Chapter 11
Force in Physics and in Metaphysics: A Brief History

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The OED provides us with a characteristically concise and illuminating definition of *force*: "An influence tending to change the motion of a body or produce motion or stress in a stationary body. The magnitude of such an influence is often calculated by multiplying the mass of the body and its acceleration." That there are forces in precisely this sense at work in our world may seem so obvious that only the most radical of sceptics would dream of denying it. As every child soon discovers, moving a heavy object (such as a brick) requires more effort—and hence more force—than moving a light one (such as a feather). Getting a bicycle to move requires more than merely sitting on a saddle: one has to apply force to the pedals, the greater the force exerted, the greater the speed. Needless to say, there are many other instances of forces at work. The force of a strong wind can almost blow one over. Many children find magnets fascinating because of the way they can exert an influence—when attracting some paperclips, say—though empty space, seemingly *directly*, almost by magic. Later on we learn that Newton's gravitational force is responsible for keeping us bound to the Earth's surface, and responsible too for keeping the planets in orbit around the sun. During our school careers, many of us will also have been taught (even if we later forget it) Newton's second law, $F = ma$, which encapsulates the relationship between mass, acceleration and force referred to in the OED definition.

As will already be clear, there are two interrelated notions of force what we need to distinguish.

First, there is the very general notion of a force as *something which makes something else happen*, where the "somethings" in question are physical objects or events. When a hammer knocks in a nail into a piece of wood, the hammer not only exerts a force on the nail (assuming for the moment that forces do exist), it also *causes* the nail to move. Since force is an instance of the more general notion of a cause, and "cause" is itself a controversial and contested concept, the metaphysical controversies surrounding the latter will naturally extend to the former.

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S. Wuppuluri and F. A. Doria (eds.), *The Map and the Territory*,
The Frontiers Collection, https://doi.org/10.1007/978-3-319-72478-2_11

The influential 18th century philosophical critiques of causation in all its forms by Berkeley, Hume—and Kant's response to these—had an impact on physics and metaphysics which endures to this day.

Second, there is the narrower and more specific conception of force as it features in one or other scientific theories. The accounts of *what makes a body move* to be found in the Democritus, Aristotle, Kepler, Newton, Maxwell and today's quantum mechanics and relativity theories differ in profound and interesting ways—as do the understandings of what "a material body" might be. Since different physical theories often posit different types of force, proponents of competing theories will inevitably have different views regarding the forces that are actually operative in nature. There are also disagreements over the kind of force *it makes sense* to think might exist. One particularly important and controversial instance is "action at a distance" forces. Forces of this kind, if they were to exist, operate directly across a spatial interval without any intermediaries. When a magnet picks up a metal paperclip it seems to be operating in this way. As we shall be exploring in more detail below, some prominent theories—most notably Newton's theory of universal gravitation—rely on action at a distance forces, whereas others—most notably Maxwell's electromagnetism and Einstein's general theory of relativity—make a virtue of *not* relying on them.

To add to an already complex picture, a further complicating factor is the manner in which scientific developments can influence metaphysical doctrines concerning forces and causes. Hume was famously sceptical with regard to causation. He is associated with the doctrine that nothing *makes* anything else happen, despite our natural tendency to think otherwise. If Hume is right, in a very real sense there are no forces—as we intuitively conceive them—to be found in nature at all, and the laws of nature do not constrain or necessitate, they merely reflect regularly occurring patterns among objects and events. The counterintuitive Humean view of causes and forces has always appealed to those hard-nosed empiricists who are wary of believing in anything that cannot be directly perceived. As we shall see in due course, it also receives support from the four-dimensional conception of the universe derived from Einstein's relativity theories.

In line with this chapter's title, the bulk of what follows will be historical in character. Inevitably, this might give rise to questions such as these.

> Why bother looking at the conceptions of force that can be found in old and discarded scientific theories? We want to distinguish the true the nature of force from the fictions and myths surrounding it. We want to know how force figures in the actual territory, as opposed to maps of it that we know to be erroneous. Given this, shouldn't we be concerning ourselves solely with *today's* physics?

This might be an option if contemporary physicists were in agreement as to the fundamental nature of physical reality, but as is widely acknowledged, this is far from being the case. General relativity is our best theory of the large-scale structure of the universe and gravity, quantum mechanics is our best theory of the (very) small-scale structure of reality. But in their current forms the two are radically incompatible, and finding a theoretical framework capable of accomodating both—the task Einstein worked on (fruitlessly) in the final decades of his life has proved very difficult.[1] There is certainly no shortage of intriguing speculation as to the form a “quantum theory of gravity” might take, ranging from classical canonical approaches to string/M theories, loop quantum gravity and causal set theory. But since there is no agreement as to which of these very different approaches is closer to the truth, contemporary physics is unable to provide an answer to the simple but basic question: “What is the fundamental nature of physical reality?”

In the light of this, it is well worth taking a brief look at how the conceptions of force have figured in earlier scientific theories and controversies. Since very different modes of physical interaction have been seriously considered by earlier scientists and natural philosophers, a historical survey provides some indications as to the modes of interaction which could easily feature in the physics of the future. No less importantly, a number of historical debates concerning the intelligibility (or possibility) of certain particular forms of physical interaction also have contemporary relevance—as we shall see in due course.

Ancient Forces

Anyone seeking to make sense of the universe will find that ordinary observable objects and processes pose a sizable number of challenges. Why do things fall when dropped? Why doesn’t the moon fall out of the sky? How does the sun manage to rise every day? Why does fire rise upwards rather than downwards (or sideways)? If you push a stone across a table, why does it stop? What path does an arrow take when it flies through the sky? How can lodestone and amber affect things without touching them? Why is it that water can be absorbed by a cloth or sponge, but not by a hunk of rock? The ancient Greek natural philosophers were very much interested in making sense of the world, and devised a sizable number of very different explanatory schemes, several of which went on to have considerable influence in the millennia to come.

Following the lead of Parmenides, the early Greek atomists—most prominently Democritus, Epicurus and Lucretius—drew a sharp distinction between being and non-being. The latter is identified with pure nothingness in the form of an infinitely vast and utterly empty space, or *void*. Being comes in the form of a very large number of very small material atoms, indestructible and impenetrable, varying in shape and size. The universe as a whole consists of nothing more than atoms moving through the void. Democritus held that atoms have an in-built tendency to move, and so are in constant motion in all directions and do not require constant pushing.

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[1] Or as Rovelli (2008, 4) puts it: “In spite of their empirical success, GR and QM offer a schizophrenic and confused understanding of the physical world. The conceptual foundations of classical GR are contradicted by QM and the conceptual foundation of conventional QM are contradicted by GR. Fundamental physics today is in a peculiar phase of deep conceptual confusion.”

