



Maximal motion and minimal matter: Aristotelian physics and special relativity

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Received: 8 September 2021 / Accepted: 3 June 2022
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Abstract

This paper shows how key aspects of Aristotle's core concepts of matter and motion, some of which have recently been shown to help make sense of quantum mechanical indeterminacy, align with some important results of the energy-momentum relationship of special relativity. In this conception, mobility and indeterminacy are inherently linked to each other and to materiality. Applying these ideas to massless particles, which relativity tells us move at the maximal cosmic speed, allows us to draw the conclusion that they must be the most basic physical bodies, that is, mobile substances (secondary, locomotive matter). The most familiar massless particle, the photon, constitutes light. Furthermore, because the photon composes luminous matter but cannot be decomposed into anything else more basic, it fulfills the definition of element.

Keywords Natural Philosophy · Aristotle · Classical mechanics · Relativity · Quantum Mechanics

1 Introduction

Physics, as we know it today, begins by abstracting the human knower from the natural world that is its subject matter. One way to restore physics to its properly human context is to situate it in a philosophy that begins with common human experience, such as Aristotle's (Augros, 2004). The effort here is not to vindicate all of Aristotle's *Physics*, much less his cosmology, but rather to show how some of his

The original online version of this article was revised.

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core conceptions of matter and motion, especially in the first three books of *Physics*, complement and extend our current understanding of the physical world.

The relevance of Aristotle for understanding the world of the natural sciences has seen a resurgence in recent scholarship, as witnessed most prominently in the anthology by Simpson et al. (2018) and the scholarly book by Feser (2019). This resurgence has extended into the world of physics, principally by connecting quantum indeterminacy to the Aristotelian concept of material potentiality. Schulman (1989), Koons (2017, 2021a, 2021b), and Simpson (2020, 2021) explore what Aristotelian concepts say about the quantum world, while other works apply Aristotle's thought to interpretations of quantum mechanics (Koons 2018, Pruss 2018).

This quantum mechanical line of thought is relevant to the physics called modern in the paradigmatic sense. But what of the part of physics called classical, that of Newton, which begins not with the indeterminacy of matter or large ensembles of particles, but with the motion of individual, apparently determinate bodies? In Aristotle's conception of nature, it is not only matter that is indeterminate, but also motion itself. What can that conception of motion teach us about the line of thought that begins with classical mechanics and eventuates in relativity?¹

Many readers may not recognize this work as physics, presently understood. To some readers it will seem like the philosophy behind physics, a kind of meta-physics. But the subject at hand is not metaphysics or philosophy of science, but *philosophy of nature*, of which philosophy of science and science itself are part.² Call it what you will, the endeavor here is to bring fresh eyes to the natural world disclosed by empirical science, and such deepening of the human understanding of nature is what physics, in its millennia-long history, has most fundamentally been about.

Werner Heisenberg (1958, p. 200) noted the importance of explaining physics in ordinary language, in contrast with the idealizations represented by scientific concepts, "since the concepts of natural language are formed by the immediate connection with reality; they represent reality." Words are much closer to us than mathematics.

The idealizations of physics are necessary and credible because they represent an idealization of human experience: controlled experiment.³ Unlike experiment, most human experience is not controlled, despite the illusions that our modern technological prowess nurtures. From conception and birth, to falling in love, to the necessity of dying—so many of the most important, most essentially *human* events of human life are not something that we as individuals *choose* and *do*, so much as something that happens *to* us.

¹ Feser (2019, ch. 4) critiques common understandings of Minkowski spacetime using Aristotelian conceptions. The focus in the present work is on more empirically basic notions from *Physics*.

² Natural philosophy, in a narrow sense, probes nature using purely "philosophical" methods akin to those of metaphysics. Natural philosophy, in a broad sense, incorporates the modern specialized sciences, such as physics and biology, in critical instrumental roles (cf. Ashley, 2006, p. 220).

³ Cartwright (1999, pp. 46–47) quotes an econometrist's praise of physicists for their cleverness in confining their predictions to the results of experiments and not extending them to the messy world at large. And she notes that technology, e.g., a flashlight battery, is simply the controlled environment of the laboratory miniaturized within the messy world.

Quantum mechanics has advanced over mechanics by including effects of “the observer” among physical interactions. But it does so only to an extent. Considered more carefully, the human knower is still alien to the world studied by physics. The quintessential locus of knowledge in quantum mechanics, as in Newtonian mechanics, is still control of a physical system. But much of even ordinary reality exceeds our control. Certainly, we cannot admit all human experience to science: there needs to be some filtering criterion. One such alternative criterion is *common human experience*, the experience common to all healthy adults (Augros, 2004).

If science is to present us with a fair, unbiased picture of the world, then it cannot afford to reject *a priori* the parts where the human knower is not in charge and that are not resolvable in terms of elements under our control.⁴ The passive or receptive parts of our experience need a language just as much as the active parts. If the most human experiences of our lives are outside our control, then they are also outside the universe of science. Does it have to be this way?

With all these things in mind, join me in discovering what we can learn from Aristotle about nature. In Part 1, we will tour Aristotle’s ideas on motion and matter beginning from the common human experience of motion; the focus is on Aristotle’s ideas, but this part necessarily refers to the landmark Newtonian notions whose limits modern physics has run against. We will see that in the former conception, matter and motion are inherently linked and indefinite, so that the more “material” a body is, the more indefinite and subject to motion it is. Part 2 introduces into the line of argumentation modern physical insights and explores how the Aristotelian conceptions illuminate a deeper understanding of them. We will see that the relativistic idea that massless bodies, such as the photons that compose light, move at the maximal cosmic speed, “the speed of light,” leads to the conclusion that they are minimal bodies and that photons are elements of the normal, luminous matter we see around us.

2 Revisiting matter and motion

2.1 Matter and potentiality

What can Aristotle’s conception of matter and motion teach us about the physical world? His basic principles are explained in the first books of his *Physics*, culminating in the definition of motion in Book III.

Book I begins with the observation that what we know first and best are the vaguest but most certain generalities, from which we gradually establish particulars. This is the plan of the whole of Aristotle’s natural philosophy: to discover first the most general principles of the natural world and gradually narrow down our exploration to specifics.

⁴ For example, when we speak of the Sun’s mass, it is in terms of the masses, measured in kilograms, used at hand in the Cavendish experiment. This procedure is not so much a fault of science as an inherent, human limitation: we also understand the remote and less known in terms of the closer and more familiar, and “control” is the most perfect way we have of knowing those things subject to our control.

Aristotle begins with the most trivial of axioms, that motion is real. This observation that “some things move” seems a minimal observation about the world, but for that reason, no one can question it (at least not without giving up the study of nature⁵). As a basis for reasoning, it is quite certain. Admittedly, it seems lame and uninformative next to the statement that, say, light moves at its very precisely defined speed in vacuum (Augros 2012). But even for the latter statement being more “scientific,” it depends on the basic truth of the observation that “some things move.” So prior to any theoretical and experimental uncertainty, the precise “scientific” statement is less certain than the vague philosophical statement. Physics today still depends implicitly on such prescientific concepts drawn from the common human experience of all healthy adults.

The primary question of Book I is a general question indeed: what is the number of “principles” or components of motion? It is important to notice that Aristotle starts his discussion of the natural world with no assumptions about the nature of change. His only assumption is that motion (“some things move”) is a real phenomenon requiring analysis.

Keep in mind that he means motion in the most general sense, that is, any kind of change, not simply locomotion. Of course, change of place is a special kind of motion. Newtonian physics teaches that whether something appears to be moving or still is arbitrary depending on the state of motion of the observer. But, critically for this paper, this arbitrariness fails especially to apply to one particular kind of locomotion, as we will see when we turn to relativity. But even if an object appears to move only because of the observer’s motion (all observers are bodily), there is still motion.

But to turn back to motion in the broad sense: Aristotle discovers two, or three, components of motion, depending on the perspective (*Physics* I.6). To summarize:

- Two: you can speak of motion as (1) something lacking x that then (2) gains x . So “the non-red (thing) becomes red.” Here the focus is on the privation that changes or is negated.
- Three: you can speak of the motion as (1) *something* that moves between (2) initial and (3) final contraries. So “the apple goes from green (non-red) to red.” Here the focus is on the substrate that underlies the contraries.

