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Bound States and the Special Composition Question

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Abstract. The Special Composition Question asks under what conditions a plurality of objects form another, composite object. We propose a condition grounded in our scientific knowledge of physical reality, the essence of which is that objects form a composite object when and only when they are in a bound state – whence our *Bound State Proposal*. We provide a variety of reasons in favour of a mereological theory that accommodates our Proposal. We consider but reject another proposal, which is quantum-physical in nature: the *Entanglement Proposal*. We close by responding to Teller's 'Suit Objection'.

Contents

1. Preamble

P. van Inwagen (1987, p. 23) raised the question what condition physical objects have to satisfy in order to compose another physical object. Three answers to this so-called *Special Composition Question* (whenceforth: the Question) have been considered and debated: *merelogical Nihilism*, according to which there are no composite objects, only elementary particles; *mereological Universalism*, according to which any collection of physical objects compose another physical object; and Van Inwagen's moderate answer (1990: 82), according to which physical objects compose another one iff their activity constitutes a life. All three versions scandalise our intuitive judgements: Nihilism and Van Inwagen deny that atoms, molecules, rocks, trucks, planets and galaxies qualify as *bona fide* physical objects, whereas Universalism affirms that, say, the nose of Cleopatra, the Erasmus suspension bridge in Rotterdam and the red giants in the Andromeda Nebula by contrast do. Such objects strike us as mereological monsters. While we agree that philosophical clarity and coherence with the sciences trump common sense any time, we prefer a view that is clear and coherent but does not trump common sense so pervasively. We expound such a view here. Slightly more specifically, we would like to propose another answer to the Question, one that both vindicates more of our common-sensical judgments and is firmly rooted in relevant portions of scientific knowledge.

2. The Bound-State Proposal

Consider an arbitrary but finite number of physical objects. They may or may not be interacting with one another. Whenever they interact, they may or may not be in a *bound state*, which by definition is a state in which the objects have a total energy that is negative ($E < 0$). In that case, the potential energy of the composing objects (which is always < 0) is larger in absolute value than their kinetic energy (which is always $\geqslant 0$); their total energy is the sum of their kinetic and potential energy. (The categorical attribution of a quantitative property of energy to objects presuppose a background of classical physics. True enough. When we move to quantum-physical theories, notably quantum mechanics, an exactly similar story can be told in terms of expectation-values of the Hamiltonian, which is the energy operator. These slight complications need not detain us here.) Our proposal now reads: *physical objects form a composite object iff these physical objects interact and are in a common bound state*, where '*common* bound state' means that the composing objects are in the potential well that results of their mutual physical interaction. An object *a* then is a *part* of object *b* iff *a* is among the objects that compose *b*. We call this the *Bound-State Proposal*. In order to find out whether objects are in a common bound state — which is an epistemic, not a metaphysical problem — one must find a physical theory in the currently accepted body of scientific knowledge that describes these objects as interacting and being in a bound state as a result. Note that the mere fact of interaction is a necessary but not sufficient condition on composition; what needs to be added is that the resulting state they are in is *bound*.

Let's give a couple of examples of the sorts of objects that our Proposal will sanction. An electron in a Hydrogen atom is in the electromagnetic potential well of the Hydrogen nucleus (a proton), and thus the atomic nucleus-electron system will qualify as an object. Once the kinetic energy of the electron has been raised above its ionization energy, however, the electron can break free from the nucleus, and we no longer have a bound state. Thus on our view it follows that all we have are an electron and a nucleus, but no third, composite object in addition. Something exactly similar can be said of all terrestrial objects which are in the gravitational potential well of the Earth. While in that well, they are parts of the composite system of the Earth and all Earth-bound objects. However, when a launched rocket passes the escape velocity of the Earth, its kinetic energy has become large enough to get out of the Earth's gravitational potential well and it is no longer part of the mentioned composite. It should be noted that while an inhabitant of a distant planet is in the gravitational potential well of that planet, and while an electron bound to an earthly nucleus is in the electro-magnetic potential well of that nucleus, the inhabitant and the planet are in a potential well distinct from that in which the electron and the nucleus are. As such, we do not here have a further object composed of the inhabitant, planet, electron, and nucleus, but just the two composites that we started with. We note finally that our definition may be said to be 'relative to physical theory' to the extent that for every particular composite system one needs a physical theory to describe the relevant potential well in detail. However, we know of no system that is bound according to one accepted physical theory and not bound according to another, so this 'relativization' is harmless.

