

# **Quantum Hylomorphism: An Aristotelian Interpretation of Quantum Thermodynamics and Chemistry**

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## **I. Introduction**

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 theory, 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, like temperature and entropy, as genuinely real, which in turn provides grounds for the reality of the direction of time and of molecular structure.

## **II. Hylomorphism and Ontological Escalation**

### **A. Definition of ontological escalation in terms of grounding**

I am going to defend a version of strong or ontological "emergence," but I prefer not to use that term. There are four drawbacks to the term "emergence" and the associated picture:

1. *An overemphasis on the bottom-up determination.* Many emergentists seek to preserve the unity of nature by keeping the micro in ultimate control. The language of "emergence" suggests a certain priority of the micro: the macro level must "emerge from" the micro level, but there is no parallel requirement that the micro level "submerge" or "diverge" from the macro. This privileging of the bottom level is associated with what I would call the

*Myth of the Universality of Particle Physics.* I would argue that political science is just as universal as biology, since it is just as much a judgment of political science that certain organisms are non-human or non-rational as it is that some are human. Similarly, it is a biological matter to claim that some chemical system is non-living, and it is a chemical matter to assert that certain particles fail to form a molecule. Thus, politics, biology, and chemistry are just as universal as is particle physics. There may be certain principles that are truly universal in a stronger sense, such as the law of the conservation of energy or the constancy of the speed of light, but these principles are no more associated with particle physics than they are with any other special science.

2. *'Emergence' as become too variegated in meaning.* In the ninety years since talk of 'emergence' was popularized by Samuel Alexander and C. D. Broad, the term has been subjected to a bewildering variety of senses and sub-varieties, including weak and strong and epistemological and ontological emergence. Many (including Jaegwon Kim) have tied the notion of *emergence* with ideas of supervenience, which is largely a red herring. It's time to consider making a new start with fresh vocabulary.

3. *New fundamental forces.* In its strong form (Broad 1925), emergentism includes the postulating of new fundamental forces—"configurational" forces. In this respect, it comes very close to vitalism or dualism. I will argue that the causal autonomy of complex entities does not require forces beyond the three or four currently accepted by the sciences (gravity, the electroweak force, and the strong nuclear force).

4. *Defined in contrast to "theory reduction," understood as a logical or deductive relation.* However, theoretical reduction is compatible with ontological and causal novelty at larger scales of composition, as I will argue below.

Consequently, I will make use of the neologism 'ontological escalation'. One advantage of this phrase is the etymological connection between 'escalate' and 'scale': according to the thesis of ontological escalation, properties and powers "emerge" at one of a number of

different levels of scale, with different levels on an ontological par. No priority is given to the very small.

What do I mean by 'scale'? I have in mind a relation that is defined in terms of composition, not size, mass, or volume.

- A set  $A$  of possible entities is *constitutively above* a set  $B$  of possible entities just in case  $B$  includes some proper parts of every member of  $A$ , and  $A$  includes no proper parts of any members of  $B$ .
- A set of properties and relations  $P$  is *constitutively above* a set of properties and relations  $Q$  just in case the set of possible bearers of  $P$  is constitutively above the set of possible bearers of  $Q$ .
- A *domain*  $D$  is a maximal set of properties and relations of such a kind that no subset of  $D$  is constitutively above any other subset of  $D$ .
- A domain  $D_1$  is *of larger scale than* domain  $D_2$  just in case some subset of  $D_1$  is constitutively above some subset of  $D_2$ .

The larger-scale relation is provably irreflexive and transitive (a partial ordering). I conjecture that it is, as a matter of scientific fact, a linear ordering.

### **Thesis of Ontological Escalation**

1. The world consists of a number of levels of compositional scale, with each scale-level consisting of a domain that includes certain fundamental entities with certain fundamental properties and 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.)

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 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 entities at each level of the scale have some ungrounded properties, and the causal powers of and relevant relations among those entities are grounded partly in those autonomous properties, partly in the ungrounded properties and relations of the entity's parts, and partly in the ungrounded properties of the wholes at larger scales in which the entity is incorporated. 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. Even if we suppose that the lower-level entities do not survive the process, we might still count Humphreys's model as a form of

ontological escalation, since the small-scale internal development of the the larger-scale entities would be synchronically grounded in the nature of those larger-scale entities, and the larger-scale entities would diachronically dependent on the dynamical properties of the small-scale *summands* that can enter into the fusion process.