Just as we talk about an apple taking on a new color, we can also talk about wood or metal taking on a new form: for example, oak timber being made into a bed, or bronze being formed into a statue (*Physics* I.7.191a11). Just as the apple persists through the color change, something—some principle—persists in the generation of the new artifact. To this substrate of change, Aristotle gives the name matter or material (*hylé*: literally, wood or timber) at the end of Book I:

For by material I mean that which first underlies each thing, out of which something comes into being, which is present all along, but not incidentally. (Aristotle 2005, I.9.192a32)

⁵ Because to study nature is to study moving things (cf. Aristotle, *Physics* I.2.184b25–185a4).

The timber that once constituted the tree now makes up the bed ... or even the termite or the wood-boring beetle. In analogy with an artificial thing coming into being from previously existing matter, we can talk about a natural thing taking on a new form.⁶ A rabbit devours a cabbage. The matter that made up the cabbage is metabolized by the rabbit and comes to constitute the rabbit.

In contrast to our modern notion of matter as *substance*, which exists independently, Aristotle's matter is a principle that does not exist on its own but rather always in partnership with a form (e.g., either of the two contraries at the limits of the change). Just as an apple always exists with color, size, and shape, matter always exists with form. Form is the principle of determination, and matter is the principle of indeterminacy.

Before we continue, we need to take a step back to examine what "substance" means. Substances are the fundamental entities of Aristotle's conception of the world. Substances are things that have within themselves their own source of motion and rest, such as animals, plants, and simple inanimate things such as stones and water (cf. *Physics* II.1.192b10), but animals, especially of the rational sort, are the preeminent substances in Aristotle's thought. Substances retain unity in place and identity over time.

Modern thought tends to give ontological priority to parts such as atoms or molecules, so that an animal is really just the sum of its molecules, atoms, or subatomic particles. In contrast, for Aristotle a substance has ontological priority over its parts. Substances, being ontologically primary, exist on their own. In contrast, *accidents* only exist *in* substances. Accidents are the characteristics of a substance: for example, a person's height or hair color. The substance is what the thing *is*, whereas an accident is something *about* the thing or things. Everything in the universe according to Aristotle is either a substance (existing on its own) or exists in a substance (i.e., an accident).⁷

Artifacts, in Aristotle's thought, are not substances, but assemblages of substances. This assemblage is put together by an outside agent, and its functioning as an artifact is extrinsic to its natural parts. For example, a wooden bed supports the reclining human form in a particular way, which is not natural to the trees from which we derive wood. You can imagine a human cultivating trees from an early stage to grow into the shape of a bed. The nutrition and reproduction of the trees are intrinsic operations of the trees, but their function as a bed is extrinsic—imposed from outside by all the pruning and twisting. As we will see, the bed is an accidental form to the natural forms (substances) of the trees.

Matter in modern thought, especially the early period, was conceived as existing on its own—that is, substantially—with more complex entities such as organisms having a derivative existence, similar to that of a machine, with parts outside each other and only extrinsically related. In contrast to this *mechanical philosophy*, matter

⁶ Notice the difference: whereas bed is an artifact and the agent that makes it from wood is external to it (a carpenter), the agent that transforms the wood into a termite is intrinsic (the termite itself). This inherent principle Aristotle calls its nature: "[N]ature is a certain source and cause of being moved and of coming to rest in that to which it belongs primarily, in virtue of itself and not incidentally" (2005, II.1.192b22).

⁷ Admittedly, distinguishing one from the other empirically can be difficult down in the margins.

for Aristotle is not a substance and never exists on its own. Rather, matter can only exist with form. Matter and form are co-relative principles that always go together in physical things. Aristotle's "matter" is applied analogously, as a proportion. Thus, to illustrate with a series of examples unavailable to Aristotle, the organism's (immediate) matter is its organs. The organ's matter is its tissues. The tissue's matter is its cells, whose matter is molecules, whose matter is atoms, and so forth.

organism : organs :: organs : tissues :: etc.

Rather like an infinitesimal limit in calculus, one can keep dividing ad infinitum to approach without ever actually reaching the ultimate matter, what the scholastics called first or *prime matter*, which is utterly formless. Prime matter has no actuality and is pure (passive) potentiality; it is all but nothing. Such formless matter cannot exist as a body, so it is not the "minimal matter" that is the subject of this paper. "Matter" in this paper refers generally to secondary matter. (Appendix II further clarifies potentially confusing terms such as matter.) The lower forms in the hierarchy of being are less formal and more material, that is, less determined. So a higher form literally "has more forms" (most of them "accidental") and is thus more formal than a lower form. All the forms thus divided in thought from prime matter are part of a single, unitary form: the *substantial form* that subsumes all the lower forms. So a material being can be thought of as a form plus its corresponding secondary matter (for example, organism made of organs) or as an overarching unitary substantial form plus prime matter (for example, the organism combining the forms of organism, organs, tissues, and so forth on the one hand, all constituted of prime matter on the other).

Another way to say this is that the parts exist potentially and not actually in the whole.⁸ When parts are separated out, they are no longer parts but are actualized as new wholes of a sort. But within a substance, the powers of the different materials are modified and incorporated into those of the one, unified substance. Aquinas delineated two ways in which materials are incorporated into substance. For the homogeneous "mixed bodies" composed of multiple elements, the elements are present only by their powers ("virtually") in the new substance, but they are not distinguishable in the new whole (Decaen, 2000; Storck, 2008). Here we might think of the presence of separate colors of paint combined in a homogeneous mixture. Alternatively, the matter may be present as quantitative integral parts; in this mode, the parts, while truly part of the whole substance, are still distinguishable in the whole and in some way actual, though without compromising the unity of the whole, as, for example, an organ such as the heart is present in a lion (Storck 2014).⁹ But in both modes, the substance remains unitary.

⁸ This is a recurring theme in Aristotle, holding not only for organisms but also for geometrical figures. So for Aristotle the line of a trajectory does not consist of an actual infinity of points, but rather the points exist *potentially* in the line and are actualized only by stops along the path (*Physics* VIII.8.263a23–b9).

⁹ It is not entirely clear which category chemical compounds fit into. When a highly reactive soft metal and a noxious green gas combine to form a colorless crystalline solid that is edible—ordinary table salt—the new substance employs powers of the components but is clearly novel. It is not the chlorine atom as

“Well,” you might say, “this idea of matter tells us about biology and chemistry, which is all well and good; what does this have to do with physics, which is about inert matter moving through space?” But this is exactly the issue: what made the matter of Newton and his followers so well suited for mechanics also made it unequal to the burden of constituting chemistry and biology.¹⁰ Its principal characteristic is inertia, as described in Newton’s first law of motion:

Law 1 Every body perseveres in its state of being at rest or of moving uniformly straight forward, except insofar as it is compelled to change its state by forces impressed. (Newton 1999, pp. 403–404)

The First Law expresses the primary principle: matter, existing in itself, untouched by anything outside and thus unseen and unsensed, is perfectly determined in its geometry. It is an abstraction, unknowable by sense experience. The first law transcends empirical measurement.¹¹ This matter exists first in itself instead of being inherently part of something else. Only secondarily, as expressed in the “except” clause of the First Law and in the Second Law, does matter interact with the rest of the world, through the action of forces.

The idea of inertia originated with Descartes (1644, II:37, 39). Newton’s *Principia*, part of whose brilliance consists of its being a tour de force of geometry, follows Descartes’ absolutization of matter as geometrically determinate substance. And while many of Newton’s writings are not as explicitly philosophical as Descartes’, the latter’s positions give an idea of not only the historical context into which Newton’s ideas were born, that is to say, the lens through which he and his contemporaries understood his views, but also the foundation on which his ideas were built, the “giants” on whose shoulders he stood (Burt, 1954).

For Descartes, body is definitionally not-mind. “That each substance has one distinctive attribute—that of mind is thought, and that of body is extension. So, extension in length, breadth, and depth, constitutes the nature of bodily substance; and thought constitutes the nature of thinking substance” (Descartes 1907, I:53). Matter can best be understood as that from which all qualities and powers but extension are removed.

