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ORIGINAL RESEARCH

A minimal metaphysics of thin-objects and nomic structure

Valia Allori[1]

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Abstract

A minimal realist thinks we are justified in believing in unobservable entities as explanatory, but we should be cautious in allowing non-empirically justified entities in our ontology. In this paper I argue that a minimalist would find my proposal for an ontology of fundamental entities without fundamental properties the best balance between empirical adequacy, explanatory power, and physical justification.

Keywords Minimalist metaphysics · Metaphysics of science · Empiricism · Properties · Laws: explanation · Classical physics · Quantum physics · Nonlocality

1 Introduction

In this paper I elaborate on a view previously presented, according to which the best way to defend scientific realism is to restrict our commitments to bare fundamental objects, namely objects without any other fundamental property than the one which defines their nature (Allori, 2023a). In other words, if the theory is about the evolution of point-like particles, then a realist could believe in the existence of fundamental physical objects with the only property of being located somewhere. The same is true for fields, as extended objects with the property of definite amplitude in each point. In both cases, fundamental physical objects are thin, or bare: they have no mass, no charge, no spin. In this view, properties are labels assigned to objects for convenience, without reflecting their true nature. Even if we artificially classify them in different families based on what we call their fundamental properties, all fundamental objects are identical. For instance, even if we distinguish between electrons, protons,

✉ Valia Allori
valia.allori@unibg.it

[1] Department of Letter, Philosophy and Communications, University of Bergamo, Bergamo, Italy

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and so on, in terms of charges, masses, and spin, all particles are identical. The reason for this is that we can appeal to a single type of force to explain the particles behavior. For instance, we explain why electrons go up and protons go down in some magnetic field or why electrons repeal one another while they attract protons, by saying that the particles behavior is governed by the electric force, which acts differently on different charges. That is, we explain the difference in behavior in terms of a difference in charge value. In my approach laws absorb the role of properties: we can account for particles having different behavior in the same physical situation by saying that they are governed by different effective laws, which form a network of nomic connections between particles which do not propagate. Accordingly, I have dubbed this view a *thin-object metaphysics grounded on static nomic structure*. In this paper I argue that my proposal is particularly interesting for a minimal realist, namely someone who is sensitive to considerations about underdetermination and empiricism, in particularly over the traditional account, and best accommodates some features of the quantum phenomena, such as contextuality and nonlocality.

Here is the organization of the paper. After clarifying the traditional understanding in terms of objects, laws, and properties in Sect. 2 articulate my view in classical mechanics in Sect. 3 and in quantum mechanics in Sect. 4 have previously argued that my proposal is particularly suited for the quantum domain as it is a better fit than the traditional schema both for quantum theories with a spatiotemporal microscopic ontology (the so-called primitive ontology approach) and for theories with a wavefunction ontology (such as wavefunction realism). I review the original argument that the contextuality of spin should be taken as evidence that spin is not a property, which in turn suggests that all other properties are 'in the laws' as well. After that, I maintain that quantum nonlocality, arguably experimentally established since the 1980s, should be taken as evidence that interaction between material bodies does not propagate. Rather, it is instantiated by the nomic structural network which in my approach is described by the effective laws, as also suggested by considerations coming from general relativity. In Sect. 5 provide additional independent reasons that my view should be favored by the empirically driven minimalist: guided by a principle of parsimony based on the idea that the least we assume the less wrong we can be, the minimalist would find my view less risky to endorse, as it postulates the existence of the least amount of (unobservable) things. I compare my approach to other empiricist-driven approaches (super-Humeanism, which is less general than my approach, ontic structuralism, which is more radical than needed, and dispositionalism, which is too connected to the notion of causation to be appealing to the minimalist), concluding that my view provides the best balance. In any case, I argue, a minimalist can be neutral about the nature of the nomic structure and hold a metaphysics of bare objects. This seems particularly appropriate when considering the pessimistic meta-induction argument against scientific realism: when restricting realism to a particle ontology, the pessimistic meta-induction argument is defeated, even if what instantiates the interaction between the particle remains unspecified. I summarize and draw my conclusions in the last Sect. 2

2 The traditional core of metaphysics of science

Should we get rid of fundamental properties? One may wonder whether I lost my sanity: of course not. Fundamental properties are essential to account for how laws act on matter. Without properties the force of the magnetic field would make every particle go in the same direction, which is not what we observe. Let me elaborate a little on this reply. Classically, matter is made of point-like, microscopic particles with properties such as mass and charge, in virtue of which the laws of nature act as they do on them. Focusing on the example above, if we observe a spot on the upper part of the detecting screen, or even a curved track across the magnet, we identify the particle as a negatively charged electron being deviated by the magnet from its otherwise straight track. If we observe a spot in the lower part, we identify the particle as positively charged. We do not observe the actual charge, but we infer its existence indirectly as the best explanation of the phenomena. Without properties like charge, laws would provide an empirically inadequate description: every particle would behave in the same way in a given physical situation. Instead, they do not: some particles go up in a magnetic field, others go down, and others just go straight. Some charged particles attract, some particles repel one another. We can explain these facts introducing charge: a positive charge 'makes' the particle go down, a negative charge 'makes' it go up, and if there is no charge the particle is not affected by the magnetic field at all. Fundamental properties are therefore needed to characterize the types of fundamental objects there are: electrons are such in virtue of being that specific mass and that specific charge. All electrons form a family of particles, in which all members share the same properties, which are different from all the other types of particles. So, not only do properties explain the phenomena, but they also help us discover the nature of matter.

2.1 Objects, laws, and properties in classical gravity

The type of ontology of matter (particles, in the example), the laws of nature (the magnetic force) and the properties (charge) form what I call the 'traditional core' of the metaphysics of science: our best scientific theories inform us about the minimal set of ingredients needed to account for the observed phenomena. The traditional core thus constitutes the set of the *fundamentalia*: objects identified by their fundamental properties guided by laws which act on them in virtue of their properties. (Humeans will disagree and argue that we only need matter and fundamental properties. We will come back to this later.)

Let me be explicit about this providing a series of concrete examples (I start in this section with classical gravitation and classical electrodynamics; after presenting the basic idea of my view in Sect. 3 generalize it to non-relativistic quantum theories in Sect. 4).[1] In classical mechanics particles, in addition of their location, have another fundamental property: the inertial mass M. Newton's second law states that objects move straight with constant velocity unless there is a force present, which modifies

[1] In the rest of this section, most footnotes provide technical details.

their velocity proportioally to M.[2] In classical mechanics there are different types of forces: gravitational, electric, magnetic. The force of gravity F^G is generated by any physical object due to another property called gravitational mass m. It attracts any other body instantiating the same property, call it now M, inversely proportional to their squared relative distance r. The strength of the force is given by G, the constant of gravitation.[3] The gravitational mass makes the body 'feel' F^G. Notice that there is no *a priori* reason to think that the gravitational mass in the definition of F^G is identical to the inertial mass in Newton's second law. Nonetheless, they have been experimentally proven to be identical.[4] Due to this equivalence, the body's motion is independent of M, and mass *does not* to characterize the object. In classical gravity *particles, aside their location, are all identical*. Masses are needed to define the force, together with its strength G. Thus, if there are N particles with locations r_i and masses m_i, the set of *fundamentalia* can be written as follows:

$$Fund_G = \left\{matter = [r_1, \cdots, \ r_N]; laws = [F^{G, m_1, \cdots, \ m_N}]\right\}.$$

2.2 Objects, laws, and properties in classical electromagnetism

According to the usual understanding, new empirical data led to postulate another force, the electric force F^E, and another property, charge.[5] Thus, keeping the same schema as gravity, fundamentally there are particles with masses m and charges q, whose motion is affected by F^E. This force is generated by other particles in virtue of their charges, and has strength k.[6] Notice that in this case, since Newton's equation involves M and not q, same masses but different charges generate a different motion. The link between properties and forces, unnecessary with F^G alone, comes from the need of explaining this difference in motion. While in classical gravity where there was no need of postulating different types of particles defined by different masses, new experiments suggested a link between charges and masses, which led to a classification of particle types in terms of properties: electrons are particles with mass m_e and charge q_e; protons have m_p and $q_p = -q_e$; while neutrons have $m_n = m_p$ and no charge.[7] Thus, m_p and m_e started to be considered as fundamental masses, in addition to the fundamental charges $\pm q$, 0. Accordingly, the set of *fundamentalia* of

[2] $F = Ma$, where $a(t) = \frac{dv(t)}{dt}$ is the acceleration.