As I argued in Koons 2014, I would defend a broader account of escalation, one encompassing Humphreys's model a special case. (In fact, I will argue in section III E below that, in the case of phase transitions in condensed-matter physics, we have good grounds for endorsing something very much like Humphreys's fusion model.) Even when the *fusands* (the things being fused) survive as components of a larger-scale entity, we can have a case of ontological escalation, so long as the dynamic interactions between the smaller-scale entities are grounded in the nature of the larger-scale fusion. This can happen, without the introduction of any new fundamental forces (including configurational forces) so long as the *spatiality* or *spatial inter-relatedness* of the smaller-scale entities depends in part on their participation in a larger-scale whole.

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 non-supervenient downward causation, involving new configurational forces (as in 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).

Bernard Williams famously accused hylomorphism of being merely a "polite form of materialism." Is ontological escalation equally vulnerable to the charge of being merely a

polite form of microphysicalism? I would argue that it is not, on the grounds that microphysicalism must be committed to the one-way dependence of all larger-scale levels on the one, microscopic level of fundamental entities. As long as we insist on an equal dependence of the small on the large, we can avoid microphysicalism. We also avoid, at the same time, the equally imperialistic extreme of cosmic monism (as defended recently by Jonathan Schaffer 2010). As often happens, the two extremes of atomism and cosmic monism have much in common, in sharp contrast to the pluralism of ontological escalation or multi-scale realism.

## **B. Escalation in contrast to supervenience and reduction**

Supervenience is a *modal* relation among facts (or properties). Reduction is a *logical* relation between theories. Ontological escalation is a *metaphysical* relation among domains of entities, natural properties, and causal powers. There is no simple definition of ontological escalation in terms of supervenience, reduction, or their absence. Let me review briefly why this must be so.

### **1. Supervenience vs. Escalation**

Take a look at supervenience. Here is the simplest definition of the (local, weak) supervenience of the A-properties on the B-properties:

Entities  $x$  and  $y$  are *A- (B-) duplicates* just in case they do not differ with respect to their *A- (B-) properties*.

#### **Supervenience of A-properties on B-properties:**

Necessarily, if two things are *B-duplicates*, then they are also *A-duplicates*.

In the late twentieth century, many philosophers hoped that supervenience could be used as a criterion for metaphysical dependency: the *A-properties* depend on the *B-properties* if

and only if they supervene on them. There is, however, a crucial difficulty with this proposal: supervenience, unlike dependency, is not asymmetric. Consequently, supervenience cannot entail dependency.

Here are two illustrations of this non-entailment.

**1. Leibnizian monads.** Consider two Leibnizian monads  $M_1$  and  $M_2$ . The class of properties of the form *perceived to be X by  $M_1$*  supervenes on the class of properties of the form *perceived to be X by  $M_2$* , since it is (by Leibniz's hypothesis) necessarily the case that each monad perceives the same set of perceptible facts as perceived by any other monad. However, it is also the case that the second class supervenes on the first class. Hence, the supervenience of the perceptions of  $M_1$  on the perceptions of  $M_2$  does not entail that the perceptions of  $M_1$  *depend on* the perceptions of  $M_2$ .

**2. The garden of forking paths.** Suppose that it is necessarily the case that any state of the universe has a unique possible past but many possible futures. In such a metaphysical model, the class of past-tensed properties supervenes on the class of future-tensed properties, since any two world-states that are duplicates with respect to future-tensed properties must be duplicates with respect to past-tensed properties. In this case, the converse form of supervenience does not hold: the class of future-tensed properties does *not* supervene on the class of past-tensed properties. Nonetheless, it is clear that past-tensed properties do not *depend metaphysically on* future-tensed properties. Again, supervenience (even when conjoined with the denial of reciprocal supervenience) does not entail supervenience.<sup>1</sup>

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<sup>1</sup> It would not help to try to define metaphysical dependence in terms of one-way supervenience (i.e., to propose that the A facts depend on the B fact just in case the A facts supervene on the B facts and not vice versa). It would be possible for such one-way supervenience relations to hold in a circle, with the A-facts supervening on the B-facts (and not vice versa), the B-facts similarly one-way supervening on the C-facts, and the C-facts on the A-facts. Thus, one-way supervenience is not transitive, unlike metaphysical dependency.