In this way we will discern that the nature of matter or body, considered in general, does not consist in its being hard, or ponderous, or coloured, or that which affects our senses in any other way, but simply in its being a substance extended in length, breadth, and depth. (Descartes 1907, II:4)

such that acts but rather the chloride powers of the ionic sodium–chloride compound. Yet the separate atoms are still distinguishable in the whole. “Virtual parts” may be applicable (Koons 2021b, p. 2754).

¹⁰ None of this is to say that inertia does not apply to biological systems, just that it fails to apply to biological systems as such. Inertia definitely applies to them insofar as they are merely isolated bodies and to their inanimate parts insofar as they are divided out, whether conceptually or physically.

¹¹ Non-interacting matter is not empirically measurable. Whitehead describes inertia as “the first article of the creed of science” (1948a, p. 171; cf. Whitehead 1948b, p. 51). The usefulness of the law of inertia is not in question. Here we are merely noting its limits both in provenance and in consequence.

And the extension Descartes (1644, II:4) proposes is even devoid of “hardness,” the discussion of which makes it clear that it lacks even the power of excluding other bodies—the impenetrability Leibniz (1669) called “antitype.” Newton of course had a different, more physical notion of bodies, attributing potencies such as gravity and electrical activity to them (Newton, 1687, 1730). But he denied that gravity (and presumably other powers) were *inherent and essential* properties of “inanimate brute” matter (Newton 1693).

“Inertia” refers to the essential inactivity of bodies. Body for Descartes is devoid of immanent activity. Matter’s activity is purely external; any internal forming or end-directed activity is excluded and swept across the line separating matter from mind (Schindler, 1986, p. 4). External change is exemplified by change of position in an abstract, geometrical space, and for Descartes such changes, such as they are, are the only true changes.

There is therefore but one kind of matter in the whole universe, and this we know only by its being extended. [...] all variation of it [matter], or diversity of form, depends on motion. (Descartes 1907, II:23)

Descartes’ matter can change in only the most superficial way and thus has only the most superficial kind of activity and possibility.

Despite the contrast with Aristotle, Descartes’ matter is not completely dissimilar, which is to be expected, given that Descartes drew many of his ideas from the scholasticism that dominated the intellectual landscape of his day. For Descartes, extension or quantity is the defining (and indeed the only essential) characteristic of matter, and motion is the only activity of matter and what differentiates material things from each other. As noted already, Newton granted matter some powers but followed Descartes in rejecting indeterminacy. Paradoxically, Cartesian–Newtonian matter is spatially both determinate and indeterminate: completely determinate in extent, while at the same time being mobile, which essentially means lacking a determinate position.

For Aristotle, quantity is also important, being the primary accident or characteristic of changeable, material things (*Categories* IV.1b25–26; Ashley 2006, p. 79), and locomotion is the most basic kind of change (*Physics* VII.2.243a11, VIII.7.260a27). On the other hand, Aristotle’s matter is *defined* as indeterminate and receives its determination from form. This indeterminacy makes Aristotelian matter less amenable to geometrical treatment, which is a decided disadvantage for doing physics—at least until physics realizes that matter really is indeterminate.

It was only when mechanics abandoned this strict determinism and became quantum mechanics that it could finally speak to chemistry and thus biology.¹² But the rejection of the inertness of matter goes only so far. Even now the common understanding of atomic physics is not so much an explanation of the transformation of substances as it is the rearrangement of the really real particles that constitute the

¹² Quantum indeterminism of position and motion is the basis for the indeterminism of character or species; a change in quantity, being the first accident, is the foundation for change of quality. A fuller discussion is beyond the scope of this article.

atom. The old classroom chestnut that the atom is “mostly empty space” rests on this idea that only the nucleus and electrons count as real substances, unchanging in chemical and biological changes, the determinate subjects of locomotion. Similarly, while non-unitarity in quantum state transitions allows for real novelty in change, the recent controversy over the so-called black-hole information paradox shows that old mechanical habits of thought die hard.

This reductionist–determinist view has become so intrinsic to our modern scientific outlook that we no longer notice its oddness. It is not that anyone positively teaches that the matter around us is really just an agglomeration of subatomic particles, but just such a belief is what we are left with when no further comment is made. It does seem odd, though, that you reading this, your self, would be at best a mere byproduct of the really real particles that have joined together to form your body. On that interpretation, would it be more accurate to say the particles are really doing the reading? Or would it perhaps be more correct to say the agent doing the reading is a ghostly entity with only a casual relationship to the eyes that take in the light from the page? In reality, the idea of you as a substance does the most justice to the phenomenon of you and the activities you originate.

The alternatives to this commonsensical view are difficult to live with, or at best concern a universe other than the one we inhabit. So let us return to the pre-Cartesian notion, in which matter can really change to become more than it is at present. But what is change?

2.2 Motion and matter

At the beginning of Book III of *Physics* (1.201a10–11), appearing seemingly from nowhere, Aristotle defines motion or change as

“he tou dunámei ontos entelecheia hé toiouton,”

which is typically translated as “the actuality of what exists potentially as such.” These few words are dense with meaning, and, contrary to appearance, have a foundation.

Entelecheia is particularly packed with meaning and is typically translated as actuality or full reality (see *Metaphysics* IX.8.1050a23). If *entelecheia* meant mere activity, then “the activity of what is potential” in the definition would be circular and not much of a definition, because activity is nearly synonymous with motion. Actuality is a more general concept than is activity.

Everything that exists has a certain *actuality*: it is what it is. But a thing also has an ability to be otherwise than what it is; this ability is *potentiality*. A thing’s potentiality is not just notional but exists along with the thing’s actuality. As Carl Friedrich von Weizsäcker puts it, “The [potentiality], however, is not simply the future, but that of the future which is, so to speak, already here and now, and thus in a certain sense the presence of the future” (Weizsäcker, 1980, p. 354; cf. Aristotle, *Metaphysics* IX.3). But potentiality is not just that future that *will* later be actualized; it is also those futures that can be, but will not be, actualized. Further, potentiality is not an abstract possibility but is grounded in the nature of the actual thing with the potentiality. A caterpillar has the abstract possibility of being a bicycle in some alternative reality,

but its potentiality in Aristotelian thought is much more limited, ranging from natural (a butterfly) to violent (food for a bird).

Now the most obvious way that a potentiality can be actualized is for the potentiality to be fulfilled and disappear in favor of the new actuality. For example, the potentiality of separate bricks to become a house is fully actualized when the bricks become the completed house: the house is the actuality of the bricks. And of course an endpoint is not motion.

But with the phrase “as such,” Aristotle is pointing out a second, more subtle way that a potentiality is actualized. When the bricks *are being changed* into a house, it is then that their potentiality *as a building material* is most fully revealed. “When the buildable, in so far as it is just *that*, is fully real, it is *being built*, and this is *building*” (Aristotle 1930, III.1.201a16–17, emphasis in original). In other words, bricks are most fully real *as building materials* when they are in the process of being built (“moved”) into the form of a house.

He is talking about the “potential thing” not so much as a privation of the final actuality but rather as the substrate of the change: it is a positive reality that stands forth in motion. The “what exists potentially” in the definition is matter, whatever kind of matter is appropriate to the kind of change being considered. Aristotle says that there are different kinds of matter underlying different kinds of motion (*Metaphysics* VIII.1.1042b6, VIII.4.1044b8, XII.2.1069b26). The main topic of this paper is locomotional matter, which I am calling “body.”

Matter shows itself as matter—is most fully itself—in change. Matter being in a place, whether we call that place an origin or a destination, shows only that matter can be in *that* place; matter most manifests its ability to be someplace *else* in locomotion, when it is transitioning between places. David Bohm points out a rough analogy in photography: what best conveys an object’s motion is not a super-high-speed photograph that makes the object look still but rather a low-speed photograph whose streaking shows the object is in no one place (Bohm, 1951, pp. 145–146). So locomotion is matter fully realizing its ability, as such, to be elsewhere; *locomotional matter* or “body” is most fully itself when it is translating.

The definition of motion highlights the fact that mobility is essential to matter. Matter shows off its materiality through change. The definition deepens what was implicit at the outset of Aristotle’s inquiry, in which we discovered the principle of matter *in the phenomenon of motion*. But it also grounds motion in the more fundamental and much more general concepts of potentiality and actuality. So, rather than the definition of motion having no priors, its roots are in the concept of matter itself.