[3] $F^G = G\frac{mM}{r^2}$, $G = 6.67 \times 10^{-11} Mm^2/Kg^2$.

[4] This is why I used the same symbol earlier.

[5] While there is only one type of mass, which produces an attractive force, there are two types of charges, positive and negative. Charges of the same sign repel; of different signs attract.

[6] $F^E = k\frac{qQ}{r^2}$, $k = 8.99 \times 10^8 \ Mm^2/C^2$.

[7] There is a single fundamental charge, $q = 1.602 \cdot 10^{-19}$C, positive and negative. The particle with $charge - q$ was called electron, the one with $+q$ proton. They have different masses: $m_p = 1.67 \cdot 10^{-27} kg$, $m_e = 9.\ 11 \cdot 10^{-31} kg$. There is also a particle with the same mass as the proton, but with no charge (neutron).

the traditional core becomes the set of fundamental particles and forces, both defined in terms of the fundamental properties:

$$Fund_{GE} = \{matter = [r_1, \cdots, r_N;\ m_e,\ m_p,\ \pm q,\ 0];$$
$$laws = \left[F^{k;\ m_e,\ m_p,\ \pm q, 0},\ F^{G;\ m_e,\ m_p}\right]\}.$$

Correspondingly, one talks about families of particles as the pair specifying their locations and their fundamental properties. If there are N_e electrons, N_p protons and N_n neutrons, then their respective families are given by $f_e = \{r_1, \cdots, r_{N_e};\ m_e,\ -q\}$; $f_p = \{r_{N_{e+1}}, \cdots, r_{N_p};\ m_p,\ q\}$; $f_n = \{r_{N_{p+1}}, \cdots, r_{N_n};\ m_p,\ 0\}$.
So:

$$Fund_{GE} = \left\{matter = [f_e,\ f_p,\ f_n];\ laws = \left[F^{k;\ m_e,\ m_p, \pm q, 0},\ F^{G; m_e,\ m_p}\right]\right\}.$$

Have we simply had gravity, we would not need to distinguish between types of particles. Instead, if one wishes to think all forces to act according to the same classical schema, since F^E distinguishes particles in different families due to their different charges, it seems natural to conclude that also masses play the same role as charges. Unlike k and G, which are constant, properties are parameters: their value changes depending on the object we are interested in (among the possible fundamental values).[8] For completeness, notice that electromagnetism, the study of the motion of charged particles, also needs a magnetic force, which depends on charges, their velocity and has a strength k_M [9] Thus, we have:

$$Fund_{GEM} = \left\{matter = [f_e,\ f_p,\ f_n]; laws = \left[F^{k,\ k_M;\ m_e,\ m_p,\ \pm q, 0},\ F^{G;\ m_e,\ m_p}\right]\right\}.$$

2.3 Interaction in classical mechanics

Notice that the gravitational force acts instantaneously at arbitrary distances: by definition of F^G, my hand moving here influences instantaneously the orbit of Jupiter. More technically, the gravitational influence is said to be nonlocal. This type of influence is contrary to the intuition that interaction travels: in order for mass 1 (Jupiter) to be influenced by mass 2 (my hand), 1 should 'feel' the presence of 2, and this requires time. By analogy, the waves generated by a rock thrown in a pond travel at finite velocity towards a toy boat. As it takes time for the waves to arrive at the boat and to make it move, so it should take time for the force generated by mass 2 to

[8] Assuming three families, k and G are fixed, and the masses can be m_e, m_p , and the charges $\pm q$, 0. An electron (charge $-q$), in presence of a charge Q, is subjects to $F_e^E = -k\frac{qQ}{r^2}$. To predict the behavior of a proton in presence of the same charge, we substitute m_p and $+q$ respectively to m_e and $-q$:. This accounts for why electrons and protons are subject to opposite forces.

[9] If a charge moves, it also generates a magnetic field B, which affects other particles in terms of the magnetic force $F^M = k_M qvB$, $k_M = 1.26 \times 10^{-6} N/A^2$. A moving electron is subject to $F_e^M = -k_M qvB$, while a proton $F_p^M = k_M qvB = -F_e^M$. This explains why an electron will turn one way and the proton the opposite way in the same magnetic field.

affect the motion of mass 1. This intuition is also connected to thinking that causes are always nearby their effects and that effects happen later than their causes. This is literally false in classical gravity, as my hand's motion and its effect on Jupiter are concurrent. Nonetheless, this nonlocality can be ignored in practice, given the force intensity decreases rapidly with the objects' mutual distance: the effect of my hand's motion, which is far away from Jupiter, negligibly affects Jupiter, and thus we can treat Jupiter as if it were isolated (i.e. alone in the universe). In general relativity instead nonlocality is completely absent because F^G is eliminated by assuming that gravitational motion is free motion in a curved spacetime (see also Sect. 5). In classical electrodynamics nonlocality is eliminated in another way: substituting forces with fields. In place of F^E and F^M there are two fields, an electric field E and a magnetic field B, which mediate 'their' force, 'notifying' one charge of the presence of another. Every particle is thus tough as generating an E in virtue of having a charge, and a B in virtue of the charge moving. Together, E and B are called the electromagnetic fields.[10] They obey laws of evolution given by Maxwell's equations, from which it follows that E and B each evolve according to a wave equation $W^{E,B,\,c}$, propagating with the velocity of light c.[11] That means that one can think of the interaction between charges as local: influence does not act instantaneously like in the gravitational case; rather it propagates at a finite velocity c. Given this, electromagnetic fields are often called 'radiation.' Traditionally, therefore, classical electromagnetism is taken to have a dual ontology: matter is made of particles, and radiation, which mediates the interaction, is constituted by fields:

$$Fund_{GEM} = \left\{ \begin{array}{c} matter = [f_e,\ f_p,\ f_n]\,;\ radiation = [E, B] \\ laws_{matter} = \left[F^{c;\ m_e,\ m_p, \pm q, 0},\ F^{G;\ m_e,\ m_p}\right]\,;\ laws_{radiation} = \left[W^{E,B,\ c}\right] \end{array} \right\}.$$

Notice that in the laws there is only c, which is a constant of nature depending on the strength of F^E. [12] So, arguably there are no properties characterizing matter in these laws (however, see next section).

To summarize and conclude, then, traditionally one defines what there is and how it moves using the notions of objects, laws, and properties. Properties have a dual

[10] The electric field E is defined as $E = k\frac{Q}{r^2}$. (In classical gravity one can also introduce a gravitational field $U = G\frac{M}{r^2}$.) B is instead thought as generated by *moving* charges. Without entering any more details, unlike E, B has no sources:. Arguably, this dissimilarity is lessened when both E and B are seen as components of the so-called electromagnetic tensor $\mathcal{F}$.

[11] Maxwell's equations are: $\nabla \cdot E = \frac{\rho}{\varepsilon_0}$; $\nabla \cdot B = 0$; $\nabla \times E = -\frac{\partial B}{\partial t}$; $\nabla \times E = \mu_0 \left(J + \varepsilon_0 \frac{\partial E}{\partial t}\right)$, where ρ is the charge density, $J = \varrho v$ the current density, $v\,\varepsilon_0$ and μ_0 are two constants (free permittivity and permeability), $k = \frac{1}{4\pi\varepsilon_0}$, $k_M = \frac{\mu_0}{4\pi}$. The wave equations $W^{E,B,\,c}$ for the fields are: $\nabla^2 E - \frac{1}{c^2}\frac{\partial^2 E}{\partial t^2} = 0$, $\nabla^2 B - \frac{1}{c^2}\frac{\partial^2 B}{\partial t^2} = 0$, $c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$. One can write them as $\Box_c E = 0$,$\Box_c B = 0$ (or together as $\Box_c(E, B) = 0$) where $\Box = \nabla^2 - \frac{1}{v^2}\frac{\partial^2}{\partial t^2}$ is the so-called generic d'Alambertian operator and $\Box_c$ is the one with $v = c$.

[12] Since $c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$, and $k = \frac{1}{4\pi\varepsilon_0}$, $k_M = \frac{\mu_0}{4\pi}$,then $c = \sqrt{\frac{k}{k_M}}$.

role: they appear into the definition of matter, and the specify how the law acts, so that:

$$Fund = \{matter_{properties};\ laws_{properties}\}$$

3 Thin-objects oriented metaphysics grounded on structure

The traditional schema seems indispensable. Also, even if it were possible, eliminating properties seems unnecessary, as it is unclear what the advantage would be. I instead propose that a more restricted set of *fundamentalia* is possible and even more desirable, at least for the empiricist inclined metaphysician who cares physical practice.