The fact that the distinction between *bound* and *free* (i.e. non-bound) states is a significant distinction in the physics of many-body systems is *prima facie* reason to think it may be significant for the metaphysics of composite systems too. We think it is more than significant: it holds the key to a scientifically informed answer to the Question. In the next Section, we discuss some reasons for adopting the Bound-State Proposal. Following that, we sketch its ramifications for mereological theory (Section 4), before considering an objection rooted in the phenomenon of quantum entanglement (Section 5), and one further objection still.

3. Reasons

We begin with two clarifications. The first of these is that the Bound-State Proposal does indeed constitute a *moderate* answer to the Question, as van Inwagen's does, and not an extreme one. While it may be true in a strict sense that all objects are interacting with one another, it is certainly not the case that every object is in a bound state with every other, and thus our Proposal does not amount to Universalism. Nor of course is it Nihilism, since plenty of collections of objects *are* in such states. The second clarification is that our Proposal allows more collections of objects to qualify as composites than does Van Inwagen's. Collections of particles that form a living physical object are in a bound state: if the particles of a cat, say, were not in a bound state, they would fly apart in all directions. But there are also plenty of bound states that are not states of living systems, such as atomic nuclei, atoms, molecules, water-droplets, toasters, mountains, planets, and galaxies. On our account, they're all in.

With these clarifications in place, we claim that the *first reason* for supporting our Proposal is that it is more congruent with common-sense judgements about what counts as an object than is the competition, where we take such judgements to include those honed through immersion in physical science. We concede that it is in some sense unfortunate, but perhaps also unavoidable, that debates in mereological discourse often turn on appeals to intuitive judgments as to what should and should not count as a genuine composite object — not least because people's intuitive judgments can diverge on this score. Van Inwagen and others are no doubt correct to take it as plain that common sense will always prefer moderate answers to the Question, yet we can expect disagreement on exactly which moderate answer is the best. However, insofar as congruence with common-sense judgements counts as a reason in favour of an answer to the Question, we submit that our own moderate Proposal performs better than van Inwagen's – which we believe that most will agree is unacceptably sparse. Our proposal is also faithful to the plausible judgements, waged against Nihilism and Universalism respectively, that an atom is a *bona* *fide* object, and that it is so in the way that the 'mereological sum' of an electron and proton at arbitrary separation is not (cf. Lowe (2008: 86)). Just as, *contra* Van Inwagen (2002, 197), according to physics the mass of a table is *not* the sum of the masses of its ('non-overlapping') parts, an atom is likewise not simply the sum of its electronic and nuclear constituents. Were not the particles in bound states there would be no mass difference, and no stable composite object at all; on our Bound State Proposal, of course, there would be no composite object *simpliciter*.

A *second reason* in favour of our Bound-State Proposal is that it avoids objections that begin from the assumption that every "interesting" (that is, physico-causal) moderate answer to the Question will rest on conditions that are "inherently vague" (Inwagen (1987: 23)). Van Inwagen (1987: 23), Lewis (1991: 7, 79–81) and Sider (2001: § 4.9) have all argued that a *vague* answer to the Question leads to unacceptable kinds of vagueness or indeterminacy (although not everybody agrees with the specifics; see e.g. Hawley (2004), Noonan (2010)). Our Proposal, by contrast, is based on a *sharp* distinction — that of whether the state of a system is bound (total energy $E < 0$) or free ($E \geqslant 0$) — and therefore does not suffer from *any* kind of vagueness, let alone the allegedly pernicious ones envisioned by van Inwagen. On the contrary, any uncertainty over whether something falls under its extension or not is purely epistemic in character, resulting merely from the fact that our energy-measuring devices inevitably have finite resolution.