Epicurus would later account for gravitational effects by holding that atoms have an innate tendency to move downwards. When atoms collide they sometimes rebound off one another, but sometimes stick together—a process made possible by their shapes: Democritus believed that some atoms had hooks. For the atomists, all compound physical things—such as planets, rocks, liquids and animals—are the product of atomic collisions and subsequent adhesions, or as Aristotle concisely summarizes: "The atoms act and suffer action whenever they chance to be in contact … and they generate by being put together and intertwined".[2]

How could magnetic and electrical attraction be explained in these terms? As noted above, magnetism *seems* to work directly across spatial intervals, with no intervening material mediation. So can physical forces be transmitted through the void? The atomists were unanimous in wholly rejecting action at a distance. The only things which can causally act on physical bodies are *other physical bodies*, and since the void is entirely devoid of any sort of physical body, no causal influence can be transmitted through it. The atomists were obliged to explain magnetic and electrical forces mechanically. We thus find Lucretius suggesting that lodestones emit invisible streams of particles which displace the atoms of air in their surroundings. The small regions of void that are produced by this process result in pressure differences which lead to pieces of iron in the vicinity of a lodestone to move in the latter's direction.

Plato agreed with the atomists on some issues. In the *Timaeus* he suggests they were right to hold that macroscopic material things are composed of interacting smaller constituents—influentially, he also argued that when accounting for the behaviour of these systems mathematics should be deployed. But he felt unable to accept that purely *mechanical* model of the universe that the atomists were proposing held all the answers.

Plato found it implausible to suppose that essentially random atomic motion could give rise to the regular motions of the sun, moon and planets, or highly complex internally powered lifeforms such as plants, animals and human beings. He was thus led to posit that the physical world was ultimately controlled by an all-pervasive *mind* or *spirit*:

> … we must declare that the only existing thing which properly possesses intelligence is soul, and this is an invisible thing, whereas fire, water, earth and air are all visible bodies; and a lover of intelligence and knowledge must necessarily seek first for the causation that belongs to the intelligent nature, and only in the second place for that which belongs to things that are moved by others and of necessity set yet others in motion. We too, then, must proceed on this principle: we must speak of both kinds of cause, but distinguish causes that work with intelligence to produce that which is good and desirable, from those which, destitute of reason, produce their sundry effects at random and without order. (*Timaeus*, 46)

When it came to explaining in a detailed way precisely how the world-soul was related to the material world Plato had little to say beyond pointing to the analogy

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[2] *On Generation and Corruption*, 325a.

with the relationship between human souls and human bodies—a relationship that is itself less than transparent.

Aristotle was the ancient Greek natural philosopher whose views had the greatest influence over the course of the subsequent millennium. Like the atomists Aristotle wanted to develop a "theory of everything", and in his *Physics* he proposes principles which can explain motion and change in all their many and varied forms, on the Earth and in the Heavens. Like Plato, he found the mindless purely mechanical cosmos of the ancient atomists implausible.

For Aristotle the world is very much as it seems to be. The Earth is motionless, sitting at it does at the very centre of the universe, and the sun, stars and planets rotate around it. The most basic kinds physical things are the primary elements (earth, fire, water, air), and material substances composed of these, the prime examples of which are living organisms: cats, dogs, horses, fish, trees and the like. In the Aristotelian scheme all physical things are "hylomorphic", combinations of basic material stuff and *substantial forms*. A dog and an oak tree are both composed of material stuff—no doubt different proportions of the four elements—but they are obviously very different. As well as differing in shape, size, colour and internal structures they differ in what they are able *to do*: dogs have the capacity to jump and run, oak trees do not. According to Aristotle the differences between dogs and trees is due the active principle of organization, the form, which animates and bestows qualitative properties and causal powers on the matter composing them. Taken by itself, basic (or "prime") matter is inert and incapable of doing anything. It is only when it is infused with (or possessed by) a controlling form that it can constitute things of the sorts we are familiar with. All the different types of thing to be found in nature have their own distinctive form.

Aristotle recognized that living and non-living things move in different ways: living things have the capacity to *move themselves*, whereas inanimate objects do not. In explaining why inanimate objects move as they do he appealed to a distinction between *natural* and *non-natural* forms of motion.

He held that the different elements each have their own "proper" or "natural" place" and when an element is removed from its natural place it immediately attempts to return to it. Fire rising is an instance of natural motion—the natural place of fire is above the air, just below the celestial sphere carrying the moon; when a stone falls it too is striving to return to its natural place: at the centre of the universe. Non-natural motion occurs, as one might expect, when something intervenes to prevent an object following its natural course—e.g. when someone catches a falling stone.

Aristotle agreed with the atomists as to the character of non-natural motion: it occurs only by immediate *contact* between mover and thing moved. Or as he puts it: "The immediate agent of bodily change of place must be either in contact with or continuous with the moved object … as we always observe this to be the case" (*Physics*, 242). Like the atomists, Aristotle observed that the vast majority of non-natural causal interactions between material bodies involve contact—generally speaking things move only when they are pushed, pulled, kicked or thrown—and drew the conclusion that *all* such interactions require contact, and so rejected of action at a distance. Aristotle diverged from the atomists on the issue of the void: the Aristotelian cosmos is a plenum, containing no regions of totally empty space. The atomists held that the void is necessary for motion to be possible at all. Rejecting this reasoning, Aristotle points out that objects can move through perfectly easily through fluids—e.g. when we draw our fingers through a pool of water —without creating any gaps or voids.

The New Mechanical View

The Aristotelian system explains—and so makes sense of—all the natural phenomenal we encounter in ordinary life in an intuitively plausible way. It also puts us right at the centre of the cosmos, a view which fits nicely with the theological doctrine that we are the favoured creations of God. However, as a program in natural philosophy, by the 14th and 15th century Aristotelianism had also largely stagnated. On many fronts our understanding of the natural world had made little real progress in centuries. Those who believed radical progress was both desirable and possible—people such as Bacon, Galileo, Hobbes, Boyle, Kepler, Descartes and Newton—also recognized that a necessary first step was the overthrow Aristotelian physics. The full story of "The Scientific Revolution" is a highly complex one, extending as it does over several centuries, and involving a great many thinkers—some famous, many forgotten—operating in different traditions (and in different countries). I will confine myself to outlining just a few key developments that are particularly relevant to the role of force in science as it evolved during this period.

In his recent *The Swerve: How the World Became Modern* (2011) Stephen Greenblatt describes how the discovery of a copy of Lucretius' *On the Nature of Things* in the 15th century led to the rediscovery of ancient Greek atomism. Inspired by the mechanistic vision of Lucretius, natural philosophers such as Gassendi, Descartes, Galileo, Hobbes and Boyle all sought—albeit in differing ways—to explain the totality of natural phenomena in terms of matter, motion and natural laws. Regarding the nature of matter they followed they generally followed in the footsteps of Democritus and Lucretius: matter is composed of invisibly small impenetrable atoms, possessing only geometric properties such as shape and size. In so confining their explanatory resources these advocates of the new "mechanistic" or "corpuscularian" worldview were consciously rejecting key elements then-dominant Aristotelian system. In the new scheme of things appealing to animating forms or the doctrine of natural places was no longer an option.

Robert Boyle was a robust defender of the corpuscularian philosophy and the experimental method. In understanding how a lock or a clock functions, we need appeal to nothing more than the constituent parts they possess, the way these are fitted together, and the way they move. What applies to locks and clocks applies to all physical things: they are mechanical in nature. It was a mistake, argued Boyle, to attempt to base scientific theories solely on a priori metaphysical theories.

First comes the gathering of empirical data, and theories developed to explain the data should be put to experimental test. His own laboratory work on compressing gasses in tubes led to the discovery of what became known as Boyle's law for ideal gases (or $PV = k$), which states that the pressure of a gas tends to increase as the volume it is contained within decreases.