As argued by Quine and Duhem, there is always the possibility of providing an alternative explanation of something: a given web of beliefs can be adjusted as needed to cope with any evidence. So, it is always possible to modify the set of *fundamentalia* as one wishes, including eliminating properties. The real issue is whether such an adjustment is preferrable, balancing costs and benefits. Notice that attempting to restrict the minimal set of the *fundamentalia* is entrenched in physical practice. Physicists have kept reducing the set of fundamental objects: for instance, arguing that atoms, which were initially thought of as fundamental, are instead composed. In addition, physicists have successfully reduced the set of fundamental forces: for instance, the electric and magnetic force have been unified into a single force (see footnote 14). What has not been done is reducing the number of fundamental properties, which instead have multiplied: from mass within classical gravity, to mass and charge in electromagnetism, to mass, charge, and spin in non-relativistic quantum mechanics (see next section), to even more exotic properties like hypercharge in relativistic quantum theories.[13]

3.1 Bare identical objects

Instead of minimizing the elements in the set of the *fundamentalia* by keeping the number of type of entities in the set constant (objects, laws, and properties) and by reducing the number of entities in each type, *I propose to reduce the number of the type of entities in the minimal fundamental set*. I argue that, while we need to specify the ontology of matter and the laws (at least from an anti-Humean perspective; otherwise, everything just supervenes on the ontology of matter, see below), we can dispense of talking about properties, as their role can be absorbed into the laws.

Before exploring the view, let me notice that this perspective is naturally suggested in the case of classical gravity. In fact, as noted, mass only appears in the definition of the interaction, thereby playing no role in characterizing the object *in virtue of its motion*. In classical electromagnetism this is not so: charges also iden-

[13] In relativistic quantum field theories, hypercharge is a label for all the properties defining a particle, including also ‘color charge’ and ‘isospin’.

tify the particles. However, if we focus on the object's motion, and we think that all properties play no role in characterizing the objects but are ingredients in the forces, then one arrives at my view. In other words, *my idea is to 'move' all properties in the definition of the forces, and leave the objects 'bare'*. More specifically, this amounts to multiplying the type of 'effective' forces that exist, while minimizing the types of particles. This is the opposite of what traditionally is done, namely multiplying the type of entities and keeping only one type of law. The idea is therefore, continuing with the examples we have given, that there are no electrons, protons, and neutrons. Rather, there are just bare particles: entities which only require a point to be completely specified. All particles are identical, in the sense that they possess no fundamental property other than their location. As I elaborate below, the difference in behavior in a given physical situation is accounted for in terms of the particles being governed by different 'effective' laws: what we used to think as an electron, goes up in a magnetic field not because of its charge, but because it is affected by a different effective law than, say, a proton, which will go down in the same magnetic field. Two particles attract, rather than repel, not because of their opposite charges but because the effective laws between them are different.

3.2 Effective laws

Formally, my view can be implemented by treating the parameters as universal constants. Instead of having a single type of fundamental force, say F^E, acting differently on particles with different fundamental charges, there are as many 'effective' electric forces, each for every fundamental charge. Each effective force has an effective strength given by the strength of the force times[14] the property values of the charges involved.[15]

The bare particles' only property is to be located somewhere, while there are as many effective laws as we need to account for the empirical data, namely the number of what we have previously identified as particle families: instead of having three families f_e, f_p, f_n, we have three effective laws F^1_{eff}, F^2_{eff}, F^3_{eff}. Effective forces come from the different ways of instantiating the same type of force. This 'general' force is to be considered 'empty', and in this sense unphysical. Effective forces instead represent something physically real because they correspond to 'fill-

[14] This is contingently due to the fact that, by definition, the strength and the charges multiply one another in F^E (same for the masses in F^G).

[15] Using the previous examples, particle 1, an 'electron,'in presence of particle 2, a 'proton,' is subjects to an 'effective' force with no free parameters: $F^1_{eff} = \frac{k_{ep}}{r^2}$, where $k_{ep} = kq_e q_p$ is constant. A 'proton' is affected by particle 2 as follows: $F^2_{eff} = \frac{k_{pp}}{r^2}$, where $k_{pp} = kq_p q_p$. Since $k_{pp} = k_{ee} = -k_{ep} = kq^2$ and $k_{ep} = k_{pe} = -k_{ee} = -kq^2$, then $F^2_{eff} = -F^1_{eff}$, an attractive force same magnitude but opposite direction when compared to the force acting on particle 1 (an 'electron'). A particle traditionally identified as a neutron would not interact with 2, thereby $F^3_{eff} = 0$.

ing' the effective constants of the empty force with definite, fixed, values, namely the property values of the partciles involved.[16]

So, in my proposal applied to electromagnetism and gravity the set of *fundamentalia* is given by the set of particles and the effective forces acting upon them. Formally, if there are N particles with location r_i, and 3 effective forces (determined by what we previously identified as fundamental properties), then the *fundamentalia* are:

$$Fund = \left\{ matter = [r_1, \cdots, r_N] \; ; laws = [F^1_{eff}, \; F^2_{eff}, \; F^3_{eff}]_{m_e, \, m_p, \, \pm q, 0} \right\}.$$

Instead of talking about particle families, one talks about a primitive pairing relation between fundamental objects and effective laws: N_e particles are fundamentally and primitively paired with F^1_{eff} , N_p are fundamentally and primitively paired with F^2_{eff}, and N_n are fundamentally and primitively paired with F^3_{eff}. Consequently:

$$Fund = \left\{ r_1, \cdots, r_{N_e}; F^1_{eff} \right\} \cup \left\{ r_{N_{e+1}}, \cdots, r_{N_p}; F^2_{eff} \right\} \cup \left\{ r_{N_{p+1}}, \cdots, r_N; F^3_{eff} \right\}$$

$$= \cup_{\mathrm{i}} \left\{ matter_i; Eff.Law_i \right\}.$$

Each particle's association with a given effective force is primitive: for each fundamental entity there is its fundamental effective force. What we labelled 'electrons' are in the first set, 'protons' in the second, 'neutrons' in the third. There are still particle families, but they are not defined in terms of properties. To be an electron, say, is not to have mass m_e, charge $-q$ and semi-integer spin (see later). Rather, to be an electron is to behave as an electron, in the sense of being associated with the effective force F^1_{eff}.

3.3 Particles and fields

According to my view, fields are not considered as physical entities as in the traditional picture. So far, I have used a particle ontology of matter. However, one can extend my proposal to other ontologies. For instance, a field ontology would be mathematically characterized by an intensity value at any spatial location, which may change in time according to some evolution equation. A type of field (i.e. a gravitational, electric, and magnetic field) is usually taken to be different from another in terms of their action on the particles, depending on their properties. Nonetheless, magnetic and electric fields are not further distinguished between one another in terms of some 'property'; rather, it is specified what type of equation they obey. That

[16] In the case of $F^E = \frac{kqQ}{r^2}$ we need to specify the value of k as well as the values of q and Q: $\pm q$ or 0. Then, we get three strengths ($kq^2, -kq^2$, 0) and thus $F^1_{eff} = \frac{kq^2}{r^2}$, $F^2_{eff} = -\frac{kq^2}{r^2} = -F^1_{eff}$, $F^3_{eff} = 0$. For an 'electron' interacting with a 'proton', we have $m_e a_1 = \frac{kq^2}{r^2}$, hence $a_1 = \frac{kq^2}{m_e r^2}$; for a 'proton' interacting with an 'electron' we have $a_2 = \frac{kq^2}{m_p r^2} = a_1 \frac{m_e}{m_p}$; for an 'electron' interacting with another 'electron', we have $a_3 = -\frac{kq^2}{m_e r^2} = -a_1$; for a 'proton' interacting with another 'proton' we have $a_4 = \frac{kq^2}{m_p r^2} = -a_2$. A 'neutron' interacting with any other particle would not be accelerated (as far as the effect of F^E is concerned).

suggests that there is a single, bare, field whose intensity values are determined by its evolution equation. This is in line with my approach, and, where 'matter' indicates more generally 'matter and radiation', the set of *fundamentalia* would be as follows:

$$Fund = \{matter = [partcile;\ fields]\,; laws_{properties}\}\,.$$

Interestingly, as mentioned already, the only 'property' which appears in the law for the fields is c, which is a constant of nature. Had it been a variable, then it could have been treated as a property describing different types of fields, like charges in electromagnetism. The role of the c 'property' is instead to characterize the evolution of the fields, and not to characterize matter (this is compatible with the fact that c is constant). This seems evidence that electromagnetism is a theory of fields. However, by definition $c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}$ (see footnote 15), where ε_0 and μ_0 can be arguably seen as properties of vacuum, as they measure how vacuum 'responds' to the fields. There are corresponding properties when the fields propagate in a different material, thereby suggesting that there is a sense in which they can be seen as characterizing matter, suggesting that c might be too, after all.

