appear in our world." (Kadanoff 2009, p. 10) Kadanoff relies on the fact that the transition from one phase to another is vague: there is no sensible answer as to when exactly a sample of water begins to boil.

The anti-realist response to phase transitions and other cases of spontaneous symmetry comes at a very high price. Surely it borders on a kind of philosophically induced madness to deny that water really comes in a variety of phases—to deny that there is really any difference between liquid water, ice, or water vapor. Even if these phases are not precisely measurable *data*, they are real scientific *phenomena* to be explained (to use Bogen and Woodward's useful data/phenomena distinction—see also Bangu 2009, pp. 500-1). The anti-realist must claim more than just that the different phases do not constitute real natural kinds, with relatively simple, uncontrived definitions—they must insist that any distinction is merely fictional or erroneous, since the use of finite QM models excludes the very possibility of the definability (whether natural or unnatural) of these phase differences.

The vagueness of phase transitions that Kadanoff points to might be a purely epistemic one (reflecting our inability to detect the ontologically sharp transitions), or it might be a kind of ontological vagueness in the very nature of things. In either case, vagueness alone should not be sufficient to convince us of either the *unreality* or the *nonfundamentality* of a phenomenon.

Paul Mainwood (2006, pp. 238-243) and Jeremy Butterfield (2011, pp. 1123-30) have defended the second alternative, insisting that the continuum-limit model is a mere idealization, adopted for mathematical convenience only. This approach runs up against the hard, mathematical fact of the von Neumann-Stone theorem: finitary models simply do not have enough states to represent the different phases of matter. The microphysicalist must claim that every physical system can be correctly modeled by such finite systems, while the Aristotelian escalationist insists that some systems cannot be so modeled, because of the existence of real thermal fusion, requiring an infinitistic QM model.[10] Mainwood proposes that a finite system be counted as undergoing a phase transition just in case there are distinct states (separated by a superselection rule) in the corresponding infinite model, but neither he nor Butterfield can explain how a model with only one state can be a good approximation to a model with a great many. Every finite model necessarily represents the situation as one without a real distinction between phases. How then, can the finite model be literally true of a situation in which a phase

[10] Note bene: this distinction persists, even if the Aristotelian escalationist adopts the fallback position of denying the literal existence of an infinite number of degrees of freedom. The issue in question is this: does the distinction between finite and infinite models reflect a real, ontological difference in the phenomena? The microphysicalists must answer, No.

transition exists, while the infinite model is supposedly a mere "useful fiction"?[11] It is far more reasonable to suppose that it is the discreteness of the finite number of molecules that is the useful fiction, and the infinite model that represents the sober truth.

As John Earman has put it (2004), 191: "A sound principle of interpretation would seem to be that no effect can be counted as a genuine physical effect if it disappears when the idealizations are removed." Yet this is exactly what Mainwood and Butterfield attempt to do. Phase transitions are genuine physical effects, and yet they disappear once the "idealization" of infinite degrees of freedom is removed. The only way to acknowledge the genuineness of these effects is to deny that the use of infinite models is a mere idealization in the first place.

If we assume that an explanation in terms of a model is successful only if the model faithfully represents the relevant features of the actual phenomenon, then we must conclude that our current scientific explanations of phase transitions are successful only if it is the infinite, continuum-limit model that faithfully represents the facts, requiring exactly the kind of real thermodynamic fusion that I have described. The required introduction of the continuum limit in our models must represent a real ontological break between the microscopic and the macroscopic, a break of exactly the kind posited by ontological escalation.

Sixth, infinite models are needed to explain the *persistence of chemical form*. The Schrödinger equation for a finite system of particles is spherically symmetrical. Thus, there is no

[11] In addition, Mainwood's proposal has the paradoxical conclusion (as he admits) that very small systems (even a single molecule!) could undergo phase transitions, unless the definition is further burdened with an ad hoc stipulation of minimum size.

explanation in standard Copenhagen interpretation for the emergence and observed persistence of chemical structure, with its breaking of spatial symmetry.

The key datum here is that of molecular stability. We know that complex molecules (including chiral molecules—molecules with distinct left- and right-handed versions) can be stable for millions of years, a conclusion based on both experimental data and theoretical reasoning.

Yet, from the point of view of finite, elementary quantum mechanics, any molecular structure, including chirality, should be transient, in the sense that it corresponds to some observable (operator) in the Hilbert space. Pure, finite quantum mechanical algebras have no non-trivial core: for every operator, there is some observable that does not commute with it. Hence, if a chiral molecule undergoes a measurement-like interaction with its environment with respect to one of those non-commuting observables, its chirality (either left- or right-handed) should go immediately into a superposition of the two states (see Amann 1993, 139). Yet we never observe such a thing.