Microphysicalists subtly assume that there is no grounding of the microphysical in the macro-levels: no real explanation of the microphysical in terms of the macro-levels. That is, they assume that the micro-level is ungrounded, independent, and fundamental. Given both those assumptions and the supervenience of everything on the microphysical, the non-fundamental character of the macro-levels does follow, if we make the plausible assumption that it is impossible for one class of ungrounded properties to supervene on another, disjoint class of ungrounded properties. If class *A* supervenes on class *B*, there must be some explanation of this fact in terms of metaphysical dependency, although this explanation need not take the form of the dependency of *A* on *B*. Thus, dependency or grounding cannot be defined in terms of supervenience, but supervenience is a phenomenon that demands explanation in terms of grounding.<sup>2</sup>

This crucial assumption (the *metaphysical ungroundedness* of the supervenience base) is falsified in my two counter-examples to the supervenience-to-dependency entailment. The perceptions of the monads are all grounded in God's power and intention to create a pre-established harmony among them. The supervenience of the perceptions of one monad on those of the other can be explained in terms of their common grounding in this divine intention.

Similarly, in the case of the garden of forking paths, the future is *not ungrounded*: it is partly grounded in the past (because, for those future-tensed facts to be facts about the future, they must stand in a later-than relation to past events). Hence, the supervenience of the past on the future does not give us any reason to suppose that the past is wholly grounded in the future.

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<sup>2</sup> Grounding can supply the needed explanation, given two plausible assumptions: (i) if the fact that *p* grounds the fact that *q*, then the truth of *p* necessitates that of *q*, and (ii) if the fact that *p* grounds the fact that *q*, then the fact that *q* is necessarily grounded by some fact like the fact that *p*.

Microphysicalism depends on a Democritean starting point, according to which facts about atoms and the void are ungrounded (metaphysically fundamental) facts. This ungrounded foundation consists of microscopic entities with certain intrinsic characteristics (*shape* and *size* for Democritus, but this can be extended to include things like *charge*, *mass*, *spin*, and so on), and certain instantaneous spatial relations. All spatial relations can be ultimately grounded in a large number of simple binary or ternary relations among the microscopic entities (distance certainly, perhaps also angles between inter-atom directions). Atoms and the void constitute the fundamental level, and everything else both supervenes and wholly *depends* on them.

Aristotle's hylomorphic model denied the ungroundedness of the microscopic realm. The intrinsic characters of and mutual relations (including spatial relations) among the microscopic entities are often grounded in the natures of the macroscopic entities of which they are parts. Consequently, for Aristotelians, the *supervenience* of the macro-world on the micro-world would be not indicate the metaphysical *dependency* of the first on the second.

Although macro-on-micro supervenience is irrelevant to the Democritus/Aristotle controversy, the same is not true for the absence of such supervenience. If macrophysical properties do not supervene on microphysical properties, this decisively refutes the Democritean picture. The quantum revolution supports Aristotle in both ways: by questioning the ungrounded character of the micro-level, and by providing some good reason for denying the supervenience of the macro-level on the micro-.

## **2. Reduction vs. Escalation**

Although it is now commonplace to accept that supervenience does not entail microphysicalism, the same is not true with respect to reductionism. Both critics and defenders of ontological emergence typically take emergentism to be committed to the denial of Nagelian reduction of macroscopic dynamic laws to microphysical dynamic laws.

However, this common assumption overlooks the fact that every scientific explanation appeals to two factors: dynamical laws *and a phase space (including a manifold of possible initial conditions)*. Consequently, every scientific theory comprises two elements: a set of dynamical laws and a space of possible initial conditions. The structure of this space implicitly encodes crucial nomological information.

In order to secure a metaphysical conclusion about dependency between the domains of two theories, it is not enough to derive the dynamical laws of one theory from the dynamical laws of the other, supposedly more fundamental theory. We must also prove that the structure of the phase space and of the manifold of possible initial conditions of the supposedly reducing theory is not itself grounded in the structure or laws of the reduced theory.