Be that as it may, I should notice that I have argued elsewhere (Allori, 2021a) that thinking of electromagnetic fields as describing matter would make electromagnetism lose symmetry properties, and I take this to be a *reductio* of the reality of electromagnetic fields.[17] Importantly, this conclusion holds only for particle generated fields, like electromagnetism. A future theory of pure field ontology could however be possible, in which case one could still use my approach with a spatially extended ontology like fields.

To summarize, therefore, one can re-write the whole 'bare objects, effective laws' approach rather generally: with any type of ontology of matter and any type of implementation of the interaction. In fact, laws may act on matter in different ways, other than through forces. For instance, in quantum mechanics there are no forces, and the interaction is generically expressed by the Hamiltonian of the system (see next section). Since in my view properties appear only in describing the interaction not matter itself, one can write the set of *fundamentalia* rather prosaically as follows:

$$Fund = \{what\ there\ is; how\ it\ moves_{properties}\}\,.$$

'What there is' might be particles, fields or what have you, while 'how it moves' may be characterized in terms of forces, Hamiltonians or the like. The distinctive feature

[17] In fact, a theory has a symmetry S if the original and the S -transformed formalism both adequately describe the world. For instance, classical mechanics is invariant under timnulle T(transforming t into $-t$) because the T-transformed image of the world does not change. It turns out that if classical electromagnetism is taken as a theory of fields then it would be T-invariant only if B flips sign, while there is no reason why it should (Albert, 2000). Even if one finds such a reason (see Arntzenius, 2004; Earman, 2002; Malament, 2004), I show that it (insanely) follows that ontology changes depending on how we look at it: the ontology in a forward evolving contains B, while in a backward solution it would contain $-B$. This is absurd. The only possibility is that the theory is not T-invariant. (The argument also extends to other symmetries).

is that, in contrast with the traditional understanding, in my view matter is stripped of all properties, which instead are packed into the specification of the evolution of matter.

4 Minimal quantum metaphysics

How does the situation change in quantum mechanics? The question does not have a unique and uncontroversial answer. 'Standard' quantum mechanics in physics textbooks instrumentally provides an effective method for systematizing and predicting experimental results. Its main equation is the so-called Schrödinger equation which provides the temporal evolution of an object called the wavefunction ψ.[18] Contact with experiments is given by the square module of the wavefunction, through the so-called Born rule, which suitably describes the distributions of experimental outcomes. This anti-realist reading is usually considered necessary because this theory is unable to precisely solve the so-called measurement problem (Schrödinger, 1935): a Schrödinger evolving wavefunction generates unobserved macroscopic superpositions such as, famously, a cat being in a 'superposition of being dead and alive'. The standard theory solves this problem by stipulating that, when a measurement is performed, the wavefunction randomly and instantaneously collapses into one of the possible superpositions, hence the name of 'collapse rule'. However, this solution is usually deemed unsatisfactory from a realist perspective, as it is unclear what a measurement is, and why it is not just a special type of physical process. Realist quantum theories are supposed to solve this problem without attributing to measurement processes a privileged status.

The three most promising realist theories are the pilot-wave theory (Bohm, 1952), the spontaneous localization theory (or GRW theory, from the initials of their proponents Ghirardi et al., 1986), and the many-worlds theory (Everett, 1957). The pilot-wave theory is a theory of particles whose motion is governed by a Schrödinger evolving wavefunction through a deterministic equation dubbed the 'guidance' equation. Since matter is made of particles, there are no superposition of matter. The GRW theory instead is a theory in which the wavefunction evolves according to a non-linear stochastic modification of the Schrödinger equation specifically designed to suppress superpositions at a suitable macroscopic scale. Finally, the many-worlds theory embraces the idea that superpositions are real: contrarily to appearances, there is a dead cat and an alive one, superimposed in the same spacetime, which effectively never interact because they have lost the relevant coherence property to do so.[19]

4.1 A microscopic ontology for quantum mechanics

Importantly, while the pilot-wave theory can naturally be thought as having a particle ontology, GRW and many-worlds are usually regarded as theories with a wavefunction

[18] $i\hbar\frac{\partial\psi}{\partial t} = H\psi$; $H = -\frac{\hbar^2}{2m}\nabla^2 + V$ is the Hamiltonian.

[19] For more see, respectively Goldstein (2021); Bassi and Ghirardi (2020); Wallace (2012), Vaidman (2021), Barrett (2023).

ontology. The issue with such an ontology is that the wavefunction is not a wave or a field oscillating in three dimensions, like electromagnetic fields. Rather, for a system of N 'particles' the wavefunction can be written as $\psi = \psi\left(r_1, \ldots, r_N\right)$, namely as a function of what we used to call the particles configurations $r_1, \ldots, r_N$. That is, the wavefunction is a field in configuration space of dimension $3N$, which is in general much higher than 3. Thus, theories with a wavefunction ontology have the additional task of explaining the emergence of three-dimensional objects and their properties from a fundamentally non-three-dimensional reality. This position is often called wavefunction realism (Albert, 2015; Ney, 2021). However, recovering three-dimensional reality requires completely rethinking our classical explanatory schemas based on a spatiotemporal microscopic ontology of matter, in which macroscopic properties are explained compositionally and dynamically. Within theories of the wavefunction instead, we need to 'close the gap' between the high dimensional fundamental space and the three-dimensional space of our experiences, and this is done postulating unexplained principles (Allori, 2013, 2023b). If one also thinks that, as a general methodological principle, we should refrain from changing what has worked in the past if there are no clear advantage in doing so, then it should be clear why people have proposed alternative readings of GRW and many-worlds in terms of a spatiotemporal ontology (Allori et al., 2008).[20] Leaving aside arguments for one or the other view, I have previously argued (Allori, 2018) that my minimalist approach is preferred to the traditional one for both frameworks. The spatiotemporal framework (also called the primitive ontology approach), according to which the quantum ontology is microscopic and in spacetime, by definition preserves the classical schema of explanation, traditionally rooted in objects, properties and laws. Fundamental properties include masses and charges but also spin σ, a novel, genuinely quantum property. Particles may have integer or semi-integer spin, and they are classified respectively as bosons and fermions. Fermions include electrons, protons, and neutrons. One can see that,[21] for instance in the pilot-wave theory, the set of fundamental fermions is given by an ontology of particles together the relevant laws, for the partciles and the wavefunction (v^j and ψ^{SP})[22]

$$Fund = \{matter = [r_1, \cdots, r_N; m = m_e, m_p, q = \pm q, 0, \sigma = \pm 1, \pm 1/2]; \\ laws = \left[v^1, \cdots, v^N; \psi^{SP}\right]_{m,q,\sigma}\Big\}.$$

Using the definitions of v^j and ψ^{SP}, one can see that properties appear both in characterizing particle families and in the definition of the interaction.[23] One can naturally

[20] Several proposals have been made for GRW (spatiotemporal events, Bell, 1987; matter field; Benatti et al., 1995; particles, Allori et al., 2014; Allori, 2020). Similarly, form many-worlds (see Allori et al., 2008).

[21] In the pilot-wave theory, a given particle j evolves as $v^j(t) = \frac{\nabla S(r,t)}{m}$, where m is the particle's mass and S is such that $\psi(r,t) = R(r,t)\, e^{iS(r,t)/\hbar}$. With spin, the wavefunction factorizes into a product state of spin and position, and spin one is a two-dimensional vector (spinor) which for fermions is $\begin{pmatrix} \psi^{1/2} \\ \psi^{-1/2} \end{pmatrix}$. Spinors obey the Pauli-Schrödinger equation, which is the the Schrödinger equation with

$H = \frac{1}{2m}\left[\sigma \cdot (p - qA)^2 - q\phi\right]$, where A and ϕ are the vector and scalar electromagnetic potentials ($A = \nabla \times B,\ E = -\nabla\phi$).

[22] Respectively, he guidance equation v^j and the Schrödinger-Pauli equation ψ^{SP} for the wavefunction

[23] There is mass in the guidance equation, and mass, charge, and spin in the Schrödinger-Pauli equation.

extend my picture here stripping the particles bare, and moving all the properties into the definition of the law by suitably defining effective laws:

$$Fund = \{matter = [r_1, \cdots, r_N]; Eff.laws_{m,q,\sigma}\}.$$

Arguably the same strategy can be extended to other quantum theories with a microscopic spatiotemporal ontology.