In addition, measurement collapse cannot produce the key features of symmetry breaking (Earman 2004, 180): "in particular, a symmetric vacuum [ground or equilibrium] state cannot be built as a superposition of degenerate,[12] asymmetric vacuum states." "If one tries to think of the different degenerate states as belonging to the same Hilbert space, then these states must lie in different 'superselection' sectors between which a meaningful superposition is impossible…. By

[12] In quantum mechanics, two states are *degenerate* when they have the same energy but very different wave functions. So, the two forms of handedness (left and right) are degenerate states of a chiral molecule, for example.

the same token, a measurement collapse of a superposition cannot produce an asymmetric vacuum state from a symmetric one." (p. 185)

Quantum chemists work around this problem in one of two ways. First, they employ "generalized quantum mechanics," in which they simply add classical observables and a non-trivial core to the pure or pioneer quantum mechanical algebra. This is an exact counterpart to Aristotle's form/matter distinction, with the pure QM observables corresponding to the proximate matter and the classical observables to the form.

The second work-around involves taking the continuum (or, equivalently, the thermodynamic limit), which introduces the possibility of unitarily inequivalent representations and superselection sectors. This too acknowledges the reality of *ontological escalation*: the individual particles and electrons merge together into a continuous chemical soup, which is only *potentially and virtually* particulate in nature. The chemical form of the thermal substance is thus an aspect of its Aristotelian form. Chemical form contributes to exactly those functions that substantial form serves in Aristotle's system: it grounds the classification of a thermal substance by means of natural kinds in terms of its chemical composition, it grounds the persistence of a thermal substance as the same substance over time, and it grounds the substance's active and passive powers in its interactions with other substances. Individual molecules should be thought of as integral parts of thermal substances, just as eyes and hands are integral parts of organisms. A hand cannot be a hand except as part of an organism, and a right-handed chiral molecule cannot be right-handed except as part of a thermal substance.

Generalized quantum mechanics attributes both classical (mutually commuting) and quantum properties to objects. The modern quantum theory of molecular structure is a perfect example. The structure of a molecule, that which distinguishes one isomer from another, including right-handed chiral molecules from left-handed ones, depends entirely on the classical properties of precise location applied to atomic nuclei. As Hans Primas put it:

> Every chemical and molecular-biological system is characterized by the fact that the very same object simultaneously involves both quantal and classical properties in an essential way. A paradigmatic example is a biomolecule with its molecular stability, its photochemical properties, its primary, secondary, and tertiary structure. (Primas 1983, p. 16)

There is, however, a complication, in that some molecules can be treated as pure quantum systems (modeled by pure or finite quantum mechanical models) and others cannot. In order to explain the difference, quantum chemists look at two factors: the difference in internal energy between the various molecular structures, and the molecule's degree of interaction with its environment, especially the long-wave radiation field that cannot be excluded or screened off. In effect, relatively small molecules can "inherit" or "acquire" classical properties from their environments, despite the fact that they are too small to undergo the sort of thermodynamic fusion observable in larger systems.

The introduction of the environment does not threaten the reality of ontological escalation, since it is only a partially *classical* environment that can induce the quasi-classical properties of the dressed molecule: in order to produce the superselection rules needed to distinguish stable molecular structures, the environment must have infinitely many degrees of freedom, due to its own thermodynamic fusion. (Primas 1980, p. 102-5; Primas 1983, p. 157-9) As R. F. Hendry points out, a molecule's acquisition of classical properties from its classical environment, thereby breaking its microscopic symmetry, should count as form of "downward causation":

> This supersystem (molecule plus environment) has the power to break the symmetry of the states of its subsystems without acquiring that power from its subsystems in any obvious way. That looks like downward causation. (Hendry 2006, pp. 215-6)

IV.

Sketch of a Hylomorphic Interpretation of Quantum Statistical Mechanics. The Aristotelian or hylomorphic interpretation of quantum statistical mechanics and quantum chemistry can be summarized in three simple points.

1. **The presence of an Aristotelian form transmutes finite ensembles into thermodynamic systems with infinitely many degrees of freedom.**
2. **The presence of such infinite sub-systems gives ground real thermodynamic properties (entropy, temperature), superselection sectors, and irreversibility.**
3. **These thermal systems ground (in a top-down fashion) enduring chemical structures.**

As we have seen, spontaneous symmetry breaking, including spatially asymmetrical molecular structures, arise naturally in the setting of infinite quantum-mechanical models. We can explain why the molecular structure of large molecules, or molecules in dynamic interaction with their environment, have stable molecular structures, despite the prevalence of superpositions at the microscopic level.