It is important to emphasize that “actuality” in the definition is not confined to mere activity. According to Rémi Brague, Aristotle uses *energeia* and *entelecheia* interchangeably (1990, pp. 8–9).¹³ Brague connects these words with self-presentation to show how actuality is a much more general concept than is activity:

Furthermore the underlying idea is the same in both cases—not “action,” but the fact of being at work, in contrast with the fact of being “on site,” which

¹³ He cites Aristotle, *Metaphysics* IX.3.1047a30f and 8.1050a22f.

could translate ‘*dunamis*’ (potency). To be at work, in this case, is not to engage in an activity; or rather, it is so only to the extent that the activity is above all that which reveals me as the one I am. In such a case, the activity is not necessarily “animated”: what I am may appear more distinctly while I am at rest than during the exercise of a capacity. Hence, it is not absurd for Aristotle to speak of an “activity of immobility (*energeia akinēsias*)” (*Nicomachean Ethics*, VII, 14, 1154b 27). Consequently, we need a concept of *energeia* wide enough to include both the mobile and immobile modes of presenting oneself. (Brague 1990, p. 9)

Actuality may be reflected in a lack of motion and apparent activity. But also note that a thing’s nature—its inner principle of motion and rest—can be “revealed” by its very invisibility. Aristotle also describes the nature or form of a thing as “the look that is disclosed in speech” (Aristotle 2005, II.1.193a30),¹⁴ that is to say, not so much in appearance perceived by sight as appearance apprehended by the mind and communicated in speech.

We have seen that corresponding to Aristotle’s different conception of matter is a different conception of motion. In contrast to the mechanical conception of matter in which motion is just an activity of matter, which is definitionally definite in space and time, for Aristotle, matter is essentially linked to motion, and both are indefinite or potential.

Thus, if we may reason beyond Aristotle’s explicit statements: in this conception, the more material a thing is, that is, the lower it falls in the hierarchy of forms, the more mobile it is. *Things that are more basic are more mobile, and, should there be things that are most basic, they will also be the most mobile. Matter is what moves, and what is most material is what is most movable.* This preliminary conclusion will be essential to the second half of this inquiry.

3 Light and elementality

3.1 What is an element?

We are going to see that light and similar bodies are physical elements, and this requires considering current conceptions of light and other matter and how they indicate such bodies are most basic. Before we turn to fully face modern thought, let us consider the notion of “element.”

In *Metaphysics*, Aristotle gives two definitions of element, and the first is more applicable here:

the primary component immanent in a thing, and indivisible in kind into other kinds (Aristotle 1912, V.3.1014a26)

He gives a similar definition, particularized to bodies, in *On the Heavens*:

¹⁴ Nature is the major subject of Book II.

An element, we take it, is a body into which other bodies may be analysed, present in them potentially or in actuality (which of these, is still disputable), and not itself divisible into bodies different in form. (Aristotle 1922, III.3.302a17-19)

In modern thought, “element” is usually understood as a chemical element. A somewhat relaxed form of Aristotle’s basic definition still holds underneath: for ordinary chemistry, nothing is more basic than the elements of the periodic table. Similarly, the definition can be applied to other types of elements, e.g., physical elements such as elementary particles.

3.2 Contextualizing modern science

More than twenty-two centuries have passed since Aristotle, and we have learned many things about the natural world since his time. Let us combine what we have just reviewed about Aristotle’s conception of matter with more recent developments in physics.¹⁵

Before we turn to these considerations, however, we must make note of the epistemological status of scientific conclusions in this new context. Axioms are always starting points for argumentation. Whereas in the older context, axioms are simply inarguable points in themselves that no one would question, in the new science, axioms are often far from evident and rely on the reasonability of deductions consequent on them to argue on their behalf. Newton’s *Principia* begins with what he styles “Axioms or Laws of Motion,” none of which is evident in itself, but for which the rest of *Principia* and its agreement with experimental and observational evidence stand as proof.

With the weakness of the modern method we are all too familiar. There can be many explanations for the same set of observed phenomena. Newton’s law of universal gravitation could be entirely correct, or the centuries-long agreement of its results with observation could simply be because it is a fair approximation of a conceptually deeper explanation. We discovered last century that the latter is the case: the theory that superseded Newton’s is general relativity. But by the same token, there is no reason relativity or any other theory favored today cannot be similarly superseded. (In fact, we know from the incompatibility of general relativity and quantum mechanics that one, but more likely both, require revision.)

Even the understanding of empirical findings, which themselves are the bedrock of modern science, depends on theoretical considerations. With such a web of mutually supporting evidence and suppositions, it is sometimes hard or even impossible to know whether the premises or the conclusion are more certain, and thus where to start. In the following discussion of modern physics, we take as our starting point widely accepted elements of physical theory well established as according with experiment. Any indication of their derivation is meant not necessarily as some sort

¹⁵ Our modern view of light is rather different from Aristotle’s conception (*De Anima* II.7), which relied on an inadequate experiential basis. It goes without saying that many of Aristotle’s ideas about the physical world have proven inadequate.

of demonstration or proof based on better known elements of that theory but rather as an elaboration of the starting point's meaning and its relation to neighboring concepts.

3.3 Relativity

This section, which is somewhat mathematical, establishes that bodies move at the speed of light if and only if they are massless. It also distinguishes between energy and mass, establishes what “massless” means, and specifies what we mean by body.

The distinctive starting point for Einstein's special theory of relativity is the assumption that the speed of light (in vacuum) is the same (“invariant”) for all observers, no matter how they are moving—that is, how fast, or in what direction. This situation contrasts sharply with the case we are used to from the everyday world, in which, for example, observers on the ground see the velocity of a ball thrown from a train as the sum of the velocity of the train and the velocity of the ball relative to the train. The difference is that all observers see light emitted from the train as moving at the same speed, no matter how fast the train moves relative to the observers. Thus the question of absolute vs. relative motion is not an issue for light or, it turns out, for other objects moving at the speed of light: all observers see such objects moving, and moving at the same invariant speed.

From this premise of the invariant speed of light and the Principle of Relativity (that the laws of physics are the same in all reference frames), we can derive the Lorentz transformations, which describe how time intervals and distances have to look different to observers in different states of motion to maintain the invariance of the speed of light. (Good popular treatments of relativity include Mook and Vargish, 1987; Collier, 2014.)

The Lorentz transformations applied to energy and momentum produce the relativistic equations for these quantities:

$$E = \gamma mc^2$$

$$p = \gamma mv$$

For momentum, the only significant difference from usual non-relativistic version is the gamma factor, $\gamma = 1/\sqrt{1 - v^2/c^2}$. Here, E is the body's energy, p is its momentum, m is the body's (invariant or “rest”) mass, v is its speed, and c is the speed of light.

Another important expression is the energy–momentum relation,

$$E^2 = m^2c^4 + p^2c^2$$

Heuristically at least, this is derivable from the relativistic energy equation, $E = \gamma mc^2$, but the derivation is left as an exercise for the reader. The important first thing to notice about this equation is that the square of the energy is a sum of two squared terms. The first term on the right-hand side is the contribution of the body's rest mass to the energy, and the second term is the contribution from the body's motion. When

the body is still, the total relativistic energy reduces to Einstein's famous " $E = mc^2$ " expression for rest energy.

On the other hand, for massless bodies, $m = 0$, and the body's energy completely consists of its motion, so $E^2 = p^2c^2$ or $E = pc$. But because $p = \gamma mv$, this means $\gamma mc^2 = \gamma mvc$ or $v = c$. So according to the equation, a massless ($m = 0$) object moves at the maximal speed, c .

Please note that "massless" means not that a body has no mass but that it has no *rest* mass. Every body, having energy, has mass, so saying a body is massless is an unambiguous reference to rest mass. Somewhat confusingly, physicists often refer to rest mass as simply "mass," particularly in the context of subatomic particles, for which each species of particle has a definite, invariant mass.