4.2 A wavefunction ontology for quantum mechanics

What about wavefunction realism? Dubbing $\psi^{eff.\ S}$ the law for the evolution for the wavefunction (which is 'effectively' the Schrödinger evolution, in the sense that it could be either exactly the Schrödinger evolution as in Everett, or the non-linear stochastic modification of GRW), one has:

$$Fund = \{\ matter = [\psi]; laws = [\psi^{eff.\ S}]_{m,q,\sigma}\}.$$

This notation makes explicit that in this approach properties appear in the definition of the evolution of matter, rather than its characterization, making my proposal a good fit for wavefunction realism as well.

In passing, however, let me notice that from a minimalist perspective wavefunction realism seems difficult to defend. An argument in favor of this view is that it provides the only local and separable metaphysics in the fundamental space, namely in configuration space. Moreover, the justification for the importance of locality and separability in that space has to do with their being intuitive, almost undeniable, notions (Ney, 2021). Nonetheless, if a minimalist comes to believe in a local interaction, namely that interaction propagate at finite velocity, it is because of what we ordinarily perceive, namely three-dimensional objects behaving as if they could be isolated and causes being proximal to their effects. If a minimalist comes to believe that the properties of the composite are given by the properties of its components, namely if they come to believe in separability, it is because they observe objects to be separable in three-dimensional space. That is, if a minimalist cares about locality or separability, they care about them in three-dimensional space, not in configurations space. Indeed, a minimalist, by observing motion in three dimensions, can empirically justify assuming an ontology with features like (three-dimensional) locality and separability. Instead, they do not have the empirical means to determine the features of an ontology in configuration space, since one does not observe motion in that space.

4.3 The contextuality of spin

Be that as it may, as it was argued previously, there is a distinctive advantage of my account connected to the contextuality of spin (Allori, 2023a). Here is why. The result of a measurement of a given property A should be the value the property had before the measurement was performed, while one obtains a different result depending on how one decides to measure spin. This is interpreted saying that spin is contextual: the value of the spin property depends on the context of measurement. However, this comes close to being ridiculous: two genuine measurements of some property should give the same result independent of their context of measurement, while contextuality is tantamount to saying that this is not the case. That is, if contextuality is true, then the value of the (genuine) weight of an object measured, say, using a mechanical scale and at the same time measuring its length, could be $10\ g$, while the value measured, say, using a digital scale and measuring its color, could be $1000\ g$. This seems to suggest that something has gone wrong somewhere. Why should it be different for spin? One (in my eyes) very natural possibility is to deny that spin is a property measurements can reveal. Nonetheless, it is argued, we need spin for the same reason as in the traditional understanding we needed masses and charges: to account for different behavior under the same physical circumstances. So, it is usually concluded, we need to accept that this new property has this 'crazy' contextual feature. Instead, since in my approach we do not need properties to account for different behaviors, we do not need to think of spin as a property at all, and the quantum contextuality mystery simply disappears. In addition, as mentioned in Sect. 2, classical gravity gives us reasons to think of mass as 'in the law', so it seems reasonable to think of also other properties, like spin, in the same way.

On a different note, let me remark the following. While to explain electromagnetic interactions we have added a property (charge) and a force (F^E) to classical gravity, to explain quantum phenomena we have not added a 'quantum' interaction, even if we have added a quantum property (spin). Admittedly this can be done in the pilot-wave theory, when formulated in terms of the so-called quantum potential. However, spin is not the source of such a potential in the same way as charge could be considered the source of F^E, and there seems to be no property associated with the quantum potential (however, see Sect. 6). In any case, even if one could find such quantum property, the very fact that we have not used forces and properties in the explanation of quantum phenomena already shows that the idea of particles interacting in virtue of their properties was not necessary after all.

4.4 Quantum nonlocality

In what follows I argue that there is another quantum feature that my approach can accommodate better than the alternatives, namely quantum nonlocality. As anticipated, before the quantum era, everyone took for granted the idea of locality, or local causality, namely that interaction propagates at finite velocity. The theory of special relativity added the constrain that there is a maximum velocity for interaction, namely the velocity of light. All physics was compatible with this (at least observable) locality. As mentioned in Sect. 2, the nonlocality of F^G disappears in the theory of general relativity, and electromagnetism is local because the electromagnetic fields are the physical mediators of F^E. The idea of local causality was so engrained in everyone's thought that Einstein used it to argue against standard quantum mechanics. In his famous paper with Podolsky and Rosen (Einstein, Podolsky and Rosen1935), he argued that the standard theory was unacceptably nonlocal due to the wavefunction collapse.[24] Einstein thought that this nonlocality was an artifact of the incompleteness of the theory, and that it would disappear upon a suitable theory completion. Instead Bell continued Einstein's reasoning and showed that such a local, complete quantum theory would make different predictions than the standard theory (the famous Bell's inequality, Bell 1964). Later, experiments were performed to empirically assess these options, and it was found that local theories are not empirically adequate (Aspect 1981). If so, the idea of local causality cannot be empirically maintained (this however remains controversial; see Myrvold, 2004 and references therein).

4.5 Effective laws as static nomic structure

Go back to electromagnetism for a moment. As discussed in Sect. 2, in my approach the fields are better seen as part of the 'nomology'. If so, they do not serve as physical mediators of the force, and thus electromagnetic interaction is nonlocal. This might seem a total disaster: going back to instantaneous action at arbitrary distance even for electromagnetism looks like a good reason to abandon my view. Nonetheless, while in electromagnetism there might be a way out of the nonlocality of interaction in terms of electromagnetic fields, this is no longer the case in the quantum domain in which the interaction is nonlocal, as we just saw. Thus, if quantum theory is supposed to be more fundamental than classical theories, then our metaphysics should first and foremost be compatible with it, and thus with nonlocality. In addition, the idea of locality is intertwined with the idea of causality. The minimalist is already suspicious of causality, so they should not be too attached to the idea of nonlocality either.

Be that as it may, effective laws express the way in which matter interacts with itself, which is instantaneous even in electromagnetism. The issue is to understand what this means. One possibility is to think that interaction propagates at infinite velocity. However, in addition to going against special relativity, 'propagation at infinite velocity' seems like an oxymoron. Another possibility is to think that *interaction does not propagate at all*. That is, effective forces do not propagate; rather they form a static, overall network of nomic structural relations interconnecting the particles. Recall now that in classical gravity as traditionally understood here is no *a priori* reason to think that the inertial mass, which provides the 'resistance' to the force, and the gravitational mass, which is the property in virtue of which the objects 'feel' the gravitational force, are identical. Nonetheless, they are. This puzzle and the nonlocality of the force eventually both evaporate in general relativity. This is the case also in my view of classical gravity. Since the inertial mass disappears from the equation of motion of a body, such a quantity is not needed. Only the gravitational mass remains, and since there is only one quantity, rather than two, there is no equivalence to be explained. The nonlocality of F^G is accounted for in terms of a rigid nomic structure interconnecting matter. Since in this picture the interaction does not propagate, then

[24] According to standard quantum theory, a pair of entangled particles have no individual definite properties. Assume the two particles are sent in opposite directions and that one of them, A, is measured, then collapses gives it a definite property. Moreover,, also the other particle B instantaneously acquires a definite property, even if B is at arbitrary distance from A. Thus, if standard quantum mechanics were complete, it would be nonlocal: something happening to A would instantaneously affect the arbitrarily distant B.