V.

Objections. I will consider here four objections: (1) one based on anti-realism about thermodynamic properties and phenomena, (2) the claim that infinite models are mere mathematical conveniences, not to be interpreted realistically, (3) the claim that we can justify infinite models without escalation, by appealing to the infinite number of degrees of freedom in the surrounding electromagnetic field, and (4) the claim that the price of rejecting atomism in favor of a literal continuum of matter is simply too high.

First objection: there simply are no thermodynamic properties, phase transitions, etc. This objection consists in going resolutely anti-realist about thermodynamic phenomena. However, this is to fly in the face of empirical fact, as Bangu has argued:

> The problem is that, on the one hand, it is unquestionable that we witness a physical discontinuity taking place—we all see the condensation of vapors on the wall of the tea kettle every morning; on the other hand, we can't point out the precise moment when the transition occurs. Strictly speaking, then we cannot observe the moment when the physical discontinuity occurs. Hence, insofar as a singularity is supposed to characterize it, a singularity does lack observational significance—while again, this does not preclude the singularity having physical significance….. Thus, singularities do not occur at the level of direct observation (the level of data) but at the next level up, so to speak, the level of phenomena, which are inferred from the data. (Bangu 2009, 500-1)

In addition, if thermodynamic properties are unreal, then so are chemical properties, including the structure of molecules. We would have to treat all of chemistry as a kind of useful fiction, leaving us with no possible explanation of the endurance of chemical form.

Second, defenders of microphysicalism could argue that infinite models are merely mathematical conveniences. On this view, although finite quantum-mechanical models lack the formal properties that are needed (including phase transitions and irreversibility), they do provide approximations to the needed features that are good enough for all practical purposes.

For example, although processes in finite models are never strictly irreversible, many of them are irreversible within the future lifetime of the cosmos and so “practically irreversible.”

Jeremy Butterfield has appealed to the convenience of fractal as an analogy (Butterfield 2011, pp. 1090-1103). Fractals are infinite models, and fractals have properties, in particular, non-integer dimensionality, that finite shapes lack. Nonetheless, fractal geometry is extremely useful in modeling nature. Similarly, microphysicalists have argued that the discontinuities of infinite models are approximated well by steep peaks in finite models. (Menon & Callender 2013, 220. Kadanoff 2013, 163)

However, these suggestions provide no explanation of the shift to new dynamical laws that infinite models enable. In addition, they take the objective arrow of time and the 2nd Law of thermodynamics for granted, with no hope of an explanation or ground.

Vague appeals to “steepness” won’t suffice, as Paul Mainwood has recognized:

> The theories really do require a genuine singularity; vague appeals to ‘steepness’ or an ‘extreme gradient’ will not do. For we can find finite systems with extreme gradients in the relevant thermodynamic variables which do not become a singularity as the thermodynamic limit is taken: these do not represent phase transitions. (Mainwood 2006, 214)
>
> The Yee-Lang theory, in common with other treatments, requires a genuine discontinuity, not just an extreme gradient in the free energy. We can easily construct finite systems with extreme gradients in their free energy that do no develop discontinuities when the thermodynamic limit is taken; these do no signify genuine phase transitions. (Mainwood 2006, 232)

There is a still deeper problem: the finite models of quantum statistical mechanics presuppose a finite number of molecules, each with its own chemical structure. These facts cannot be explained by finite models of quantum particle theory, because they require spontaneous symmetry breaking, which, as we have seen, arises only in infinite models. Thus, attempts to explain the thermodynamic phenomena (like phase transitions) using such finite models are viciously circular, as Hans Primas recognized: (190, 107):

> I would like to stress that every method whatsoever (e.g., the adiabatic approximation, the generator coordinate method) which is intended to give a description of a molecule in terms of electronic structure and a nuclear framework cannot avoid using a commutative algebra of observables. (Primas 1980, 107)

Any commutative algebra of observables requires superselection rules, and an infinite model (to escape the Stone-von Neumann theorem). Laura Ruetsche summarizes the argument for macrophysical realism:

> …without the idealizations committed to reach the thermodynamic limit, we lack rigorous mathematical models of macroproperties like magnetization, and the relations into which those properties fall—including the relations constituting critical phenomena and exhibiting universality. Lacking models of critical phenomena in individual systems, we also lack a collection of models featuring the same critical behavior: we lack any systematic theoretical purchase on universality. Lacking this purchase, we cancel the explanatory agenda of explaining universality. Canceling that agenda, we do away with Renormalization Group theory, an approach whose explanatory bona fides come from advancing that agenda. In short,… [the] idealizations of the thermodynamic limit are

essential for modeling the full range of behavior that falls under the ambit of enormously fruitful Renormalization Group approaches to critical phenomena and universality. (Ruetsche 2011, 339)

Third objection: we can get infinitely many degrees of freedom by coupling with the electromagnetic field in an infinite universe. The microphysicalist could agree with me that the correct models of thermodynamic and chemical phenomena have an infinite number of degrees of freedom but propose that the additional degrees of freedom come not from some hylomorphic transformation of the finite system of molecules but rather from the coupling of the finite system with the universe's electromagnetic field. The total system (molecules plus electromagnetic field) could then have infinitely degrees of freedom, thanks to its inclusion of the field. (See Earman 2004, 192; Emch and Liu 2005.)

Alternatively, the microphysicalist could hypothesize that each simple particle has an infinite number of unknown, as yet undiscovered parameters, as Jeremy Butterfield has suggested (Butterfield 2011, 1077). I have three responses to this objection.

First of all, we don't know that the electromagnetic field really does have infinitely many degrees of freedom. In order to avoid the infinite energies resulting from self-interaction, quantum field theorists posit some sort of energy cutoffs, which reduce the number of degrees of freedom of any given field to a finite number.

Second, as noted above (footnote 8), it is not sufficient for the model to have infinitely many degrees of freedom: it must have infinitely many sub-systems, resulting in a non-separable Hilbert-space representation.

Third, and more importantly, it is not sufficient to simply add an infinite number of extraneous degrees of freedom to our finite models of chemical phenomena. The additional parameters must have some explanatory relevance to the phenomena in question, as Mainwood recognizes (Mainwood 2006, 228). What is essential is that we add infinitely many degrees of freedom by taking the finite system to its continuum or thermodynamic limit. The result perfectly matches Aristotle's hylomorphic model: the finite models represent material causation (constraint from the bottom up), and the continuum limit represents formal causation (constraint from the top down).

Turning now to the fourth objection, the microphysicalist could argue that the cost of abandoning atomism, the ultimately discrete character of matter, is simply too high. However, in the context of quantum mechanics this seems quite wrong. In the quantum world, we're used to accepting a pervasive particle/wave duality. Why not an equally pervasive duality of the dense and the discrete?

The use in QM of Einstein-Bose and Fermi statistics suggests that individual quantum particles lose their determinate identities when fused into a quantum system. If that individual identity of particles can be truly lost, why is it hard to believe that matter in the resulting fusion could act in certain circumstances as though it were continuously and not discretely distributed in space?

As an additional analogy, we could look to the matter density version of GRW theory, in which the primitive ontology or "beables" (to use John Bell's term) of the models consist in a continuous distribution of matter. One final analogy is provided by quantum field theory, in which even the number of fundamental particles can be indeterminate—in a state of quantum superposition—and can even vary (in relativistic QFT) depending on one's frame of reference.

VI.

Conclusion. As we have seen, molecular structure is a relational rather than an intrinsic property of molecules. So are thermodynamic properties like temperature. A robust version of hylomorphic escalation would hold the biological domain responsible to a significant degree for the macroscopic structuring of the chemical and microphysical domains. Think of the role of stitching that holds together the patches in a patchwork quilt: thermodynamics and chemistry are responsible for the internal structure of the patches (the atoms and molecules), biology for their determinate spatial and dynamical inter-relationships. This doesn't require any new fundamental forces—no *vis vitalis*.

Even a robust conception of free will can find a natural home in this framework: free will is just one more kind of spontaneous symmetry breaking, of much the same sort as we saw in the context of thermodynamics, with the difference that the symmetry that's broken is psycho-physiological rather than chemical. Spontaneous symmetry breaking means that we human beings can be in a state that is, insofar as it is grounded entirely at the micro-level, a symmetrical superposition of both possible choices, but which at the social and human level must take one definite form or the other, in a way that is not fixed from the bottom-up. This does have the consequence that the human level could be indeterministic even if the quantum level is (taken on its own) deterministic.

I have not claimed that any of the quantum theory discussed in sections III and IV provide any direct evidence of the ontological escalation of the biological and social domains. I am only claiming that quantum chemistry provides a useful model for thinking about escalation, yielding a situation in which makes the further extrapolation of the model to larger-scale domains is plausible and reasonable, especially in light of our awareness of our own agency.

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