Now we turn back to the first expression, the one for relativistic energy, and write it out as

$$E = \frac{mc^2}{\sqrt{1 - \frac{v^2}{c^2}}}.$$

As the speed, v , increases and approaches c , the denominator goes to zero, and the energy approaches infinity. Infinite quantities are unphysical and undesirable in physics. So this expression seems to imply that nothing can travel at the speed of light. The exception would be when the numerator is zero. Then the energy could remain finite; therefore, this new discovery doesn't affect our previous insight that $m = 0$ bodies travel at c .

In sum, we find that a body can move at c if and only if it has $m = 0$.

Now this conclusion applies to all massless bodies, but the most obvious object to move at the speed of light is clearly light. By "body" I mean a mobile thing, that is, a material substance that can change place, that is, "locomotional matter."¹⁶ As explained above in Part I, a substance is a something that has at least a relatively stable and independent existence.

Physics describes a few entities that travel at c , and they are all known as vector bosons, particles that carry the fundamental forces. Photons constitute light and carry the electromagnetic force. Gluons carry the strong nuclear force that binds the components of atomic nuclei together, and gravitons, which have not yet been observed, presumably carry the gravitational force. But which of these are bodies?

Gluons never exist separately from the hadrons of which they are part, so they are not substances. Neither are virtual particles. Recall that parts exist potentially in their whole. Light exists independently of its emitter and eventual absorber, as witnessed most dramatically by the ancient light from the Big Bang that still pervades the universe after more than 13 billion years, so it qualifies.¹⁷ Gravity might also

¹⁶ The term "body" as I am using it does not necessarily have the connotation of impenetrability in all circumstances. Light, for example, is not usually impenetrable to other light. But "body" does imply being relatively limited in extent, so space or spacetime are excluded.

¹⁷ There is something to be said for the view that light is "part of" the universe as a whole, but if we are going to say that, then do any substances at all exist except the universe as a whole?

fit the bill; though its nature is less understood, it is presumed also to be quantized. The technical appendix (Appendix I) discusses the uncertainties associated with concluding that photons and gravitons travel at the maximal speed. Please note that the claim is not that everything called “photon” (or “graviton”) is a substance. Virtual particles are not substances, as just said. The claim is that individual photons and gravitons *can* be substances and that some of them are, albeit in a minimal way.

Photons are the best known of the massless particles, but what we say about them and light presumably also extends to gravitons and gravity. Having no rest mass also implies that light cannot be at rest: left to itself it can only move. As relativity tells us, there is no inertial frame with the speed of light in vacuum, so it is not possible to pull up next to a packet of light with the same speed to see it stand still; there is no such thing as still light.¹⁸

Before we move on, we need to address some doubts about the substantiality of elementary particles. Nowadays an elementary particle is more commonly claimed as a fundamental existent than an animal is, but addressing objections opens an avenue for clarification. The crux of the argument of Verrill (2017) is that elementary particles are not bodily substances because they lack tangible surfaces, the evidence being that experiment has yet to discover any features of, say, an electron. Additionally, he says even theoretically there is no quality to distinguish the body of the electron from everything that is not the electron. Koons (2021b) thinks particles do not qualify because they fail to retain their individual identity and *per se* unity over time. His first objection is that interacting particles become entangled to the point of losing their individual identities (*vide* Bose–Einstein and Fermi–Dirac statistics). His second objection is that the number of particles in a system in quantum field theory can vary depending on the inertial frame of the observer, and such dependence of being is incompatible with the independence required of substances. His third objection is that quantum particles do not follow definite paths or have definite positions usually, and that more generally it is impossible to assign powers, whether active or passive, to any particle in isolation, apart from a measurement event.

Verrill makes the mistake of taking the current state of experiment as the definitive word on the featurelessness of elementary particles. In reality, our finest resolution, a function of the inverse proportion of the energy of our best colliders, is always finite. If theory can simplify by treating electrons as point-particles, that is not a statement about the underlying reality. As long as the radius of a particle is compatible with zero, the best an honest experiment can do is give an upper limit on the radius. As far as localizing particles, cloud chambers and more advanced evolutions of particle trackers show the track of where, say, the muon has been and distinguish it from its surroundings.¹⁹

To Koons’s first point, although it is true that quanta readily interact with other quanta and lose their individual identities, the point of this paper is not that photons are always independent substances but that they *can* be and sometimes are. The fact

¹⁸ Light interacting with other matter is not light *per se*.

¹⁹ “Tangible” is not clearly defined in the paper, and private communications with Verrill were unable to clarify the term in the limited time available. Thanks to him and his conference respondent Timothy Kearns for their correspondence.

that they join with other substances readily, to be subsumed into a new substance, is what we would expect of a *minimal* substance.

Koons's second point is difficult to understand as true because it apparently violates the principle of relativity. In field theory, the number operator commutes with the Lorentz transformation in the free case, and it tends to commute in the interacting case in the limit of weak interactions. Certainly, particle number is not conserved in interacting field theories, but this is due to interactions, not to changing frames. Regardless of interactions, relativity says all observers should agree about whether a particular event happened or not, even if they disagree about its particular timing.²⁰ For concreteness, imagine a double slit experiment in which only a single photon is allowed through. According to the claim, there should be observers in some frames of reference who, instead of one, see two photons on the screen (zero would blatantly violate the conservation of energy). Two instead of one is different physics, which relativity prohibits: problematic to say the least.

Koons's third point relies on the assumption that substances should have well-defined properties. Certainly, if a particle were completely undetermined, it would not exist at all. Particles of a particular species have at least a definite rest mass at all times, not to mention charge and total spin. But why should it need to be the case that substances be completely determined much of the time in all aspects? As we've seen in the first part of this paper, indeterminacy is fundamental to motion. All material substances, whether quotidian or elementary, need to be indeterminate in order to move. Minimal substances will of course be less determinate than others. Koons admits that even larger substances' "definite location and intrinsic characters" is only "more-or-less," but there is a whole continuum of sizes, and he describes no boundary for the degree of indefiniteness allowed "substances," let alone any justification for such a boundary. As far as we can tell, De Broglie wavelength is inversely proportional to momentum for all objects, regardless of size.²¹

3.4 Masslessness and motion

So we have seen that bodies travel at the maximal cosmic speed, c , if and only if they are massless ($m = 0$). Our suspicion is that massless bodies are the most basic, most material substances. Let us examine the physical content of "masslessness" to confirm that suspicion.

David Bohm explains what rest mass means in terms of "rest energy":

In this connection it must be noted that every form of energy (including kinetic as well as potential) contributes in the same way to the [total relativistic] mass. However, the "rest energy" of a body has a special meaning, in the sense that even when a body has no visible motion as a whole, it is still undergoing inward movements (as radiant energy, molecular, electronic, nucleonic, and

²⁰ Private communication with Manuel A. Buen-Abad. Separate, brief communication with Stephen M. Barr broadly concurred with the evaluation of the paragraph.

²¹ Molecules of over 25,000 Da (equivalent to the mass of over 2,000 carbon atoms) have recently demonstrated quantum interference (Fein et al., 2019).

other movements). These inward movements have some “rest energy” E_0 and contribute a corresponding quantity, $m_0 = E_0/c^2$ to the “rest mass.” (Bohm 1996, p. 117)

It is particularly instructive to consider how, in this point of view, one understands the possibility for objects with zero rest mass to exist, provided that they are moving at the speed of light. For if rest mass is “inner” movement, taking place even when an object is visibly at rest on a certain level, it follows that something without “rest mass” has no such inner movement, and that all its movement is outward, in the sense that it is involved in displacement through space. (Bohm 1996, p. 118)

What does he mean by “inner movements”? One example he gives is from the pressure that electromagnetic energy, quantified by E_R , exerts on the walls of the box that contains it (Bohm 1996, pp. 94–95). When we take careful account of these forces, we find that when a force F is applied to the box to produce acceleration a , the radiation pressure exerts a net force on the box that opposes the acceleration with force $F_R = -E_R a/c^2$. So the box’s total equation of motion is

$$m_B a = -\frac{E_R a}{c^2} + F.$$

This means the equation of motion of the box plus radiation is

$$\left(m_B + \frac{E_R}{c^2} \right) a = F.$$

Comparing this expression to Newton’s second law of motion, $F = ma$, we see the radiation adds to the box an effective mass $m_R = E_R/c^2$. Whereas light moving freely in a plane wave, or as photons, has no rest mass, light confined to another body contributes to the rest mass of the body through its mass-equivalent energy ($E = mc^2$). The box is a good analog for the confines of any physical system, including a subatomic particle.²²

Because photons have no rest mass, their unconstrained movement is purely outward.²³ Because they lack any inward motion, they must be simple, containing nothing, and being composed of nothing inferior. All massless bodies similarly lack the structures or organization required to bind subsidiary motions inside. (Mass is a structured form of energy, and massless bodies lack this structure.)