strictly speaking interaction is by definition nonlocal. Compare with general relativity, in which spacetime is curved by the presence of matter, so that what counts as natural (unperturbed, or free) motion depends on the curvature of spacetime. Bodies will go straight if the presence of matter does not substantially change the flatness of spacetime. Rather, their trajectories will bend, *as if* acted on by a gravitational force, if spacetime is sufficiently curved. That is, F^G is replaced by the curvature of spacetime, so that motion of matter is always free, and there is a law, given by Einstein's field equation, to connect the distribution of matter to the spacetime curvature. This picture seems compatible with my idea of dispensing with properties. What is crucial about matter is to be located somewhere and to be able to bend spacetime. That is, the presence of mass somewhere changes the geometry of spacetime in a neighborhood of that location. As a massive body moves in spacetime, the spacetime curvature changes. While that means that one can think of the geometry of spacetime as a whole as approximated by a series of locally defined geometries which change in the surroundings of the object with the same velocity as the body is moving, nonetheless, geometrical relations between different spacetime locations change instantaneously. Assume that a massive body starts from a spatiotemporal point A and moves towards another point B. During its motion, the body creates a deformation of spacetime which propagates at the same velocity as the body moves. In contrast, the distance between B and an arbitrarily distant point C instantly changes because the geometry around B has changed. That is, C is instantly affected by what happens in B, as far as its geometrical properties go. In other words, geometrical relations between arbitrarily distant points may instantly change. This is in stark contrast with what one usually thinks about physical interaction, which we think propagates at finite velocity. However, in general relativity gravity is no longer understood as an interaction but as a geometrical constrain. In classical gravity the gravitational interaction is nonlocal, so in the passage to the general theory of relativity this nonlocality is transferred from F^G (which no longer exists) to the geometry of spacetime. Thus, it seems we can think of general relativity as a theory in which the behavior of matter is governed by a structure of geometrical relations, which therefore can be seen as having a nomological role:

$$Fund = \{matter;\ nomic\ geometrical\ structure\}\,.$$

Since in general relativity the changes in the geometrical relations are instantaneous, there is no propagation, these structures can be labelled, with abuse of language, nonlocal. We have seen in the previous section that a quantum world is nonlocal. Perhaps we can see quantum nonlocality in similar terms as the geometrical structure in general relativity: there is a network on nonlocal structural relations which may change instantaneously. This is compatible with my approach when thinking of effective laws as nomic networks of structures, and by thinking of the electromagnetic fields not as propagating but as part of such primitive and fundamental interconnections of nomic relations between particles.

To summarize, then, one can think that matter is made of moving identical particles. Gravitational interaction is accounted for geometrically, as in general relativity.

Electromagnetic interaction is accounted for in terms of nomic structural connections spelled out in terms of non-propagating fields. If we include quantum phenomena, quantum nonlocality can be similarly accounted for by assuming that the behavior of matter is governed by a network of nomic relations instantiated by objects such as the wavefunction, understood as an ingredient of the law rather than a material object oscillating in a high dimensional space (see Allori, 2021b).

5 The minimalist metaphysics stance

Consider again the original question: Why go through all the trouble of eliminating properties? In the previous sections I have argued that there are reasons coming from the quantum domain. In this section I also wish to argue that, more generally, my perspective would be favored by someone attracted to a minimalist metaphysics. I have already noticed that reductionist perspectives drive progress in physics, and my proposal falls within the same lines. Physicists look to unify forces, and minimize the number of fundamental objects, arguably to reduce the number of unjustified postulates of their theories. In doing this, however, they multiply the number of families of particles, as well as the number of properties which characterize them. I am driven by the same ideas, but I eliminate an entire category of entities (properties) instead of reducing their number. Consequently, I do not need to explain what properties are, and how laws act on objects through properties. To make a bold comparison (only partially motivated by the discussion of nonlocality), my proposal is like eliminating causation from physics (see, e.g., Russell, 1912; French & Ladyman, 2003, Woodward 2007). As the notion of causation has no role in fundamental physical theories, even if it may emerge at the macroscopic level, similarly I argue that the notion of fundamental property has no role in characterizing the nature of an object, even if properties may become useful in informal talks. As empiricists are suspicious of causation, they should be suspicious of properties. The minimalist metaphysician, being someone who is not so comfortable with in principle unobservable features, should try to reduce as much as possible the empirically unsupported entities in the traditional core, as anticipated in Sect. 2. In other words, I think my approach is best motivated for a minimalist because they think that, as a matter of method, one should minimize this type of assumption and be 'as empiricist as possible'. That is, minimal metaphysics strategies are a collection of empiricist-inspired attitudes guiding one's choices about what we are justified in believing exists according to science. That is, when doing naturalized metaphysics, we should be faithful to "old and wise" empiricism and do not assume the existence of entities, properties or more generally features which only have a transcendental (i.e. non-empiricist) justification. To put it differently again, someone with minimalist metaphysical tendencies tries to balance the scientific realist leanings, which sometimes lead astray, with the empiricist warning that one needs a solid experimental basis. They therefore believe that one can do naturalized metaphysics, but they are suspicious about those postulation which have no chance of ever being assessed empirically.

Let's look back at the traditional core from this perspective, and ask again: did we really get to the minimal set of *fundamentalia*? In principle, there are at least three possible ways of restricting it. One could eliminate objects, eliminate laws, or eliminate properties. In my proposal I absorb all properties into the laws, keeping objects. As I discuss below, my view is compatible with both Humean and anti-Humean approaches. Aside from this, *prima facie*, if we are to explain the phenomena in terms of a set of fundamental entities, we do seem to need at least objects. The idea is that we are justified in believing in the existence of these objects, even if we do not directly observe them, in virtue of their explanatory power. Structuralist would disagree, if of the radical variety, as they will argue that every phenomena can be accounted for in terms of structure, as I discuss later. Nonetheless, since I have no empirical reason to believe otherwise, and it is the simplest hypothesis, I assume that objects are fully described by the property which characterizes their nature. If we are talking about particles, they are fully characterized by their spatial position. After all, I see track in detectors, I see spots on screens, I see stuff moving from one place to another. This is the evidence I have: they are particles, and as such they are located somewhere. Similar for fields: they are fully characterized by their amplitude in space, based on the evidence of diffraction and interference patterns. Be that as it may, in my approach, assuming that there is some fundamental unspecified 'stuff' in spacetime, and assuming its motion is guided (or described) by some laws (either part of the *fundamentalia* or read off from them, depending on one's Humean attitudes about laws), I can identify at least two questions: What justification do we have in believing in the existence of properties? Do we need properties in addition to what we already have? Accordingly, at the end of the section I compare and contrast my approach to dispositionalism, which eliminates laws in favor of properties.

5.1 Humeanism and super-humeanism

In general, Humean approaches are the most compatible with the minimalist stance, as they are driven by the same ideas: postulate the least possible which lacks empirical justification. This leads Humeans to assume that everything supervenes on (that is, it is determined by) the Humean mosaic of local state of affairs. In the original formulation, the Humean mosaic is the overall collection of the distribution of local "natural intrinsic properties." Thus, the set of *fundamentalia* is given by:

$$Fund_H = Humean\ mosaic = \{matter;\ properties\},$$

And nothing else is needed over and above the mosaic. In particular, laws are generalizations which appear as postulates or theorems of the best system of the world, namely the one which best balances simplicity and informativeness (Lewis, 1994; Loewer, 1996).

The position dubbed super-Humeanism goes even more radical (Esfeld, 2014 2020; Esfeld & Deckert, 2018): driven by minimalist attitudes, super-Humeanism claims that all there is, is a set of particles, without any fundamental properties other than their (relative) location; all the rest, supervene on this:

$$Fund_{SH} = \{matter\}.$$

My approach is driven by similar minimalist tendencies, and it shares with super-Humeanism the idea of eliminating properties from the *fundamentalia*. However, I am not committed to the supervenience thesis: laws may or may not supervene on the Humean mosaic, regardless of whether it includes properties or not. Indeed, in the discussion so far, I have assumed that laws have to be postulated in addition to matter.

There are strong objections against the Humean account of laws, mostly connected to the supervenience thesis: it has been argued that Humean supervenience is false; Humean laws are pale imitations of laws (they are not explanatory, they do not govern the motion of matter, etc.); and so on (for a review of both the Humean account of laws and objects, see Bhogal, 2020; see also Carroll, 2020; Loewer, 2019). If these criticisms are sound, then, the next best approach for the minimalist is mine, whose spirit is independent on the truth if the Humean supervenience thesis.