Suppose, for example, that we have two theories,  $T_{\text{macro}}$  and  $T_{\text{micro}}$ . Theory  $T_{\text{macro}}$  consists in a set of dynamical laws  $D_{\text{macro}}$  together with a phase space  $S_{\text{macro}}$ , and  $T_{\text{micro}}$  similarly consists of laws  $D_{\text{micro}}$  and space  $S_{\text{micro}}$ .

Let's suppose that we have a Nagelian reduction of  $T_{\text{macro}}$  to  $T_{\text{micro}}$ : a translation  $*$  from the vocabulary of  $T_{\text{macro}}$  into  $T_{\text{micro}}$  such that  $D_{\text{micro}}$  entails  $(D_{\text{macro}})^*$  with respect to space  $S_2$ , but  $(D_{\text{macro}})^*$  does not entail  $D_{\text{micro}}$  with respect to  $S_{\text{micro}}$ : that is, the set of trajectories (the flow) through  $S_{\text{micro}}$  that are logically consistent with  $D_{\text{micro}}$  is a proper subset of the set of trajectories through  $S_{\text{micro}}$  that are consistent with  $(D_{\text{macro}})^*$ . Would this give us grounds for taking the entities and properties of  $T_{\text{macro}}$  to be *grounded in* those of  $T_{\text{micro}}$ ?

Not necessarily: we have to take into account the role of the spaces  $S_{\text{macro}}$  and  $S_{\text{micro}}$ .

Suppose, for example, that the structure of  $S_{\text{micro}}$  (the space of the supposedly reducing theory  $T_{\text{micro}}$ ) is metaphysically *grounded* in the structure of  $S_{\text{macro}}$ : that is, suppose that it is facts about the natures of the supposedly reduced theory  $T_{\text{macro}}$  that explain the structure of the space of possibilities used to construct explanations in terms of theory  $T_{\text{micro}}$ . It may be, for example, that the structure of  $S_{\text{macro}}$  is "tighter" or more restrictive than the

structure of  $S_{\text{micro}}$  (under any metaphysically sound translation between the two), and this tighter structure might be inexplicable in terms of  $D_{\text{micro}}$ , theory  $T_{\text{micro}}$ 's dynamical laws. In addition, there might be no *natural* restriction on space  $S_{\text{micro}}$  that would close the modal gap between  $S_{\text{macro}}$  and  $S_{\text{micro}}$ . On these suppositions, the Nagelian reduction of the dynamical laws of  $T_{\text{macro}}$  to  $T_{\text{micro}}$  would carry no metaphysical implications. It is not enough to look only at the dynamical laws.

I will argue that the relation between ordinary quantum mechanics (QM of particle physics) and the theory of quantum statistical mechanics (the quantum theory of thermodynamics) fits the pattern between the theories  $T_{\text{micro}}$  and  $T_{\text{macro}}$ . That is, we can plausibly derive the dynamical laws of quantum statistical mechanics from the dynamical laws of ordinary QM, but the *space of possibilities* defined by QSM is not reducible to the space defined by ordinary QM. Hence, quantum statistical mechanics, and related quantum theories of thermodynamics, solid-state physics, and chemistry, are not wholly grounded in the quantum mechanics of the constituent particles.

Laura Ruetsche (Ruetsche 2011) has recently defended a similar conclusion:

Identifying physical possibility with primordial [microphysical] possibility, period, we undermine the nomic force of many explanations encountered in physical practice—explanations mediated by laws which hold only of a proper subset of primordial possibilities. On the other hand, identifying physical possibility only with a particular such proper subset, we deprive the space of primordial possibilities its role as a reservoir from which different physical possibility spaces might be coalesced, to meet different practical or explanatory practices. (Ruetsche 2011, 290)

It was easy to overlook this possibility, so long as we took for granted the ungrounded and even universal nature of the essentially Democritean phase space. In classical mechanics, the space of possible boundary conditions consists in a space each of whose “points” consists in the assignment (with respect to some instant of time) of a specific location,

orientation, and velocity to each of a class of micro-particles. As long as we could take for granted that this spatial locatedness and interrelatedness of particles is not metaphysically grounded in any further facts (including macroscopic facts), reduction of macroscopic laws to microscopic dynamical laws seemed sufficient for micro-physicalism. However, this ungroundedness of the spatial locations of microscopic particles is precisely what the quantum revolution has called into question.