In a word, massless bodies have minimal *form* and are maximally material. In this way, physics by itself also gives us an indication that massless bodies are most fundamental in the sense of having the least form and being the most material.

²² Photons bound within another quantum do not exist as substances. Whether they exist as accidents or as quantitative integral parts is a matter for empirical study, but their elementality would seem to indicate virtually.

²³ Contrast with the internality of organism and the emergence of self-hood (Jonas, 2001, pp. 82–83, 91).

Special relativity thus corroborates what we saw in the first part: motion is what most characterizes matter, so the more basic a thing is, the more mobile it should be, with the most basic material things having the maximum motion.

3.5 Elementality

Massless bodies such as photons are minimal bodies. But we also know that photons compose other bodies, namely electrically charged particles, the only particles with which photons interact. This composition is evident in particle–antiparticle annihilation. For example, when an electron collides with its antiparticle, a positron, it produces two photons. As we’ve seen, massless bodies when confined contribute to the mass of massive bodies.

Now it is also true that theoretically the reaction works in reverse: two photons of sufficient energy can collide to produce an electron–positron pair. But note the asymmetry: massive bodies cannot be present in the constitution of a massless body. Photons can be *transformed* into massive particles but not decomposed or subdivided.

So photons fulfill Aristotle’s definition of element: “the primary component immanent in a thing, and indivisible in kind into other kinds.”²⁴

It is important to note that photons’ composition of other bodies is non-trivial: they compose the charged particles not in isolation, but as particle–antiparticle pairs. Of the seventeen species of elementary particles in the Standard Model of Particle Physics, nine are charged, namely the six quarks and three charged leptons. And for those nine, the photon is elementary. Clearly it is elementary not in the same sense as the elementary particles but in a more fundamental, kinetic–dynamic sense.

By analogy, we can wonder of what sort of matter gravitons, should they exist, might be an element. Are there mixed forms of matter composed of both gravitons and photons? Might there be an invisible sector of matter composed of gravitons but not photons? Or are gravitons the element of all matter with mass and thus in another sense more elementary than photons?

3.6 Distinctions about “motion”

Having come to our main conclusion, let us review what we have learned and draw out some further aspects of the subjects of mass and energy. With relativity we saw that bodies without mass are the only ones that travel with the maximal motion, the speed of light. We further saw that bodies with mass are composed of inward motions, and these inward motions are lacking to massless bodies.

We contemplated the maximal motion and established a minimum of form. Massless light lies at the bottom. Coinciding with the climb from light to higher forms, bodies gain rest mass, along with the ability to stand still. Mass is the principle of stability and determinateness; it opposes the restlessness inherent in matter. So mass must represent a formal component of locomotion.

Furthermore, we notice that in the classical regime (speeds much less than c), communicating motion (velocity) to other bodies, that is, *activating* them, requires

²⁴ Many thanks to Thomas McLaughlin for pointing out the connection.

mass. In collisions, momentum and kinetic energy, which are functions of velocity *and* mass, go into partitioning the motion between the colliding bodies and deciding their resulting velocities. The more mass a body has, the more energy and momentum it contributes to the result of a collision and the more speed it imparts to a smaller body with which it collides. So again, mass is an active, formal principle.

There are two senses of motion. Our natural tendency is to think of motion as active; motion is after all an activity, a positive reality that can be passed on. This is the reality quantified in Newton's "quantity of motion," momentum.

But the sense of motion in the definition of motion is more passive. Translation reflects the ability to be elsewhere, that is to say, the potentiality or indefiniteness of the moving body. In describing the motion visible in the world, we use the kinematic quantity of speed or velocity.

To the degree the object in motion with a given speed has mass, that motion has greater definiteness or actuality. So momentum and energy are the more active or actual ways of quantifying motion, and velocity is more passive or potential.²⁵ The two distinct senses of motion are complementary.

Mere motion, that is, translation, is primarily evidence of potentiality, as the definition of motion shows. But to the extent that motion has momentum or energy, it has an actuality that can be communicated to another body. It is not clear why Young (1807, p. 52) chose "energy" for Leibniz's *vis viva*, but the appropriateness of choosing a derivative of Aristotle's *energeia* (actuality) becomes apparent when energy is contrasted with speed or velocity. In the context of classical physics, this difference between potentiality and actuality requires mass; in the context of modern physics, it involves energy, which can take the form of mass. Mass is a more stable, structured form of energy; kinetic energy is material with respect to mass/rest energy.

4 Conclusion

Physics as we know it today, that is, the physics bequeathed to us by the Newton, makes certain assumptions, assumptions that are perilously unarticulated. These assumptions are largely of a piece with Descartes' division of the world by fiat into two mutually exclusive kinds: matter on the one side and mind on the other. Matter is paradoxically completely determinate with regard to geometry, yet subject to motion and utterly separate from the principle of form and determination (mind).

If we remove Descartes' poorly founded assumption about the nature of matter, we can return to Aristotle's more fully human conception of matter, as the substrate of change, where "change" is not arbitrarily restricted to locomotion. Matter in this conception, being definitionally linked to motion, is also inherently indefinite. This indefiniteness or potency was rediscovered as a property of matter in the 20th century with quantum mechanics (Heisenberg, 1955, p. 13; Heisenberg 1958, pp. 53, 180–181).

²⁵ Bohm calls energy and momentum "causal factors" in contrast with "spacetime factors," position and time (Bohm, 1951, p. 157).

The major conclusion of this paper is that massless particles, such as those that constitute light, must be the minimal bodies, that is, locomotive substances. We reached this conclusion by first reexamining Aristotle's conception of matter and his definition of motion; accordingly, we saw that the more material a thing is, the more it can move and the more indefinite it is. Then we noted that from modern physics, we know that massless particles such as light move with maximal speed and therefore must be the minimal kinds of bodies.

This conclusion was corroborated by modern physics. We saw that relativity's interchangeability of mass and energy means that rest mass represents a sort of "internal motion." Lacking rest mass, light must consist of purely outward motion; it has no internal motions, so it can contain nothing inferior.

The two disciplines, physics and philosophy, agree in the conclusion without saying the same thing. There has been an exchange of gifts. Philosophy teaches physics just how thoroughly matter and motion define each other. Physics teaches philosophy that basic matter is not only mobile, but must move.

Growing from the conclusion, we also distinguished two senses of locomotion: the active one operative in Newton's definition of momentum as "quantity of motion" and in energy (Leibniz's "living force"), and the passive one operative in Aristotle's definition of motion and evident in the mobility quantified as speed or velocity. The formal presence of mass/rest energy is what marks the difference, and it is what allows the body to establish its place.

We have seen that for massless bodies motion is essential: not only the potential to move, as per Aristotle, but also the actuality of always moving. Light's continued motion might seem acausal and more specifically appears to violate the principle that "everything that is moved is moved by another," that is, a present agent (cf. Aristotle, *Physics* VII.2). At this point we begin to intrude into a much larger topic—how inertial locomotion fits with Aristotle and the common experience of change and agency—that will have to wait for a future paper. But the agreement about motion and matter described in this paper suggests a deeper compatibility between the conceptions of motion of the two forms of physics.

While a particular motion requires a particular cause, what enables motion in general is simply the indefiniteness that comes with being material. With elementary bodies moving by nature, outward motion is the fundamental mode of the existence of anything material. Starting from this essential motion, it now becomes apparent that the wonderous thing is not why anything moves but why anything can stand still. How does the actuality for stillness originate? What are the principles that pin matter to place to give it mass? Furthermore, which comes first and in what senses: place or locomotion? The Standard Model of Particle Physics might provide the Higgs mechanism in partial response, but a more rigorous understanding in terms of common experience is a task for philosophical physics.