Prior to Newton, the most impressive and ambitious theory of the world in the corpuscularian tradition was due to Descartes. Although the latter is now best known for his purely philosophical works, during his lifetime he devoted the bulk of his intellectual efforts to mathematics and physics—and in the eyes of some he has as much claim to be the originator of modern physics as Newton.[3] All the essentials of Cartesian physics had been developed by the time Descartes completed *Le Monde* in 1633. When he learned of Galileo's troubles with the inquisition he decided to withdraw *Le Monde* from publication—perhaps wisely, since in it he reveals a commitment to the sun-centred Copernican view of the cosmos, and discards Aristotelian heliocentrism. Most of *Le Monde*'s doctrines resurfaced in Descartes' posthumously published *Principles of Philosophy* (1644).

These days Descartes is probably most famous for his mind-body dualism. He argued that by virtue of differing in their essential natures, mental and physical phenomena exist, in effect, in two entirely separate universes. One consequence of this dualism—presumably not a coincidence—is that the physical realm is entirely free from any lingering trace of mind, spirit or animating Aristotelian forms. Other proponents of the mechanical world-view were not so rigourous: Gassendi, for example, despite being an atomist also found it necessary to bring in something akin to Aristotelian forms to account for the differences between living and non-living matter. Descartes was determined to extend the mechanical model to matter in all its forms, and viewed—to the horror of some of his contemporaries—animals as mere machines.

For Descartes the essence of matter is simply spatial extension: "the extension in length, breadth, and depth which constitutes the space occupied by a body, is exactly the same as that which constitutes the body" (*Principles* II, 10). If matter simply *is* space, it makes no sense to suppose that one could remove all the matter from the inside of a bottle (say) and leave a region of empty space (or vacuum or void) behind. Like Aristotle before him, Descartes rejected the possibility of a true void. Descartes also followed Aristotle in holding that matter is in principle infinitely divisible. However, he also believed that matter often takes the form of relatively stable and long-lasting small particles, and it from these particles that macroscopic objects are constructed. These particles also come in different shapes and sizes: the smallest and faster-moving particles constitute fire and flames, the larger ones constitute larger bodies such as tables, chairs and planets.

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[3] As one commentator puts it: "While nearly all of Descartes' physics is wrong in detail, his grand attempt is the beginning of theory in the modern sense" Truesdell (1984, 6).

If the universe is a fully-filled plenum is motion even possible? It is, provided the particles surrounding a mobile body are themselves free to move. Of course, as Descartes realized, the displaced particles will themselves need to be able to move, and this will only be possible if the particles in front of *them* are free to move as well, and so on ad infinitum. One way for this to occur—a way which opens the door to dynamic structures that are also comparatively stable—is for moving particles to form continuous circular and spherical matter-streams. Descartes developed a sophisticated cosmology on precisely this basis: he held that the universe consists of vast spinning vortices centred on stars. These vortices carry the planets in our solar system around our sun, and are also responsible for gravitational effects. The Earth's rotation generates a centripetal force directed away from the centre of the planet, which—if left unchecked—would hurl us off the Earth's surface. Fortunately for us the Earth is surrounded by a slowly rotating ethereal matter-field, and the downward pressure from this cancels the outwardly directed centripetal force.

Descartes' laws of motion were particularly influential on future physics. The first tells us that "each thing, as far as is in its power, always remains in the same state; and that consequently, when it is once moved, it always continues to move" (Pr II 37), while the second holds that "all movement is, of itself, along straight lines" (Pr II 3). While these laws may look familiar to contemporary eyes—not least because Newton's first law incorporates them both—to Descartes' contemporaries they were innovative. For Aristotelians, natural motion is along circular paths; this is why the planets stick to their orbits. For Descartes natural motion is straight-line motion. Natural philosophers had previously assumed that rest was more natural than motion, and that moving objects would come to a stop unless something keeps on pushing them. For Descartes motion and rest are equally natural properties; once an object is set in motion it will keep on moving in the same direction forever unless something stops it—after the initial push no further force is needed. Descartes third law describes what happens when material bodies come into contact: "a body, upon coming in contact with a stronger one, loses none of its motion; but that, upon coming in contact with a weaker one, it loses as much as it transfers to that weaker body" (Pr II 40). Descartes here anticipates later energy-conservation principles. The total *quantity of motion* in the universe is fixed, and is invariably preserved in collisions. For Descartes an object's "quantity of motion" is a function of its size (in the guise of volume) and speed. If, as he held, spatial extension and mass are identical, an objects mass is necessarily determined solely by its size.

Cartesian physics is remarkable in several respects. It is highly ambitious, aiming as it does to explain all physical phenomena in terms of a small number of basic principles. It is also highly economical in the resources it draws upon. By reducing the physical world to matter (construed as extension) and motion Descartes' cosmos is free from *forces*. He makes clear in the *Principles* that he does "not accept or desire any other principle in physics that in geometry or abstract mathematics, because all the phenomena of nature may be explained by their means, and a sure demonstration can be given of them."

Newton on Gravity

Although the Cartesian version of the corpuscular programme would continue to find adherents well into the 17th century, the history of physics was about to take a different turn, one that was significantly less hostile to natural forces.

Newton's *Philosophiae Naturalis Principia Mathematica* was first published in 1687, and immediately recognized as a monumental advance. Newton's mechanics is still in use today, as is the calculus—the mathematical innovation which Newton used to calculate rates of change. His theory of universal gravitation allowed him to predict the movements of planets and comets with unprecedented accuracy—as well as explaining why the orbits of planets have elliptical rather than circular orbits. He also made important contributions to optics. As Julian Barbour puts it: "So comprehensive was his genius, it appeared to open all doors into nature, to leave nothing really major to discover. Life after Newton seemed a mere walking through the garden into which his genius had directed us" (1989, 629). We will be focusing here on just one element in this garden—but for present purposes it is the most significant.

In its essentials, Newton's theory of gravity is simple to state: every object in the universe exerts an attractive force on every other object in the universe, no matter how distant. The precise magnitude of this force is directly proportional to the mass of the bodies and inversely proportional to the square of the distance between them—so the more massive the bodies the stronger the force of attraction pulling on them, and the farther apart the bodies are, the weaker the force. In formulating this theory Newton rejected Descartes' purely volumetric conception of mass. For Newton similarly sized objects can differ in mass by virtue of possessing different densities (or "quantities of matter").

Newton's gravitational influence operates instantaneously. Consequently, if the sun were suddenly to vanish (let's not inquire how or why), every object in the universe—no matter how distant—would immediately be affected: the gravitational pull that had hitherto been exerted by the sun would no longer be felt. For similar reasons, every time you raise (say) your right arm, *you* are causing an instantaneous change—very small, but nonetheless real and quantifiable—in every portion of matter in the most distant galaxies.