A *third reason* for endorsing our Bound State Proposal is that it exhibits a simplicity and unity that comparable proposals lack. To see this, note that, according to Van Inwagen, the appropriate physico-causal relation that objects will have to stand in in order to form wholes will typically vary with the kinds of objects involved. Thus elementary particles will be said to compose something iff they are 'maximally P-bonded', where P-bonding incorporates features and mechanisms that we take particle bonding to consist in; atoms, on the other hand, will be said to compose iff they are 'maximally A-bonded', where 'A-bonding' refers to whatever *sui generis* relation is appropriate in the atomic domain (1987: Section 7). As a result, Van Inwagen proposes (and later rejects) an answer of the following form, which he terms 'series-style':

> $\exists y$ such that the x's compose y iff the x's are elementary particles and are maximally P-bonded or the x's are atoms and are maximally A-bonded or there is only one of the x's. (Of course, if new *sui generis* composition relations are required as we traverse to macroscopic domains, that relation and its appropriate kind will appear in a new disjunct.)

The disjunctive, open-ended structure of this criterion, in which different types of relation appear according to their appropriateness for the kinds of objects involved in each disjunct, is the definitive feature of 'series-style' answers. Our Bound State Proposal, by contrast, does not posit *sui generis* composition relations, which vary with the kinds of objects involved. On the contrary, whether the system involved consists of the quarks inside a proton or the stars in a distant galaxy, the same principles govern whether we have a composite object or not (*viz.* whether they comprise a common bound state). Of course, the *forces* involved in *generating* the relevant potential may differ from case to case, but this is irrelevant from the perspective of our analysis. Our Proposal may therefore be regarded as completely generic, and as such it enjoys a unity lacked by the series-style solutions envisaged by Van Inwagen.

We should nonetheless point out that the reason Van Inwagen rejects series-style solutions has little directly to do with unity. Rather, he rejects them because they apparently violate the transitivity of the part-whole relation (see Inwagen (1990: 65)) — a condition that is standardly (and plausibly) taken as a necessary condition on parthood.[1] But it will be clear that – as we have thus far defined it at least – *our*

[1] Note however that not everyone regards transitivity as necessary: see Rescher (1955), Cruse (1979).

proposal will violate transitivity as well. The reason for this is that while a electron and the proton are in each others electro-magnetic potential well (and in doing so comprise the parts of a Hydrogen atom), and while every quark inside the proton is in the gluon potential of the other quarks (thus comprising parts of the proton), the electron is *not* in the potential well of the quarks (electrons are leptons, and leptons do not interact strongly, only hadrons do). As such, it seems that our Proposal cannot recover that the quarks are part of the atom, contrary to what transitivity and common sense requires.

At this point, then, we need to amend our Bound State Proposal so as to recover transitivity while remaining in the spirit of the original scheme. We do this by enriching our proposal to take account of *direct* and *indirect* parts. To do this properly, we need to enter briefly the larger topic of mereological theory.

4. Mereological Theory

We have noted that we want our final proposal to entail transitivity. We also demand that our proposal recovers that proper parthood is irreflexive. The question is then how to formulate our Bound-State Proposal precisely so as to entail both of these.

Generically composition is defined in terms of the primitive part-whole relation — so that a composite is the least part-inclusive object of which the given objects are all parts; this is a natural approach because the axioms of mereological theories usually concern the part-whole relation directly. We proceed differently. Our overall framework is some modest set-theory, and physical objects, which are treated logically as primordial elements (German: *Ur-elemente*).

Let S be any finite set of physical objects, let $\#S \in \mathbb{N}^+$ be the cardinality of set S, and let $\mathrm{Comp}(S, a)$ abbreviate: material object a is some composition of the objects in S. The Bound-State Proposal as previously formulated will now be an axiom in our mereological theory, and we formulate it as follows.[2] As usual, the part-relation is primitive, and denoted by '$\sqsubseteq$'.

Bound-State Proposal.
If S contains a single object, say a, then: $\mathrm{Comp}(S, a)$ iff $S = \{a\}$. If $\#S \geqslant 2$, then: $\mathrm{Comp}(S, a)$ iff (i) if $b \in S$, then b is a part of a ($a \sqsubseteq a$); and (ii) (the expectation-value of) the energy of every $b \in S$ is negative, i.e. every $b \in S$ is in a common bound state.