### **C. Escalation and hylomorphism: forms as ground of structure**

There is clearly some intimate relation between Aristotelian *form* and the structure or organization of a composite thing. In recent years, some neo-Aristotelian philosophers (e.g., Eleonore Stump, Kit Fine, Mark Johnston, Kathrin Koslicki, William Jaworski<sup>3</sup>) have proposed that this relation is simply identity: forms *are* structures. I propose both that Aristotelian forms (especially substantial forms) are essential elements in an adequate ontology and that they form a *sui generis* category. Substantial forms are **not** identical to the structure of composite substances: instead, they are metaphysical components of substances that constitute the metaphysical *ground* of that structure, in a sense of *ground* that has been rehabilitated in recent years by Kit Fine, Jonathan Schaffer, Gideon Rosen, and others. Forms are that *in virtue of which* substances are structured internally as they are.

### **III. Quantum Theory and Thermodynamics: Six Reasons for Escalation**

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<sup>3</sup> Only Koslicki (2008) and Jaworski (2016) are explicitly committed to the forms = structures thesis. Stump (1995) speaks of “configurational properties,” Johnston (2006) of “relational properties,” and Fine (1999) of “variable embodiments” of “relational properties,” but I understand them all as defending something equivalent to the identification.

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.) and substances at the level of thermodynamic systems. I will call 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 in subsection C below). Any mere collection or heap of fundamental particles has only finitely many degrees of freedom (as measured by the position and momentum of each particle), while thermal substances (as studied in quantum statistical mechanics) have literally and in fact *infinitely many* degrees of freedom. This inflation of 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 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 variables. 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.

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. 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 representation (von Neumann 1931). Infinite systems, in

contrast, admit of infinitely many inequivalent Hilbert-space representations.<sup>4</sup> 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 is richer than that provided by any irreducible representation of observables.... Furthermore, the wealth of inequivalent representations of the observables permits a natural classification of the states in 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 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*, 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

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<sup>4</sup> As Kronz and Luper (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. It is not sufficient for the system to have infinitely many degrees of freedom.

suppose that there is literally an infinite number of infinitesimal molecules, but we must suppose that the molecules *cooperate in such a way that they fuse (spatially) into a dynamic continuum*. 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 (and 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.

#### **A. Explaining the direction of time, possibility of measurement.**

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.”

## **B. Rigorous definitions of thermodynamic properties**

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)

### **C. Explaining 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 123<sup>rd</sup> 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.

#### **D. Spontaneous symmetry breaking**

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 inconvenient 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; emphasis mine)

#### **E. Definition of Phase Transitions**

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....

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. Among the noteworthy features of these structures is the following.

(1) The macroscopic and microscopic descriptions of the model are quite distinct from one another. In particular, the macroscopic specification of a state serves to determine the island in which it lies, while the microscopic one identifies it as a definite element of that island.

(2) The model admits a clear-cut characterization of symmetry breakdown in phase transitions,....

(3) The dynamics of an infinite system, unlike that of a finite one, is generally free from Poincaré cycles, and thus the model is amenable to a systematic theory of irreversible processes. Furthermore, the dynamics in different islands may, in general, be quite different from one another, in accordance with the empirical fact that the non-equilibrium properties of a macroscopic system generally depend on which phase it is in. (Sewell 1986, p. 19, pp. 34-35)

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 vagueness to 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 the *unreality* 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. 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 transition exists, while the infinite model is supposedly a mere “useful fiction”?<sup>5</sup> 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.”

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

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<sup>5</sup> 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.

exactly the kind of 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.

## **F. Explaining the persistence of chemical form**

The Schrödinger equation for a finite system of particles is spherically symmetrical. Thus, there is no 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,<sup>6</sup> 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 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 form of the chemical substance is thus an Aristotelian form. 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

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<sup>6</sup> 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.