This is remarkable enough in itself. It can seem almost magical: if Newton's theory is correct, everything in the universe is invisibly (but not intangibly) connected to everything else. But the *kind* of connection we are dealing with here is also very distinctive. On the face of it at least, Newton's gravitational force looks to be acting directly across space, with no intervening or mediating factors. It has all the characteristics of what is known as an action at a distance force. Hence the problem: if proponents of the new mechanical world-view and their Aristotelian predecessors agreed on anything, it was that forces or connections of this kind have no role to play in legitimate science. Following in Aristotle's footsteps Aquinas encapsulated this position nicely: "matter cannot act where it is not". For Descartes, as we have seen, all motion is produced by contact. Hobbes agreed: "There can be no cause of motion except in a body contiguous and moved …" (*De Corpore*, 1655, ix para 7). As did Locke in the first three editions of his *Essay*: "How bodies operate on one another … is manifestly by impulse and nothing else. It being impossible to conceive that body should operate on *what it does not touch*" (1689, II, viii, 11).

Newton himself was well aware that his theory of universal gravitation was radical, and bound to prove controversial. His writings clearly reveal that he would much preferred to have found a mechanical explanation of some sort for gravity—one relying on an intervening aether in the manner of Descartes, for example. But despite much effort and many attempts he had been unable to find a viable model along these lines. Consequently, while endorsing the action at a distance model Newton opted to remain neutral on the mechanism (if any) underlying gravitational attraction. In Book 1 (§11) of the *Principia* he tells us:

> I have not as yet been able to deduce from phenomena the reason for these properties of gravity, and I do not feign hypotheses. For whatever is not deduced from the phenomena must be called a hypothesis; and hypotheses, whether metaphysical or physical, or based on occult qualities, or mechanical, have no place in experimental philosophy.
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> …. The impenetrability, mobility, and impetus of bodies and the laws of motion and law of gravity have been found by this method. And it is enough that gravity should really exist and should act according to the laws that we have set forth and should suffice for all the motions of the heavenly bodies and of our sea.

So far as the reception of the new theory among his contemporaries was concerned, Newton's fears were not misplaced: initially at least, many *did* find the notion of an action at a distance acting across any and all distances difficult to accept. Leibniz, who independently discovered the calculus at around the same time as Newton, fully recognised that Newton's theory was an impressive advance over Descartes'. Nonetheless, he firmly rejected action at a distance, remarking in a letter to Clarke: "That means of communication (says he) is invisible, intangible, not mechanical. He might as well have added, inexplicable, unintelligible, precarious, groundless and unexampled … 'Tis a chimerical thing, a scholastic occult quantity" (Alexander 1955, 162).

However, in the decades to come the hostility to action at a distance gradually faded. Although many mechanical models of a gravitational force which avoided appealing to action at a distance were proposed and investigated, they all proved inadequate. Consequently, it was not very long before most physicists accepted that the universe *was* in fact as Newton had reluctantly proposed: bound together by an invisible, all-penetrating force, acting both instantaneously and without intermediaries.

Dynamism

Leibniz may have been hostile to forces acting at a distance, but he was by no means hostile to forces per se. In fact, he was one of the leading 17th century advocates of the new *dynamic* conception of matter. During the early phases of the scientific revolution the corpuscularian mechanical theorists construed atoms in essentially the same way as Democritus and Lucretius: their only properties were size, shape and impenetrability. It is by virtue of being impenetrable that moving atoms bounce off one another after colliding, and for the atomists impenetrability was taken to be a primitive and unexplainable property. Leibniz found this wholly passive conception of matter problematic on a number of fronts.

For Descartes and Newton when a particle is moving inertially—i.e. when not subject to any external forces—it will continue to move in a straight line forever. The object's continuing to move is not grounded in any inherent capacity or power possessed by the object. For Leibniz even inertial motion should be viewed as essentially involving a force or power, a mode of activity whose manifestation is simply the object's *continuing on* moving. (In his later writings it becomes clear that this active power is what we now call *kinetic energy*.)

Leibniz also argued that collisions between classical atoms were profoundly problematic. These atoms were standardly construed as being totally rigid and incompressible. When one incompressible and inelastic atom strikes another, both will undergo an *instantaneous* change in direction. If, as Newton and Leibniz both believed, forces are proportional to accelerations then we immediately encounter a problem: an instantaneous acceleration is an infinite acceleration, requiring infinite forces. We can avoid this difficulty, suggested Leibniz, by construing atoms as point-like particles surrounded by short-range spheres of repulsive forces. When moving particles approach one another these repulsive forces *gradually* slows them down and the particles never actually come into contact. If we willing to acknowledge the existence of compressible repulsive forces inter-atomic collisions are no longer problematic.

In his 1699 *Confessions of Nature* Leibniz pointed out that orthodox atomists had a problem explaining how atoms manage to stick together to constitute compound objects such as table and chairs:

> … Democritus, Leucippus, Epicurus, and Lucretius of old, and their modern followers … asserted that the whole cause of cohesion in bodies may be interweaving of certain shapes such as hooks, crooks, rings projections, and, in short, all the curves and twists of hard bodies inserted into each other. But these interlocking instruments themselves must be hard and tenacious in order to do their work of holding together the parts of bodies. Whence this tenacity? Must we assume hooks on hooks to infinity?

The alternative dynamical solution is to hold that atoms possess both repulsive and *attractive* forces, operating at different strengths at different distances. A theory along these lines was elaborated in considerable detail by Roger Boscovich in his *Theory of Natural Philosophy, Reduced to the Single Law of the Forces existing in Nature* (1758). Boscovich proposed that a strong repulsive action at a distance force operated over very short distances whereas particles separated by very large distances particles were attracted by a force accurately described by Newton's law of gravity. He also held that additional attractive and repulsive forces operated at small scales—albeit at progressively different distances—and hoped to explain phenomena such as cohesion, evaporation and fermentation by appealing to them.

Since Boscovich envisaged these forces as inhering in spatial points—rather than material atoms of any kind—he, in effect, reduces the physical world to a dynamic spatially extended field of force.

Greatly impressed by Newton's achievement in accounting for gravity Kant showed none of Newton's own hesitation in accepting action at a distance—he unhesitatingly endorsed it throughout his career (Friedman 1992, p. 1). In publications spanning several decades Kant sought ways of accomodating Newton's innovations with his own evolving philosophical doctrines, and was ultimately led —in his *Metaphysical Foundations of Natural Science* (1786)—to adopt a position similar in some respects to that espoused by Boscovich. In his early *Thoughts on the True Estimation of Living Forces* (1747) Kant claims:

> There would be no space and no extension, if substances had not force whereby they act outside themselves. For without a force of this kind there is no connection, without this connection no order, and without this order no space.

In making material substances and forces central Kant is evidently working within a Newtonian framework, but Newton held that causally interacting physical objects exist within an all-embracing substantival space. In claiming that space is not foundational or primitive, but a product of the connections between objects generated by forces—which was his intent here—Kant is going well beyond Newton. Kant goes on to make the provocative and intriguing suggestion that force is responsible for the dimensionality of reality: "It is probable that the threefold dimension of space is due to the law according to which the forces in the substances act upon one another."

In his *Physical Monadology* (1756) Kant firmly rejects the passive matter of the corpuscularians. He claims that impenetrability is not a primitive inexplicable feature of matter, but essentially involves an active cause in the form of an action at distance repulsive force. He goes on to argue that a force of attraction must also exist between objects, for if it didn't the material contents of the universe would be dispersed to infinity by the action of the repulsive force. It is the interaction between these attractive and repulsive forces which determines the boundaries of material bodies.