Many objections have been recently brought up against super-Humeanism as well. In particular Lazarovici (2018) argues that super-Humeanism wishes to account for spacetime as supervenient on the mosaic (Huggett, 2006), but it has not enough structure to accomplish this. Since this is not what I aim to do, my approach is not affected by this objection. Matarese (2018) instead builds on the observations of Cohen and Callender (2009) and argues that super-Humeans do not have the tools to respond to the objection that what counts as the best system for the Humeans is unavoidably language dependent and thus not objective. My account does not have this problem because I do not rely on the notion of best system. Simpson (2021) argues that there is a tension between super-Humeanism and thinking that symmetries are a guide to metaphysics. This is true under the assumption of Humean supervenience, thereby making this objection inapplicable to my approach. To summarize, since the idea on which my view is based is independent of Humean supervenience, my approach is immune to these objections. My proposal is thus more general than super-Humeanism. If Humean supervenience is false, laws need to be postulated over and above matter in the *fundamentalia*, like I have assumed so far. Comparing my approach again to the traditional core, let me notice that laws are mysterious entities, especially from a minimalist perspective: since they are abstract, we do not know where they are and how they act on matter. If the traditional core is correct, on top of matter and laws, we also need properties, in virtue of which laws act in an empirically adequate way. But we do not observe laws, and we do not observe properties. When we see a track in a detector, we just see matter moving. Having specified what matter is, explaining how it moves is just up for speculation: it could be a law which acts differently on matter depending on its properties, like the traditional view maintains; or it could be a set of effective laws primitively paired with a set of particles. From a minimalist point of view, we have no evidence for either. Is it better to postulate two super-empirical entities, namely laws and properties, or just one, like I propose? All things being equal, since it is speculatively less risky, my view seems the safe bet for the minimalist (for a view postulating only properties, see Sect. 5.3; for a comparison with my view, see 5.4).

On another note, it has been objected that super-Humeanism is in tension with scientific realism and the attitude of naturalizing metaphysics, as it eliminates properties, deviating too much from physical practice (Matarese, 2020; Wilson, 2018).

One can make the same charge to my view:[25] (P1) naturalizing metaphysics means that we should take fundamental physics ontologically seriously: a scientific realist thinks our best theories are a reliable guide to metaphysics; (P2) our best fundamental physical theories use fundamental properties to explain and predict the phenomena; (C1) so, we should think of fundamental properties as real; (P3) my view does not; (C2) so it is in tension with scientific realism. However, (P2) simply expresses a contingent historical fact, not a necessary one: physicists usually think of their theories in terms of properties, but this is not the only possible attitude. In my proposal, one interprets the very same physical theories and can use them to predict and explain the phenomena without knowing or mentioning properties: they would just need to know the relevant effective law. In addition, (P2) has not been true throughout the history of fundamental physics: as discussed, properties were introduced in electromagnetism, while they are not needed in classical gravity and general relativity. Therefore, a better characterization of a theory compatible with realism is as follows: (P1) naturalizing metaphysics means that we should take fundamental physics ontologically seriously: a scientific realist thinks our best theories are a reliable guide to metaphysics; (P2*) our best fundamental physical theories use *suitable ingredients* to explain and predict the phenomena; (C1*) so, we should think of *these ingredients* as real; (P3*) the traditional view uses fundamental properties, while my view uses effective laws; (C2*) so neither is in tension with scientific realism. The problem remains for super-Humeanism, which has no ingredients other than matter to appeal to.

5.2 Epistemic and ontic structuralism

Another approach motivated by minimalist considerations is structural realism (structuralism for short). One can distinguish between epistemic and ontic structuralism. Ontic structuralism, especially in the eliminativist version, moves towards dispensing of objects altogether: they maintain that there are no objects but only structure and nomic relations. Their idea is to be as faithful as possible to the empirical data and assume nothing which is not empirically motivated. One of the cardinal arguments for eliminativism comes from the underdetermination between individuals and non-individuals in quantum physics, where one defines ‘individual’ an object with a property that others lack. Classical particles with the same properties belong to the same family: all electrons share the same values for mass and charge, for instance. They are identical individuals, as they can be distinguished by the fact that they have a different location. In standard quantum mechanics instead quantum particles are *indistinguishable.* Thus, quantum objects are not individuals, unless one stipulates that they can be identified by some ‘haecceity’ or ‘primitive thisness’, which is a super-empirical, transcendental feature that can receive no empirical support. Because of this, it is ‘suspicious’ for the minimalist. Different approaches can originate from this observation. French and Ladyman (2003) have gone eliminativists, and have argued that, in absence of a decisive argument, we are not justified to assume too much, and the best choice is to assume that there are no fundamental objects but only relations.

[25] I am grateful to an anonymous reviewer for pressing me on this.

For similar reasons, eliminativists have also argued that we should also dispense of properties and laws in favor of a structural network of nomic connections:

$$Fund = \{structure\}.$$

Eliminativism faces many challenges: from the charge that it is unintelligible to talk about relations without relata, to the fact that the notion of structure is too vague (for more about these criticisms, see Ladyman, 2023). In any case, it seems an unnecessarily radical move: one could still be sensitive to cases of underdetermination without eliminating objects. Rather, it seems more balanced to go epistemic and conclude that there are objects whose features we are unable to know empirically (Worrall, 1989). Otherwise, one could maintain that the more empirically supported view is the one which excludes haecceities (French & Krause, 2006):

$$Fund = \{non - individuals;\ structure\}.$$

This view however requires modifications to classical logic, so it is not an easy choice. In any case, my proposal shares with structuralism the need to be empirically grounded and the importance of structure (see also Allori, 2022). Nonetheless, my view is not epistemic: we can be realist about objects, as well as structure (see later for an argument for this). Moreover, from underdetermination challenges I do not conclude that there are no objects as individuals, especially if we endorse a microscopic spatiotemporal ontology also in the quantum domain. In fact, as we have seen, in this framework the ontology of matter possesses a definite position, as it does classically, and we can use it as individuating property for identical particles. Accordingly, there is no need to dispense of an ontology of objects, and my approach does not suffer from the same objections of the structuralist perspectives we have just mentioned.[26]

5.3 Dispositionalism

If eliminativism dispenses of objects and properties in favor of structure, and if super-Humeanism develops an approach similar to mine within the Humean framework, dispositionalism does just the opposite: it eliminates laws in favor of properties.[27] Usually, one distinguishes between categorical and dispositional properties. Categorical properties are supposed to individuate types, or families, of objects. For instance, they serve the purpose of distinguishing electrons from protons: to be an electron is to have mass m_e and charge q_e, which have specific values. Dispositional properties instead characterize the object's behavior in given circumstances. For instance, this

[26] A more nuanced position is moderate ontic structuralist (Esfeld & Lam, 2011), in which objects are not eliminated. Notice that if Humean supervenience is true, this view reduces to super-Humeanism (matter is all there is and laws are the axioms and theories of the best system). Instead, if Humean supervenience fails, this view becomes very similar to mine.

[27] Also, one can notice minimalist tendencies in approaches of this kind in which one eliminates relations reducing them to properties (see Hiel, 2012).

piece of glass has the dispositional property of being fragile because if I throw a stone on the glass, it has the disposition to break. Thus, while categorical properties characterize matter, dispositional properties characterize how matter moves. This distinction reflects that properties play a dual role: an ontological and a nomological role. Both my approach and dispositionalism take this to be evidence of the fact that we can restrict the set of *fundamentalia*: laws already take care of the nomological part, and objects of the ontological part. While dispositionalists wish to absorb all the work done by laws in terms of these properties, I wish to do the opposite. Dispositionalism is sometimes spelled out in terms of causal powers, which are close relatives of dispositions (Cartwright, 1983), and in general we have:

$$Fund = \{matter;\ properties = [categorical,\ dispositional]\}\,.$$

A hard-core dispositionalist might be tempted to go all the way and eliminate categorial properties. The usual objection to this move is that we need them to identify the nature of things and to account for why there is a difference in behavior under the same physical circumstances. However, one can immediately see how the categorical-dispositional distinction is not straightforward. Think about charge and mass: they define a family of objects, and thus they are naturally interpreted as categorical properties, but they can be as naturally interpreted as dispositions. In fact, having a certain charge will make this particle disposed to turn this way, rather than that way, in a magnetic field. I think that the fact that the categorical-dispositional distinction is difficult to characterize is evidence that there is no such distinction: that all properties are dispositional properties, and that fundamental objects are bare. Indeed, one could say that objects behave differently because they have more dispositional properties than we thought, rather than using categorical properties. That is, instead of saying that an electron goes up in a magnetic field because it has a negative charge, we say that it goes up because it is disposed to do so. If fragility is explained dispositionally, why can't we explain the electron's behavior similarly? If so, we can use dispositional properties acting on bare entities. That is, all fundamental objects are identical, like in my account, and they are primitively paired with fundamental dispositions:

$$Fund = \{matter;\ dispositional\,properties\}\,.$$

This means absorbing categorical properties into dispositional properties, which already have absorbed laws. This is very similar in spirit to my approach. Is there a reason to pack everything into laws, like I do, and not into properties like dispositionalists might prefer?