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)

If we were to try to represent molecules in pure, pioneer quantum mechanics, we would have to suppose that molecular systems spend most of their time in a symmetrical state of structural superposition: a quantum “mixture” of the various pure states corresponding to this or that classical structure. When we observe individual molecules in a chemical mixture, we should always find that the systems collapse to a variety of classical structures: we should never find a sample whose molecules persist over time with precisely the same molecular structure. In fact, we observe such consistency all the time. Life on earth depends on it, since stable molecular structure is essential to functioning of all cells. In order to save the phenomena, quantum chemists are forced to use generalized QM models, with non-trivial cores of universally commuting, classical observables.

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.**

The Aristotelian interpretation of quantum mechanics has some similarity to GRW and other objective collapse theories—in addition to objective collapse events (which occur whenever an isolated quantum system encounters a semiclassical substance), we have objective fusion and dissolution events, involving the coming to be and corruption of composite thermal substances (with infinitely many degrees of freedom). There could be a

stochastic law governing such generation and corruption events, depending on the number of entangled particles or waves.

**2. The presence of such infinite sub-systems gives ground real thermodynamic properties (entropy, temperature), superselection sectors, and irreversibility.**

As we have seen, infinite models give rise to superselection rules, which can be used to define classical (mutually commuting) superselection properties, which cannot enter into superposed states. These classical states correspond to thermodynamic properties, like entropy, heat, temperature, and chemical potential, which can be given rigorous theoretical definitions in the quantum setting, as opposed to the loose and pragmatic definitions used in classical statistical mechanics. The infinite models are non-periodic, with true irreversibility and an objective arrow of time. Thus, observation, measurement, and measurement records can be treated as objective realities.

**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**

**A. There are no thermodynamic properties, phase transitions, etc.**

One possible response to these arguments is to go 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.

### **B. Finite models work fine for all practical purposes**

Secondly, 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 purpose. 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 2<sup>nd</sup> 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 not develop discontinuities when the thermodynamic limit is taken; these do not 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)

**C. We can get infinitely many degrees of freedom by coupling with EM 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).

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 3), 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).

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 of Einstein-Bose 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 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. Implications of the Model for Biology and the Human Sciences**

Chirality is a relational matter. 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: chemistry is 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*.

At the level of sentient animals, there are complex processes of joint perception-cum-action, which could be responsible for subtle but crucially important spatiotemporal

coordination and synchronization of smaller-scale biological and biochemical systems. It may be that, even in the absence of actual sentient creatures, the sensible (even the so-called “secondary”) qualities of macroscopic objects may contribute to the spatial organization of the microscopic realm. Thanks to chaotic, nonlinear dynamics, extremely small differences in relative spatial position and orientation can make huge differences in terms of long-term evolution of chemical and thermodynamic processes.

Biology comprises one or more broader domains: such as dissipative systems, ecological systems, and the evolutionary process. Thus, political and social science can find their places in the ladder of domains. We can find reason to embrace the escalation of social science relative to individual psychology in the fact that our perceptual capacities extend to the recognition and participation in symbolically sustained social practices. Insofar as human beings are both *motivated by* participation in social practices and *reliably sensitive to* the internal norms of those practices, human behavior escapes the bounds of methodological individualism. This epistemic sensitivity to the intrinsic meanings of social practices can thus shape the biological properties of individual human beings, which in turn can influence the chemical and microphysical structure of the human organism. This cascade of top-down influences neutralizes the threat of an exclusively bottom-up determination.

Even a robust conception of free will can find a natural home in this framework: free will is simply another case 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. Hylomorphism is consistent with both determinism and indeterminism at the level of human choice: spontaneous symmetry breaking simply 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.

In summary:

1. The principal argument for physicalism has been the monotonic success of microphysicalism, with its Democritean assumption of the metaphysical fundamentality of the micro domain.
2. Quantum thermodynamics and chemistry provide strong grounds for rejecting that narrative
3. Just as thermodynamic forms can be the grounds of microphysical properties of its constituent particles, so biological forms can be the grounds for the thermal and chemical properties of its thermal constituents; and rational and social forms can be the grounds for the biological properties of constituent organisms.
4. Consequently, quantum theory can open the door to fundamental rational agency.

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