An object b is by definition *simple* iff it has no proper parts. Then the singleton-set of b is the one and only set whose member composes b:

$$\mathrm{Simple}(b) \;\text{ iff }\; \forall\, S:\; \mathrm{Comp}(S, b) \longrightarrow S = \{b\}\;. \tag{1}$$

We next define a special kind of part: a is a *direct part* of b (denoted by: $a \sqsubseteq_{\mathrm{d}} b$) iff a is a member of some set of objects that compose b:

$$a \sqsubseteq_{\mathrm{d}} b \;\text{ iff }\; \exists\, S\big(\mathrm{Comp}(S, b) \;\wedge\; a \in S\big)\,. \tag{2}$$

With these definitions in place, we advance the following axiom.

[2]Reformulations into plural logic are possible.

Part Axiom.
Physical object a is a part of b iff there is some finite sequence of direct parts that begins with a and ends with b:

$$a \sqsubseteq b \ \text{ iff } \ \exists\, n \in \mathbb{N}^+,\ \exists\, c_1, c_2, \ldots, c_n :\ a \sqsubseteq_{\mathrm{d}} c_1 \sqsubseteq_{\mathrm{d}} c_2 \sqsubseteq_{\mathrm{d}} \ \ldots \ \sqsubseteq_{\mathrm{d}} c_n \sqsubseteq_{\mathrm{d}} b\,. \tag{3}$$

A part is a direct part iff $n = 1$ in this axiom, and therefore direct-parthood is a special case of parthood. Call parts that arise for $n \geqslant 2$ *indirect parts*. Then a is by definition a proper part of b (notation: $a \sqsubset b$) iff a is part of b yet not identical to b:

$$a \sqsubset b \ \text{ iff } \ (a \sqsubseteq b \ \wedge \ a \neq b)\,. \tag{4}$$

To illustrate definition (3), consider that according to it some top-quark is a part of this Aston Martin Vanquish, because the top-quark is a direct part of a nucleon, the nucleon is a direct part of an atom, the atom is direct part of some molecule, the molecule is a direct part of some car-part (in the car-mechanic's sense of the word, such as the bonnet), and that car-part is, as the name says, a direct part of this Aston Martin Vanquish. In this sequence of (proper) direct parts, the nuclear interaction is involved in the first two sequents and from then on all wholes involved are result of electro-magnetic interaction. Part-whole sequences like this one show that they are not always in harmony with the received ontological hierarchy of natural kinds: the sequence quark–nucleon–nucleus–atom-molecule is presumably just such a sequence, whereas molecule–bonnet–car is presumably not.

One now easily verifies that simples (1) have no proper parts and have only themselves as parts. Further one easily verifies that $\sqsubseteq$ is reflexive ($a \sqsubseteq a$ because of $\mathrm{Comp}(\{a\}, a)$) and transitive ($a \sqsubseteq b$ and $b \sqsubseteq c$ leads to two finite parthood sequences that form a longer one, having a and c at its beginning and end, respectively, so that $a \sqsubseteq c$). Hence both of the desiderata on a mereological theory mentioned earlier are fulfilled. We consider the fact that these features of the part-whole relation follow from our Bound-State Proposal, and therefore need not be assumed axiomatically, to constitute a *fourth reason* in favour of our Bound-State Proposal.

5. The Entanglement Proposal

For all the successes of our Bound State Proposal, however, one might worry that physical theory motivates a different proposal that we have not yet considered. This is what we can call the *Entanglement Proposal*. What encourages this proposal is the fact that quantum theory seems to recognize another species of composite system in addition to bound states: namely, collections of N particles that are in entangled states. As such, the *Entanglement Proposal* will say that a collection of objects forms a composite if and only if the state of the collection is entangled.