These claims are reiterated and developed more fully in the later *Metaphysical Foundations*. His proposition 7 is a resounding endorsement of action at a distance: "The attraction essential to all matter is an immediate action through empty space of one matter upon another." Kant goes on to defend action at a distance forces from the objection "that matter cannot act *where it is not*". Far from being a contradiction this is a truism: *everything* that has an effect on something else is acting where it is not, and this includes a billiard ball that induces another ball to move by colliding with it. In his *Physical Monadology* Kant had taken the fundamental constituents of matter to be point-like material substances, surrounded by a sphere of repulsive force emanating from the material points. This picture is rejected in the *Foundations*. The defining characteristic of matter is impenetrability—a portion of matter *just is* an impenetrable region of space—and for Kant impenetrability is created by an expansive or repulsive force. Consequently, a region that is pervaded by a repulsive force is thereby pervaded by *matter* as well. In which case, the *Monadology* view, and its distinction between material points and force-filled regions of space is simply incoherent. On Kant new view matter is a continuum *every point of which* exerts an expansive force on its surroundings, or as Kant puts it: "… every part of it contains repulsive force, so as to counteract all the rest in all directions, and thus to repel them and to be repelled by them".[4]

Maxwell, Einstein and the Vindication of Locality

In advocating a wholly force-based account of matter, and taking the universe to be entirely pervaded by forces, Kant was in certain respects anticipating the "field theories" which would be developed in the 19th century, most notably by Faraday and Maxwell in their investigations into electricity and magnetism. However, as we shall see the fields advocated by Faraday and Maxwell differ in one key respect from those proposed by Kant. So far as the nature of forces, and the ways they propagate through the physical world, this difference will prove very significant.

In 1820 Oersted's observed that variations in the current flowing through a wire will cause a compass needle to alter its direction; his subsequent discovery that a wire carrying a current acts as a magnet confirmed that magnetism and electricity are closely connected. Although a number of scientists had suspected as much, Oersted's results triggered a period of increased interest in electromagnetic phenomena, and the most extensive and impressive of these investigations were carried out by Michael Faraday. The latter's *Experimental Researches in Electricity*, published in 1844, brought together many of his results, which included the discovery of induction, the fact that current can be generated in a wire by moving a magnet in the wire's proximity—the vast bulk of the world's electricity is now produced by generators working on precisely this principle. Faraday was fond of carrying out a simple experiment: if you spread iron filings over a sheet of paper, and place a magnet under the sheet, a pattern similar to the one depicted in Fig. 11.1 will result. The manner in which such patterns come into being inspired Faraday's conviction that electricity and magnetism were caused by stresses and strains in a space-pervading invisible aether, transmitted (very probably) at a finite speed.

In a diary entry in 1845 Faraday used for the first time the term "field" in this connection, but he had previously used formulations such as "lines of magnetic force" or "magnetic curves":

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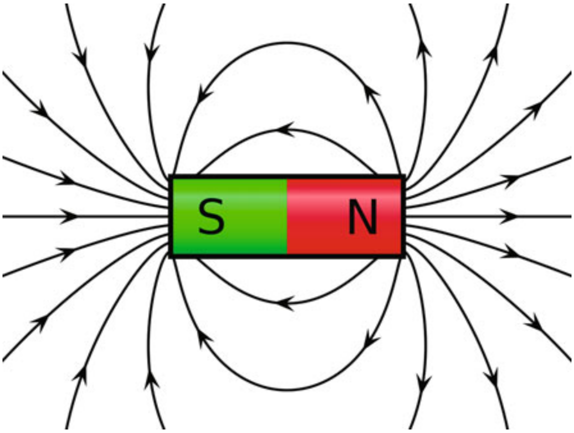
[4] Kant (1994, 503); for more on Kant's view of matter in the *Metaphysical Foundations* see Michael Friedman (1992, 2013).

Fig. 11.1 Magnetic "lines of force" extending through the space surrounding a magnet



> I will now endeavour to consider what the influence is which paramagnetic and diamagnetic bodies, viewed as conductors, exert upon the lines of force in a magnetic field. Any portion of space traversed by lines of magnetic power may be taken as such a field, and there is probably no space without them. The condition of the field may vary in intensity of power from place to place, either along the lines or across them … and I have formerly described how this may, for a certain limited space, be produced.

If you look at a magnet surrounded by empty space you will not see anything resembling these lines of force emerging from it, but for Faraday they were nonetheless present, as real and *powerful* physical phenomena in their own right.

The task of devising a mathematical framework capable of accomodating Faraday's field conception and the diverse experimental results concerning electromagnetic phenomena that had by now accumulated fell to James Clerk Maxwell, who succeeded brilliantly. The essentials of Maxwell's comprehensive new theory of electromagnetism were presented in a series of papers which appeared between 1661 and 1665. One particular discovery of Maxwell's stands out. Maxwell's equations captured the manner in which changing magnetic fields give rise to changing electrical fields in their vicinity, and vice versa. Maxwell realized that this mode of interaction would give rise to a self-sustaining and self-propagating wave phenomenon in the electromagnetic field. By drawing on already known results concerning the basic properties of electricity and magnetism Maxwell was able to calculate from first principles the expected velocity of this wave: it turned out to coincide almost exactly with current estimates of the speed of light in a vacuum. Maxwell did not shy from drawing the obvious but nonetheless remarkable conclusion: light *is* a form of electromagnetic radiation. Although Maxwell appreciated that it was likely that only a small part of the electromagnetic spectrum would be constituted by visible light in his *Treatise* he provided no indications as to how go generate higher and lower frequency waves. It was not long before other scientists were attempting to do just this, and Hertz became the first person to transmit and receive radio waves in a series of experiments conducted between 1886 and 1889. The rest is history.[5]

At first glance the electromagnetic forces introduced by Faraday and Maxwell may appear to be similar to Newton's gravitational force: both are invisible, both extend through seemingly empty space. However, they are in fact profoundly different in character: whereas a force as envisioned by Newton and Kant directly connects spatially distant objects, electromagnetic forces always act *locally*: they have to pass *through* the regions of space separating objects they influence. According to Faraday and Maxwell, a magnet creates a pattern among iron filings because it generates a spatially continuous field which unfolds at a finite speed through nearby space—it may operate over a distance, but it does not act at a distance. As this passage from the preface to Maxwell's *Treatise* makes clear, they were well aware of their divergence from the Newtonian conception of gravitational force:

> Faraday in his mind's eye saw lines of force traversing all space where the mathematicians saw centres of force attracting at a distance: Faraday saw a medium where they saw nothing but distance: Faraday sought the seat of the phenomena in real actions going on in the medium, they were satisfied that they had found it in a power of action at a distance impressed on the electric fluids. (1954, Vol 1, p. ix)[6]

Irrespective of its other merits, the new theory of electromagnetism was not vulnerable to the criticism that it relies on forces of an occult or magical kind—the criticisms levelled at Newton's action at a distance gravitational theory when it first appeared.