There is a noteworthy trend with increasing mass. A massless body such as light, lacking even an inertial reference frame, cannot stand still. Massive, but low-mass bodies, such as a charged particle modeled in "the particle in a box," can be localized with a reference frame but to the degree they are localized cannot stand still. As bodies increase in mass up to the classical scale, they acquire the ability to be still and are better able to resist outside forces. Up to this point, bodies have gained

with increasing mass the ability to have a determinate place, but as we move up to masses on the astronomical scale, bodies such as planets and stars acquire the ability to gravitationally determine the motions of bodies around them to a noticeable degree. The natural teleology of bodies, which manifests itself through gravitational and electromagnetic forces, is to seek greater actuality in unity (Keck, 2007). With increasing mass, bodies establish places for and around themselves and provide the stationary context for the places of other bodies.

For centuries the dominant story has been that ancient and modern concepts—the immediacy of normal experience and the precision of controlled experiment—are irreconcilably divided. Connecting these two seemingly separate territories gives physics a broader experiential base on which to build or, if you will, a bigger conceptual toolbox for understanding the universe. Instead of solely resolving the natural world as a projection along the dimension of human power, we can bring together two complementary methodologies for a broader basis of understanding.

To be sure, there are tensions and questions to be worked out between the two frameworks, and thus opportunities for discovery: not only discovery of the universe, but also how our experience as human discoverers fits in the universe, as it can only. The most obvious tension is between the apparent absoluteness of motion in Aristotle's definition and the relativity of motion in modern physics, as applied to non-massless bodies: whether and in what sense their motions have a natural or special frame of reference. This divide reflects the fundamental tension between Newtonian mechanics and human experience that is set aside starting from introductory physics.

Drawing also on the pre-Cartesian conception of matter provides a more general, more robust framework for understanding the discoveries of modern physics than does the early modern conception that still lurks in the background of much scientific thinking. The truth of this insight is not restricted to quantum mechanics: the real scientific observer is human and, unlike the abstracted, disembodied observer bequeathed to physics by Descartes and his heirs, not an omnipotent mathematician with no participation in the physical (Jonas, 2001).

5 Appendix I: Technical issues

Surely it would be a tautology to say that light moves at “the speed of light,” but paradoxically it is not a given. Though light certainly moves at its own speed, what we mean here by “the speed of light”—or more precisely “the speed of light in vacuum”—is the maximal cosmic speed. As we have seen, no body can move at the maximal cosmic speed if it has even a small mass. It could be that light has a very tiny mass that we have been unable to measure so far. In that case, it would travel very close to but not exactly at the “the speed of light.” Our measurements of light's speed always come with a finite experimental uncertainty or “error.” For comparison, it was once thought that neutrinos were massless and traveled *at* the speed of light, but now we know from experimental results viewed through complicated theoretical reasons that they have mass (albeit very tiny), though we remain unable to measure the difference between their speed and the speed of light.

Experimentally we do not know with absolute certainty that light is massless. Rather, we constrain an upper limit on its mass. The current best upper limit for the mass of the photon is 1×10^{-18} eV (Zyla et al. 2020b). For comparison, the mass of the electron is 511 eV and that of the proton is 938 MeV or 1.67×10^{-27} kg.

Meanwhile, the upper limit for the mass of the graviton is 6×10^{-32} eV (Zyla et al. 2020a); though its existence has not been experimentally confirmed, there is a strong presumption that it exists. Oddly enough, though we are less certain that gravitons exist compared to photons, we are experimentally more certain that gravitons are massless.

The reason we believe that light is precisely massless comes from quantum field theory. In order to preserve a symmetry called local gauge invariance, the photon must be massless. Without gauge invariance, quantum electrodynamics loses renormalizability (a highly desirable property that allows theories to make finite quantitative predictions) and charge conservation (empirically very certain).

6 Appendix II: Clarification of some confusing terms

As in the remark attributed to Shaw about Britain and America, common language often divides. The relative isolation of modern fields of study from their ancient and medieval antecedents has led to the reuse of words to mean something very different—or at least different enough to create confusion.

6.1 Physics

“Physics” comes from the Greek word for nature.²⁶ In this paper “physics” generally has its usual current meaning: the empiriometric study of the motions and constituents of the material world. But “physics” was traditionally used broadly to designate natural philosophy; “the Physics” refers to Aristotle’s foundational treatise on the philosophy of nature.

6.2 Classical and modern

In physics, the break between classical and modern occurred at the beginning of the twentieth century, broadly speaking. In a chronological sense, modern physics includes relativity as well as quantum mechanics, but in a paradigmatic sense, modern physics includes only quantum mechanics and not relativity, because relativity relies on the classical, geometrically definite conception of matter.

In a broader, cultural context, *classical* is also distinct from the *modern*, among other ages. Classical thought is ancient to us moderns. The medievals sought to bring themselves into continuity with what came before; the modern break, ostensibly a radical break with the past, might be dated to the beginning of the Enlightenment, but

²⁶ On the etymology and the importance of “nature,” see Schindler 1986, pp. 1–2.

has roots back to the late middle ages. There is also a Classical era in ancient Greece that spanned the fifth and fourth centuries BCE.

6.3 Matter

In the modern sense, matter takes up space and moves in space. In a more restrictive sense common in physics, it includes massive, impenetrable bodies and excludes gauge bosons (force carriers) such as light.

In the Aristotelian sense, matter is primarily the substrate of substantial change but can also be used in a broader sense (*pros hen* equivocation) to refer to the substrate of accidental change (i.e., substance), e.g., in saying that matter translates or changes color. “Matter in itself” or “matter per se” is matter without form and equivalent to prime matter. In much the same way that physicists sometimes say “mass” to indicate rest mass, philosophers sometimes say “matter” to mean prime matter. In this paper matter generally means secondary matter (i.e., matter with form).

In a broader, social context, “material” means something essential, relevant, or substantial, e.g., “material witness.” This usage reflects the modern understanding of matter as what is most fundamental.

6.4 Form

In the modern idiom, a form has the connotation of being extrinsic or superficial, as in the phrase “It’s just a formality.” In contrast, for classical philosophy, form is the heart of what a thing actually is.

So in modern logic, the form of a syllogism is called valid if the truth of its premises, whatever they may be, guarantees the truth of the conclusion; form is an abstraction from the particular premises. Similarly in physics, formalism is mathematical description that matches empirical results, without committing itself to any “metaphysical” truths about what is really happening.

In classical philosophy, form means almost the opposite of what it does in the modern world. “Form” goes back to Plato and refers to the Ideas, which can be instantiated in matter by an outside agent. His student Aristotle had a more robust concept of form as actually making things what they are, especially in the forms of substances, i.e., substantial forms. The form is the principle of actuality in contrast to the matter, which is the principle of potentiality or receptivity. But a characteristic or “accident” can also be called a form in another sense, viz. an accidental form, such as the color of a substance.

6.5 Mass

“Mass” can refer to the rest mass of a body or to its full, relativistic mass. “Massless” particles or bodies, such as photons, have no rest mass but do have relativistic mass, also known as mass–energy; of course, as we have tried to make clear in this paper,

relativistic mass of even a massless constituent particle can contribute to the rest mass of the particle it constitutes. In discussions of particles, “mass” almost always refers to the rest mass, probably because it is the only value of mass unique to a given species of particle that can possibly be discussed.

The relativistic mass is numerically equivalent to the gravitational mass. Thanks to the equivalence principle, we know that gravitational and inertial mass are numerically equivalent. Analogous to electrical charge, gravitational mass is the “charge” in the law of gravity, whereas inertial mass is what resists acceleration.

There is a philosophical distinction between active and passive mass.²⁷ Active mass does the gravitational attracting, and passive mass is attracted. Of course, every active mass is also passive and vice versa (“universal gravitation”), so the difference holds in speech but not in nature. This conceptual distinction lies behind a typical example in most physics textbooks: a large mass that gravitationally acts on a much smaller “test mass,” which contains negligible quantity of mass to affect the motion of the former, e.g., a space capsule orbiting a planet.

Before the modern era, the closest thing to mass for quantifying the size of a body was simply its volume or extension, literally called “quantity” even in the age of Descartes. Newton defined mass as quantity of matter in distinction from this existing understanding.