Entanglement Proposal. Suppose we have a collection of N objects, the j-th object having Hilbert-space $\mathcal{H}_j$ as representing its possible physical states, and suppose Hilbert-vector $|\psi\rangle \in \mathcal{H}$ represents the state of the collection that provides the correct measurement results and their relative frequencies, notably including correlations between measurement results of the different objects. The collection of N forms a composite object iff (i) $\mathcal{H} = \mathcal{H}_1 \otimes \ldots \otimes \mathcal{H}_N$; and (ii) $|\psi\rangle \in \mathcal{H}$ is *entangled*, which means that $|\psi\rangle$ is *not* $\otimes$*-factorisable*, which in turn means that there are no Hilbert-vectors $|\phi_j\rangle \in \mathcal{H}_j$ such that: $|\psi\rangle = |\phi_j\rangle \otimes |\phi_2\rangle \otimes \ldots \otimes |\phi_N\rangle$.

Like composites in bound states, composites in entangled states are distinct from mere 'fusions': characteristic of entangled states is the fact that they cannot be determined just from the properties of the component parts. Nevertheless, the *Entanglement Proposal* is clearly at odds with our own. While it is true that quantum mechanics tells us that interacting systems get entangled with each other as a result of their interaction (so that composites satisfying the *Bound State Proposal* also meet this new proposal too), the converse is false: we can have entangled states of composite systems of particles that do not, or no longer, interact. For example, when a pair of photons leaves an atom in an entangled state, they come into being at the moment the atom drops to a lower energy state and immediately fly apart; they do not interact and have not interacted (because bosons, save gluons, cannot interact and do never form bound systems), but are in an entangled state. Thus while we emphasized above that interaction is necessary but not sufficient for composition according to the *Bound State Proposal*, here precisely the opposite situation prevails: interaction now turns out to be sufficient but not necessary. As such, the *Bound State Proposal* and the *Entanglement Proposal* give different answers to the Question. Since the last-mentioned is motivated by our most fundamental theory of matter, one might think that our first Proposal should graciously give way to it.

Nevertheless, we contend that our Bound State Proposal remains the right answer to the Question. We shall provide three reasons in support of it. The *first* derives from the fact, already noted, that in a strict sense every object is interacting with every other, for two of the four fundamental physical interactions have an infinite range (electro-magnetic and gravitational). (Although in many cases the entanglement will be so slight as to be neglicible 'for all practical purposes, that by no means entails that it may be regarded as insignificant for *metaphysical* purposes.) As such, strictly speaking the *Entanglement Proposal* amounts to Universalism. Since we hold that moderate answers to the question are to be preferred over their extreme counterparts, this counts against the tenability of the Entanglement Proposal as an answer to the Question.

The *second* reason derives from the fact that scientists seem to succeed in discriminating composite systems even in regimes in which quantum-physical effects do not enter into their considerations. For example, we discussed above planetary and galactic systems and identified conditions in which the systems may be said to comprise composites that were in agreement with our intuitions. But of course, pending a quantum theory of gravity *we have no idea* how to model such situations quantum-physically. Thus whatever it is that was driving these intuitions, it cannot be quantum in character. To be clear, we are *not* claiming that systems such as these do not have a nature that is ultimately quantum-physical, however it is that that nature will turn out to be understood. What we *are* claiming is that it is not in virtue of some feature of this unknown nature that makes it the case that they comprise a composite system: rather it is simply by virtue of the feature, known to us now as it has been for centuries, that they are in a bound state.

The *third* and final point that we would like to emphasize is that we are not denying that entanglement represents another way — indeed another way rubber-stamped by physics — for systems to compose in a significant sense. But as Healey notes, there are all sorts of notions of composition at work in physics (Healey 2013). What we *are* claiming is that the *Bound State Proposal* identifies the sort of composition *that is relevant to the Special Composition Question* discussed in metaphysics. Since that is the question we set our ourselves to the task of answering, we take it that our task is complete.

Or, perhaps we should say, almost complete. For P. Teller (2015) levelled the following counterexample to the Bound-State Proposal (see picture): jacket and trousers are parts of a suit, but they are not together in a bound state due to their mutual physical interaction. The Entanglement Proposal parenthetically provides the same judgment. Now what? Well, our judgement that trousers and jacket are parts of a suit is conventional, compared to property rights; and when the composition is conventional, mereological proposals need not cover it.

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