Although, not surprisingly, Maxwell's account of light was soon widely accepted by physicists, it also gave rise to a serious difficulty. One of the foundation stones of classical physics is that the laws of nature are blind to uniform straight line velocities. Experiments conducted in a laboratory on a moving train will produce exactly the same results as the same experiments conducted in a stationary laboratory; as Galileo and Newton realized, this is the reason why the Earth's motion around the sun is not obvious to those of us confined to the surface of the planet. If Maxwell was right, and the speed of light is a consequence of basic physical laws, then anyone measuring the speed of light-beam should always get the same result—299,792 km/s—no matter what their own state of motion is. But this too seems

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[5] As Richard Feynman put it in the second volume of his *Lectures on Physics*: "From a long view of the history of mankind—seen from, say, ten thousand years from now—there can be little doubt that the most significant event of the 19th century will be judged as Maxwell's discovery of the laws of electrodynamics. The American Civil War will pale into insignificance in comparison with this important scientific event of the same decade."

[6] By "the mathematicians" Maxwell is referring here to theorists in Germany and France, such Weber, Gauss and Ampere who construed electrical and magnetic forces in a Newtonian action at a distance fashion. Maxwell returned to this theme in the concluding paragraph of his *Treatise*, where he observes "In fact, whenever energy is transmitted from one body to another in time, there must be a medium or substance in which the energy exists after it leaves one body and before it reaches the other …" (1954 Vol. II, 493).

bizarre, both by the standards of common sense and classical physics. According to the latter, if a beam is measured as travelling at 299,792 km/s by a scientists who is stationary (with respect to the Earth), then a scientist on a train who measures the speed of the same beam but who is travelling at 50,000 km/s in the opposite direction to the beam should find that the latter is travelling at 349,000 km/s.

It seems something has to go: either Newton's classical mechanics doesn't apply to light (and other forms of electromagnetic radiation) or the speed of light cannot be a basic physical constant.

A compelling solution to this conundrum was put forward in 1905 by Einstein, in the guise of his Special Theory of Relativity (STR). According to the latter, the speed of light *is* a basic physical constant, and has the same value for all observers, irrespective of their state of motion. To make sense of this, Einstein proposed that observers moving relative to one another will measure time and space differently, e.g. if you are moving relative to me then time (as measured by clocks and your body) will pass more slowly, events which are simultaneous for me will *not* be simultaneous for you. In more general terms, subjects who are moving at a constant speed relative to one another will possess their own "frames of reference"; each of these frames of reference will divide spatial and temporal intervals differently, and —crucially—all these frames of reference are equally valid. So from my perspective two events E1 and E2 might be simultaneous, but from yours these same to events will *not* be simultaneous, and both perspectives are equally legitimate.

It didn't take long for the full metaphysical implications of STR to emerge. In September 1908 Hermann Minkowski—one of Einstein's maths teachers at the Zurich polytechnic—began his talk to an assembly of German mathematicians and scientists thus: "The views of space and time which I wish to lay before you have sprung from the soil of experimental physics, and therein lies their strength. They are radical. Henceforth space by itself, and time by itself, are doomed to fade away into mere shadows, and only a union of the two will preserve and independent reality" (1954, 75–91). The union of the two that Minkowski went onto propose took the form of a four-dimensional spacetime continuum. Within this continuum there is no privileged universe-wide present, and all spatio-temporal locations are fully and equally real—those lying in the future included. Persisting objects—just as lumps of rock or human bodies—are themselves four-dimensional objects, existing as worldlines (or collections of such) embedded in the four-dimensional spacetime continuum. It is only because all times are real that different inertial reference frames can generate different but equally valid ways of dividing events up between past, present and future. What would soon become known as "Minkowski spacetime" would also became the standard way of interpreting STR in physics.

As Einstein was well aware, the relativization of simultaneity does not sit easily with Newton's account of gravity. For Newton, as we have seen, gravity is an action at a distance force that directly connect every object in the universe. Moreover it is a force which operates *instantaneously*, there being no delay between gravitational causes and effects. If simultaneity is relative in the way Einstein proposed, then events which are simultaneous—and so related by Newton's gravitational forces—in one frame of reference will not be simultaneous in others. Clearly, a new theory of gravity was required, one which did not require instantaneous interactions.

It took Einstein a decade of hard work to devise a new account of gravity, in the guise of his General Theory of Relativity (GTR), which made its first appearance in 1915. Einstein's key move was radical: he solved the problem posed by Newton's gravitational force by abolishing it entirely. According to GTR gravity is not a *force* at all: material objects under the influence of gravity do not attract one another. Instead, a massive body such as the sun or a planet creates a spatiotemporal distortion in its vicinity. For a useful (if only partial) analogy think of the way in which a heavy iron ball will produce a curved region in a previously flat rubber sheet or mattress on which it is placed. In a similar fashion, a massive body will induce curvature in the surrounding region of four-dimensional spacetime, an effect that lessens with distance—just as with Newton's gravitational force. In the absence of significant mass a region of spacetime will be entirely flat—just like a mattress.

According to Einstein, the gravitational effects that were previously attributed to the effects of a force are the products spacetime curvature. In GTR the principle of inertial motion advocated by Descartes and Newton is fully retained: objects that are not subject to any external forces will continue to move in a straight line, at the same speed, forever. However, when we are dealing with curved spaces what counts as a "straight line" is not as straightforward as is the case in flat space. In a flat space a straight line in the familiar Euclidean sense—a line with no bends or curves—will also be the shortest distance between two points it connects. In many curved spaces there are no straight lines in the Euclidean sense at all. If for example we take as an example of a curved space the surface of a sphere, then all the lines in such a space will be curved. Even so, in such a space it remains the case that for any two spatially separated points some connecting lines will be longer than others—e.g. a line stretching straight down from the north pole to a point on the equator will be shorter than a windy "S" shaped line between the same two points. There are also paths of shortest distance in four-dimensional spacetime—though inevitably these are harder to visualize—and according to GTR objects that are falling freely (i.e. which are not subject to any forces) will follow these paths of shortest distance. This is precisely what the planets are doing when they orbit the sun—and similarly for an apple that falls from a tree.

Although Einstein's GTR and the Newton's theory of gravity make very nearly the same predictions in most ordinary circumstances, there are some divergences, and in all such cases Einstein has invariably triumphed over Newton. An early instance was Einstein's prediction that starlight travelling towards the Earth should be deflected by 1.75 arc seconds due to the spacetime curvature created by the sun —a tiny but still measurable amount—a prediction which made the headlines when it was experimentally confirmed by Eddington in 1919. More recently, in 2016 the discovery by LIGO (the Laser Interferometer Gravitational-Wave Observatory) of the existence of gravitational waves—predicted by GTR but hitherto unobserved—also made headlines around the world. Gravitational waves are ripples in the fabric spacetime; those detected by LIGO are thought to originate in the collision between two massive black holes—enigmatic entities whose existence was also predicted by GTR.[7]

Time, Dimensions and Causes

In his *Treatise of Human Nature* (1739) and *Enquiries Concerning Human Understanding* (1748) the philosopher David Hume set out to undermine our common sense beliefs concerning the nature of causation. When we see a moving pool ball strike a stationary one, and the stationary one moves off—perhaps going into a pocket, perhaps not—we are naturally inclined to think that the first ball *made* the second move. Causal interactions such as these are not just a matter of one event being followed by a second, they involve a kind of necessitation: given the first event, the second *had* to happen. As Hume realized, the idea that causation involves necessitation naturally extends to the way we think of natural laws—indeed it largely explains why we talk of "laws" at all. In Newtonian mechanics, for example, it's natural to think that objects fall under the influence of gravity because they *are made to*—by the attractive force of gravity. The laws of nature don't just reflect regularities in how objects behave and interact, they *govern* the movements of objects.