5.4 Comparison

In general, it is difficult to justify hypotheses about what makes matter mutually interact. How do we know laws or properties exist? Experience alone does not tell us whether objects have this or that property, or whether they are governed by this or that law. While we observe that a particle goes this way rather than that way, this observation does not tell us what makes it do that. It could be a property, an effective law, or something else which we fail to imagine. All we observe is a spot on the upper part of the detecting screen. Or sometimes we can even see a curved track, if the detector fills the space after the magnetic field. Indeed, experience alone does not tell us these tracks were left by a particle, let alone that this particle has, say, a negative charge. In fact, it is always possible that what appears as a point-particle track has been left by a non-spreading wave-packet (forgetting all the less reasonable possibilities, such as they are created by unobservable ghosts). However, one could say, we are justified in believing that these are particles because postulating their existence provides the best explanation of the observed data. Using super-empirical virtues like simplicity and coherence one can argue that, all things being equal, we are justified believing that these tracks are left by particles. Instead, we cannot say the same for properties or laws: first, it is heavily underdetermined whether it is properties alone, like dispositionalists are suggesting, properties and laws, as it is traditionally maintained, or laws alone, as I claim.

It is not so straightforward to use super-empirical virtues to uncontroversially rank between my approach, dispositionalism and the traditional view. However, always all things being equal, what I have been arguing so far may be taken to show that the traditional view, being dualist in the nomological ontology (assuming there are both particles and laws), seems less justified than dispositionalism and the effective laws view from a minimalist perspective, as both these views are 'monist': why have two mysteries if you can do everything with one?[28]

Turning now to monist approaches like mine or dispositionalism, I think that dispositional properties or causal powers should be particularly suspicious for the minimalist, just in the same way as causation is suspicious. If we do not know what causation is, we also do not know what causal powers, or dispositions, are. It is true that one can stipulate them to be primitive notions, like I stipulate that there are primitive effective laws paired with fundamentally bare entities. Nonetheless, even if it is mysterious how laws act on fundamental matter, one can still explain the emergence of 'disposition talk' at the macroscopic level, while the opposite is not the case. That is, one can explain why a macroscopic object like glass is transparent under visible light or why it is fragile in terms of its fundamental components and the laws. An object is transparent if visible light passes through it unaffecting it. This happens when, as in the glass, the outermost electrons require more energy than the one of visible light to be stripped from their orbitals. Glass is also fragile because atoms in it do not have a crystalline structure to relieve stress, which therefore can produce cracks which tend to grow and widen until the material breaks. These explanations of transparency and fragility, which are macroscopic (non-fundamental) dispositions, are in terms of matter behaving according to given laws (the propagation of light, and the bond between electrons). What are the corresponding explanations in terms of the fundamental dispositions of electrons? In any case, what

[28] One could object that within my approach explanation becomes overly complicated when compared to the traditional view: don't we need to specify an effective law for any specific context? However, this is not so: one needs only as many effective laws as there are fundamental masses, charges and the like. So, the multiplication of effective las is the same as the multiplication of properties. Notice, in addition, that within my approach it is not necessary to think effective laws as any different from law as traditionally intended: one can be Humean or anti-Humean about effective laws as well. Moreover, it is general enough that it is compatible with both approaches.

does it even mean that an electron is disposed, or has the causal power, to do certain things? I think using the term 'disposition' for something like an electron is a category mistake like saying that particles have free will or that objects prefer to go where there is a minimum of potential energy. To cut a long story short, being disposed, free or prefer to do something, as intentional states seem proper of conscious beings rather than fundamental particles. This language can of course be understood metaphorically: it is *as if* electrons are disposed to do such and such. If so, however, we also need a deeper explanation of these behaviors, which is usually presented in terms of laws. This is indeed the argument for eliminating causation from fundamental physics: it is not the right concept to explain things through physics. Moreover, as we saw, in the quantum domain, it is unclear how to account for spin if one is a dispositionalist: a contextual disposition? On another front, one could propose that the wavefunction is a dispositional property of matter 'generating' the quantum potential. Nonetheless, it is not going to be a property of the object alone, because of entanglement, forcing the dispositionalist to explain how the disposition of the whole translates into the dispositions of the single entangled objects. Furthermore, the concept of law seems more compatible with quantum nonlocality than the notion of property, especially if we consider causal powers, as causation and locality are intertwined concepts, as we saw. Because of this, trying to understand quantum nonlocality in terms of laws rather than properties might have more chances of success.

5.5 Modest minimal realism

In any case, if you are not convinced of my last argument that a minimalist would rather eliminate properties than laws, here is a compromise. The core ideas of my view and of dispositionalism are the same, especially if we think that the fundamental dispositions form a network interconnecting the objects. To elaborate, all matter is bare, and it mutually interacts. It may interact in virtue of matter's fundamental dispositional properties, or it may interact in virtue of the set of effective laws. Perhaps the best minimalist attitude is simply to be metaphysically neutral about what precisely instantiates the nomology: either effective laws or dispositions. Let's simply assume that there are bare objects whose behavior is explained in terms of some generically unidentified nomic structure, about which we stay metaphysically neutral: being good empiricists, since everything is compatible with both a metaphysics of laws and one of dispositions, and since we have no compelling reason to choose the one or the other, we would better be silent about the nature of the interaction. That is, one can provisionally conclude that:

$$Fund = \{bare\ matter;\ nomic\ structure\},$$

where the usual property talk is confined to the unidentified nomic structure.

Before concluding, let me remark the following. I have argued that a minimalist should favor a metaphysics of bare objects and nomic structure, following considerations from quantum theory and other general empirical constraints. While a particle ontology seems the best fit for my view so far, in a future theory one may move to other type of ontology such as fields or even strings. Nonetheless, notice that keeping a particle ontology would be best for scientific realism. Scientific realism is usually justified claiming that the truth of our best theories is the only explanation for their empirical success: it would be a miracle that a false theory would be so successful. The pessimistic meta-induction instead shows that it is no miracle at all, as it has kept happening in the past: the history of science is full of successful theories which turned out to be false. Even if one can safely rule out many past theories as not in the same category of classical and quantum theories, there is still a problem, as classical theory was successful but false. As a response, one can restrict realism: past theories were not completely false; rather they had true components. If one can show that these components are responsible for the theory's success and they are preserved in the classical-to-quantum transition, then one is justified in thinking of these components to be true. Within my approach, as we have seen, it is possible to think of particles as the ontology of both classical and quantum mechanics. Elsewhere I have argued that particles are the source of the success of both theories (Allori, 2018), thereby justifying a minimalist realist commitment to particles in both domains. It is controversial what one should think the ontology of relativistic quantum theory such as quantum field theories is (see Myrvold & Smeenk, 2011). However, relativistic quantum theories of particles, empirically equivalent to quantum field theories, have been proposed (see, e.g. Dürr et al., 2005). Thus, there appears to be no advantage to switch to a non-particle ontology in the relativistic quantum domain (even if it is always in principle possible). To conclude and summarize, then one could explore different ontologies for quantum theories, but the burden of proof to explain their motivation is on them, as particles seem to do what is needed.

6 Conclusions

In this paper I have articulated what I take to be the best metaphysics suited for a minimalist, namely a realist who does not feel comfortable in postulating more than is strictly needed from an empiricist point of view for realism to succeed. First, a minimalist should postulate fundamental objects; in our current theories one should postulate particles, as what we directly observe is tracks in detectors. Since there is no direct evidence that these particles are distinct, the minimal assumption is that they are all identical. What else does the minimalist need? If Humean supervenience is true about laws, then everything supervenes on the distributions of these objects, leading to positions like super-Humeanism. If instead Humean supervenience is false (like I think), then one needs some nomological apparatus, which can be spelled out in terms of purely dispositional powers, or in terms of effective laws. In contrast with dispositionalism, my view requires rethinking the idea that properties characterize fundamental objects, as they are only ingredients in the law, which now 'effectively' guide objects. That means that the structural nomic network is given by effective laws. Considerations from quantum mechanics, I argue, favor my view, in terms of laws, rather than properties. First, I take that the contextuality of spin is evidence that spin is not a property, dispositional or otherwise. Moreover, quantum nonlocality suggests that interaction does not propagate, indicating the existence of some 'static' nomic structure interrelating the fundamental objects as the mediator of the interaction. Since dispositional properties more or less explicitly invoke the notion of causation, I maintain that for the minimalist it is best to think of such nomic network in terms of effective laws. Even so, however, perhaps it is more cautious not to assume anything about the nature of the nomic network and be realist only about the fundamental identical particles, as this ontology has persisted from the classical to the quantum description. This allows realists to defeat the pessimistic meta-induction argument against their view, without however giving us confidence about the nature of the nomic structure.

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