6.6 Fundamental

There is a sense in modern particle physics that less fundamental particles are composed of more fundamental particles. But who would argue that an electron, which is inarguably more fundamental than a proton, is a constituent of a proton? The philosophical understanding in this paper is that bodies that are more basic are simpler, less formal and more material, and, in other words, closer to prime matter.

In Aristotle’s thinking, substances are the most fundamental entities. Organisms are the prime example of substances, and they exercise a top-down causality on their parts.

6.7 Element

The physical elements of Aristotle were the famous earth, water, air, fire, and aether—what would today be recognized as phases of matter from solid to plasma. But he singled out these particular elements based on an understanding of element defined in *On the Heavens* III.3 and quoted in the body of the paper.

Even further, physical elements are a specific case of a much wider concept of element, as summarized in Aristotle’s definitions of element in *Metaphysics* V.3, as cited in the main body of the present text (§ 2.1).

Modern uses of “element” cluster around the chemical elements of the periodic table. But even in the modern world, it is understood that element has a more general

²⁷ Thanks to Anthony Rizzi for this distinction.

meaning of rudiments or most basic essential parts, such as in the title of Strunk and White's *The Elements of Style*.

Acknowledgements I am grateful for thoughtful feedback from Manuel A. Buen-Abad, Michael A. Augros, Stephen M. Barr, Richard F. Hassing, Joseph K. Cosgrove, Thomas Davenport, James A. Barham, and the anonymous referees. Special thanks to Thomas McLaughlin for all his invaluable help.

Authors' contributions There is only one author.

Funding No external funding sources.

Data Availability Not applicable.

Code Availability (software application or custom code) Not applicable.

Declarations

Conflicts of interest/Competing interests None.

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References

- Aristotle (1912). *Metaphysics*. Translated by W.D. Ross. Oxford: The Clarendon Press.
- Aristotle (1922). *On the Heavens*. Translated by John Leofric Stocks. Oxford: Clarendon Press
- Aristotle (1930). *Physica*. In *The Works of Aristotle*, edited by W. D. Ross, translated by R. P. Hardie and R. K. Gaye. Vol. II. Oxford: Oxford University Press.
- Aristotle (2005). *Aristotle's Physics: A Guided Study*. Translated by Joe Sachs. New Brunswick, NJ: Rutgers University Press.
- Ashley, B. M. (2006). *The Way Toward Wisdom: An Interdisciplinary and Intercultural Introduction to Metaphysics*. Notre Dame, Indiana: University of Notre Dame Press.
- Augros, M. (2004). Reconciling Science with Natural Philosophy. *The Thomist*, 68, 105–141.
- Augros, M. (2012). A Bigger Physics. *Second Spring*. Spring: 58–76.
- Bohm, D. (1951). *Quantum Theory*. New York: Prentice-Hall, Inc.
- Bohm, D. (1996). *The Special Theory of Relativity*. New York: Routledge.
- Brague, R. (1990). Aristotle's Definition of Motion and Its Ontological Implications. *Graduate Faculty Philosophy Journal*, 13 (2), 1–22.
- Burt, E. A. (1954). *Metaphysical Foundations of Modern Science*. Garden City, NY: Doubleday and Company.
- Cartwright, N. (1999). *The Dappled World*. Cambridge University Press.
- Collier, P. (2014). *A Most Incomprehensible Thing*. Harlow, England: Incomprehensible Books.
- Decaen, C. (2000). Elemental Virtual Presence in St. Thomas. *The Thomist*, 64, 271–300.
- Descartes, R. (1644). In *Principles of Philosophy*.

- Descartes, R. (1907). On the Principles of Material Things. In *Principles of Philosophy*, translated by John Veitch. London: William Blackburn and Sons.
- Fein, Y. Y., Geyer P., Zwick, P., Kiałka, F., Pedalino, S., Mayor, M., Gerlich, S., & Arndt, M. (2019). Quantum Superposition of Molecules beyond 25 KDa. *Nature Physics* 15: 1242–45.
- Feser, E. (2019). *Aristotle's Revenge: The Metaphysical Foundations of Physical and Biological Science*. Neunkirchen-Seelscheid, Germany: Editiones Scholasticae.
- Heisenberg, W. (1955). "Development of the Interpretation of Quantum Theory." In *Niels Bohr and the Development of Physics*, edited by W. Pauli. New York: McGraw-Hill.
- Heisenberg, W. (1958). *Physics and Philosophy: The Revolution in Modern Science*. New York: Harper & Row Publishers.
- Jonas, H. (2001). "Is God a Mathematician?" In *The Phenomenon of Life*, 64–98. Evanston, IL: Northwestern University Press.
- Keck, J. W. (2007). The Natural Motion of Matter in Newtonian and Post-Newtonian Physics. *The Thomist*, 71(4), 529–554.
- Koons, R. C. (2017). Hylomorphic Escalation: An Aristotelian Interpretation of Quantum Thermodynamics and Chemistry. *American Catholic Philosophical Quarterly*, 92, 159–178.
- Koons, R. C. (2018). The Many Worlds Interpretation of QM: A Hylomorphic Critique and Alternative. In *Neo-Aristotelian Perspectives on Contemporary Science*, edited by W. Simpson, R. Koons, and N. Teh. New York: Routledge.
- Koons, R. C. (2021a). Powers Ontology and the Quantum Revolution. *European Journal of Philosophy of Science* 11 (1): 1–28.
- Koons, R. C. (2021b). Thermal Substances: A Neo-Aristotelian Ontology for the Quantum World. *Synthese* 198 (s11): 2751–72.
- Leibniz, G. W. (1669). "Letter to Jacob Thomasius," April 20, 1669.
- Mook, D. E., & Vargish, T. (1987). *Inside Relativity*. Princeton, NJ: Princeton University Press.
- Newton, I. (1687). Rules for the Study of Natural Philosophy. In *Principia*. 3.
- Newton, I. (1693). Letter to Bentley, February 25, 1693. <http://www.newtonproject.ox.ac.uk/view/texts/normalized/THEM00258> (accessed August 31, 2021).
- Newton, I. (1730). "Question 31." In *Opticks*.
- Newton, I. (1999). *The Principia*. Translated by I. B. Cohen and A. Whitman. Los Angeles: University of California Press.
- Pruss, A. R. (2018). A Traveling Forms Interpretation of Quantum Mechanics. In *Neo-Aristotelian Perspectives on Contemporary Science*, edited by W. Simpson, R. Koons, and N. J. Teh. New York: Routledge.
- Schindler, D. L. (1986). The Problem of Mechanism. *Beyond Mechanism*, 1–12. New York: University Press of America.
- Schulman, A. L. (1989). *Quantum and Aristotelian Physics*. Harvard University dissertation.
- Simpson, W. M. R., & Koons, R. C., & Teh, N. J. (2018). *Neo-Aristotelian Perspectives on Contemporary Science*. New York: Routledge
- Simpson, W. M. R. (2020). *What's the Matter? Toward a Neo-Aristotelian Ontology of Nature*. University of Cambridge dissertation.
- Simpson, W. M. R. (2021). Cosmic hylomorphism: A powerist ontology of quantum mechanics. *European Journal for Philosophy of Science* 11 (1): 1–25
- Storck, M. (2008). Parts, Wholes, and Presence by Power: A Response to Gordon P. Barnes. *The Review of Metaphysics*, 62 (1), 45–59.
- Storck, M. (2014). *Pars Integralis* in St. Thomas Aquinas and the Parts of Living Substances. *The Thomist* 78: 379–99.
- Verrill, R. (2017). Elementary Particles Are Not Substances. *Proceedings of the American Catholic Philosophical Association* 91: 63–72.
- von Weizsäcker, C. F. (1980). *The Unity of Nature*. New York: Farrar Straus Giroux.
- Whitehead, A. N. (1948a). *Essays in Science and Philosophy*. New York: Rider and Co.
- Whitehead, A. N. (1948b). *Science and the Modern World*. New York: Pelican-Mentor Books.
- Young, T. (1807). *A Course of Lectures on Natural Philosophy and the Mechanical Arts*.
- Zyla, P.A., et al. (Particle Data Group) (2020a). Graviton. In *Progress of Theoretical and Experimental Physics*.
- Zyla, P.A., et al. (Particle Data Group) (2020b). Photon. In *Progress of Theoretical and Experimental Physics*.

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