This way of thinking may come very naturally to us, but it is unjustified—or so Hume argued. Think again of what precisely you see when you watch two pool balls collide. Do you really see one ball *making* the other ball move? Or merely one ball moving until it comes into contact with the other, and the other ball moving off? Surely only the latter, Hume urged—and the same applies for all the causal interactions we observe. We are inclined to think the first ball *makes* the second move only because we have perceived lots of similar interactions in the past. In such situations the second ball always moves away when hit by the first, and so in the current case we *expect* the second ball to move—and this expectation is the source of our conviction that the ball in question *has* to move when struck. When we combine this analysis of why we tend to think causation involves necessitation with the fact that we never actually observe any necessitation, we should conclude—or so Hume argued—that causal necessitation does not actually exist in the world, it is simply projected into the world by us. All that exists in the world are certain patterns of events—regular successions, as Humeans call them—and to the

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[7] See Dainton (2010) for a more detailed introduction to Einstein's relativity theories.

extent that laws of nature exist in the world they consist of nothing more than these regular successions.[8]

Quite what stance Hume really adopted viz a vis causation remains controversial, but the Humean doctrine that no trace of natural necessitation is to be found in nature is an influential one in contemporary metaphysics. Indeed it enjoys a good deal more popularity now than it did in the 18th and 19th centuries—it was not for nothing that Hume complained of his *Treatise* falling "dead-born from the press, without reaching such distinction as even to excite a murmur among the zealots".

In comprehending why so many of Hume's contemporaries found his causal scepticism difficult to take seriously it is illuminating to consider an imaginary game or pastime. You have in front of you a photograph of Leonardo's *Mona Lisa*. Your task is to construct a metre square representation of this famous work using nothing more than 1 cm wide coloured toy building blocks, one row at a time, from the bottom up and from right to left. This is by no means an impossible task, provided you have enough bricks in the appropriate colours—and happily this is the case, you have more than enough bricks for the task at your disposal. There is however a twist: the rules of the game are quite specific when it comes to how you are to go about choosing which blocks to use. Each successive row of your construction will be composed of 100 blocks, and these have to be selected at random from a container containing tens of thousands of variously coloured blocks. To make matters still worse, once a block is placed in the frame destined to house your picture it is not permitted to remove and replace it with another block; its location is permanent. Needless to say, as you embark on your task you are not optimistic of success: your chances of replicating the *Mona Lisa* by this method are astronomically small.

In Hume's period—as in most others prior to our own—it was universally accepted that time differs from space because time *passes* or *flows* whereas space does not. What does the passage or flow of time involve? It can be characterized in a variety of ways, but there are two key ingredients. First, there is the claim that the present time is metaphysically privileged: perhaps only present events are real, perhaps they are real in a way that past events are not. The second thesis is the seemingly self-evident truism that presence is transitory: what is happening *now* will soon not be happening now because the events in question will soon sink into the past.

For anyone who thinks about time in this common sense sort of way, it will be natural to assume the cosmos comes into existence only gradually, in a succession

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[8] In his analyses of Newton's mechanics in *De Motu* (1721) and *Siris* (1744) George Berkeley argues along similar lines to Hume: "Those who assert that active force, action, and the principle of motion are really in the bodies, maintain a doctrine that is based upon no experience, and support it by obscure and general terms, and do not themselves understand what they wish to say" (*De Motu*, §31). In his *Treatise* (§32) Berkeley observes that "When we perceive certain ideas of sense constantly followed by other ideas, and we know that his is not of our own doing, we forthwith attribute power and agency to the ideas themselves"—the relevant "ideas" here are (presumably) the objects of immediate perception.

of momentary universe-wide phases or layers, with each newly created present phase giving way to another as time passes. The process as we are now envisaging it is more fine-grained than the *Mona Lisa* game's, but metaphysically it is analogous. And precisely the same potential problem arises. As we have just seen in the imaginary *Mona Lisa* case, in the absence of tight constraints on the elements chosen for each successive line of blocks, the result will almost certainly be total anarchy: a picture without recognizable forms or patterns. The same applies in the case of the real universe. If *it* were to come into being in a succession of phases or layers, in the absence of tight constraints on the contents of new layers the odds are astronomically high that the result will be utter chaos. Since our world is not chaotic —at least in the extreme sense that is relevant here—we have no reasonable option but to conclude that the process of phase-creation is a tightly constrained one.

It also seems reasonable to conclude that it was considerations along these lines which—in part at least—made it difficult for Hume's contemporaries to take his causal scepticism seriously. In this period the idea that time flows was not seriously questioned. Newton, for example, in the *Principia's* Scholium writes: "Absolute, true and mathematical time, in and of itself and of its own nature, flows uniformly and by another name is called duration."[9] True, in this period many would have followed Descartes in supposing that an all-powerful and benevolent God is directly responsible for re-creating the world instantaneously from moment to moment, which makes the orderliness of the universe a product of divine choice. But the increasing numbers of philosophers and scientists in the 18th and 19th centuries who were reluctant to grant God any overt role in their theories an alternative source of natural order had to be found. A very natural alternative—almost unavoidable in the circumstances—is to take the required constraints to be located *in material world itself*, whether in the guise of universe-wide natural laws to which all physical processes conform, or inherent causal powers that reside in and determine the behaviour of material things.[10]

These days, as we saw in the previous section, thanks to Einstein's relativity theories the majority of physicists assume that our universe takes the form of a four-dimensional spacetime. In such a universe there is no ontological difference between past, present and future: all objects and events are equally real, there is no temporal passage and no privileged present. As a consequence such a universe cannot *come into being* in a succession of momentary phases, in the way that Descartes believed. If the universe comes into being at all—as opposed to existing eternally, an issue which remains unresolved in contemporary cosmology—it can only do so *as a whole*, with past, present and future all being created together.

When we conceive of the universe in this four-dimensional manner the need to explain why chaos is avoided as new slices of reality enter existence simply

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[9] Newton was by no means alone. For example in the first *Critique* Kant observes that "space alone is determined as permanent, but time, and thus everything in inner sense, continually flows" (B291).

[10] For some contemporary arguments along these lines see Foster (1982) and Strawson (1982).

vanishes: on the four-dimensional view there are no new slices of reality being created moment-by-moment. If future happenings are already fully real, it makes no sense to suppose that causes bring their effects into being—causes and their effects are both (timelessly) parts of the four-dimensional manifold of events. Holding that law-like regularities are underpinned by a necessary connection of some kind may still be an option, but since positing such a connection lacks any real explanatory value it looks to be redundant. As a consequence a powerful consideration which undermined the case for the Humean regularity view of causation itself vanishes.[11]

If this is not the entire rationale for why the Humean view is taken more seriously than was the case pre-Einstein, it may well be a significant part of it.

Quantum Theory

Quantum theory, currently our best theory of the micro-realm, emerged only gradually in the first three decades of the 20th century. The theory defies easy summary, and remains mired in controversy: there is a still-expanding number of "interpretations" of the theory, each providing very different accounts of what quantum mechanics truly implies about the nature of physical reality. We will focusing here on some of the more obvious implications concerning the nature of physical interactions and causation.

The development of quantum theory was initially triggered by a cluster of puzzling discoveries concerning the behaviour of light and other forms of radiation, and the structure and composition of atoms. The first step took place in 1900 when Planck solved baffling puzzle concerning so-called "black-body" radiation by positing that energy-levels did not form a continuum—as generally assumed hitherto—but rather came in multiples of a very (very) small unit, or *quantum*. In 1905 Einstein successfully resolved a puzzle concerning the photoelectric effect by arguing that rays of light are composed of discrete quanta as well—the particles which would soon be called *photons*. But while the considerations advanced by Einstein for taking light to be composed of particles were very plausible, there remained powerful reasons for supposing that light must also have a *wave*-like nature. Even before the advent of Maxwell's theory, the two-slit experiment devised by Thomas Young in 1801 showed that light-rays produce interference patterns very similar to those produced by water waves—see Fig. 11.2.

This was all very baffling: how can anything be both a wave and a particle? It was not until the 1920s, with the breakthroughs of Heisenberg and Schrödinger, that the new quantum mechanics was put on a solid mathematical footing. The equation proposed by Schrödinger doesn't (directly) tell us how a particle—an

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[11] In his more recent (2012, 5–6), while Strawson acknowledges that adopting a four-dimensional conception of spacetime requires a re-conceptualization of causation and natural laws, he argues that natural necessity—of a sort—does still have a role to play in the new temporal context.

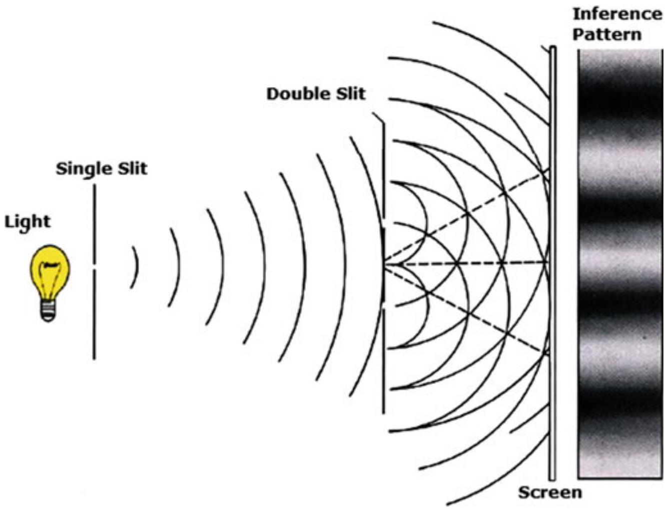

Fig. 11.2 Thomas Young's double slit experiment

electron, say—behaves, but rather how a wave evolves over time. Schrödinger's waves are unlike water or sound waves by virtue of extending through all of space, but just as with classical waves they associate certain numerical values with specific spatial locations. These numbers don't tell us anything definite; they supply only the *probability* that a particle will be detected at a particular location, or possess a certain momentum—if we happen to measure it. Prior to a measurement of position or momentum all the different possibilities and probabilities exist in a "superposition" and the particle does not have a definite position or momentum at all. The measurement process is said to *collapse* the wave function. Or at least this is how things stand on the orthodox (or "Copenhagen") interpretation of quantum mechanics, which is still to be found in textbooks—though there are alternatives, as we shall see shortly.[12]

Earlier classical physics theories, most notably Newtonian mechanics, were entirely deterministic. In principle, if you were supplied with accurate data concerning the locations, masses velocities of all the particles in the universe you could

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[12] The wave function in quantum mechanics is fundamentally different in nature to the space-pervading waves found in classical theories such as Maxwell's electromagnetism. The wave function for a physical system exist in an abstract mathematical "Hilbert" space, which possesses 3N dimensions, where "N" is the number of particles in the system—since there are billions of atoms in a drop of water, the dimensionality of these Hilbert spaces will typically be very large indeed. If quantum mechanics provides a complete and correct account of physical reality at its most fundamental level, then if the wave function is the most basic ingredient in quantum theory, shouldn't we conclude that our universe in fact has 3N dimensions, where "N" stands for the number of particles in the universe? So called "wave function realists" argue for precisely this conclusion—for more on this debate see Ney and Albert (OUP 2013).

use Newton's equations of motion to predict precisely how the universe would evolve from that point in time till any point in the future. Since according to quantum theory a particle's wave function provides us with an exhaustive account of its physical properties, if the theory is true we have no option but to accept that at the atomic level reality is inherently probabilistic and indeterministic. Even if you knew everything there is to know about the distribution and motions of particles throughout the universe at one moment in time you would not be able to predict precisely what is going to happen over the next few seconds.

Empirical studies of the ways atomic- and sub-atomic particles such as electrons, photons, protons, neutrons behave all suggest that reality *is* indeterministic in precisely the way quantum mechanics predicts. If in a series of experiments high-energy protons are fired into the nuclei of a succession of wholly indistinguishable hydrogen atoms there is no unique outcome of these collisions, but rather a number of different outcomes, occurring with just the frequencies predicted by quantum mechanics.

If the micro-world is as indeterministic as it appears to be, there are obvious implications for our understanding of causation. So far as fundamental physical particle interactions are concerned, when an event E1 causes E2, it will never be the case that E1 *makes* E2 happen in the strong sense of "given that E1 occurred E2 *had* to happen, it was *necessary* that E2 occurred as well." It seems that causation at this level—if we assume it still exists in any form at all—must be viewed as inherently probabilistic rather than deterministic. For anyone accustomed to thinking of the world in a deterministic way, this will be a revisionary step.[13] However, on reflection is can easily seem to be a very natural one: smoking may do no more than *raise the probability* of one's getting cancer, but it can still count as *causing* cancer—or so most of us are prepared to accept. Partly in response to developments in quantum mechanics philosophers have developed a number of different probabilistic accounts of causation. One option, for example, is to holds that we can still regard particles as possessing causal powers, but these powers take the form of *probabilistic dispositions* to behave in certain ways in certain circumstances.[14]

It is by no means the case that all physicists are happy with the indeterministic world bequeathed to us by quantum mechanics as standardly construed—a disquiet Einstein famously expressed by claiming that God "does not play dice with the universe"[15] Given this, it is not surprising to find that alternative ways of making sense of the basic mathematical framework quantum mechanics have long been sought. Although some of these alternatives do restore determinacy after a fashion, they do so in ways which bring their own costs.

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[13] Hume appears to be in this category, given that in section VII of his *Enquiry* he offered this by way of a characterization of causation: "We may define a cause to be *an object*, *followed by another*, *and where all the objects similar to the first are followed by objects similar to the second*."

[14] See Popper (1990); for a survey of different approaches to probabilistic causation see Hitchcock (2010).

[15] Einstein made the remark in a letter to Max Born in 1926.

One of the more influential of the alternatives is the “de Broglie-Bohm approach”, first advanced by de Broglie in 1927, then later re-discovered and elaborated by Bohm in the early 1950s. According to this view, the standard form of quantum mechanics is incomplete: in addition to the wave function there is a quantum potential which acts as a “pilot wave” guiding particles along their trajectories. As a consequence, particles *always* have a quite definite location and velocity—something that is very much not the case under the Copenhagen interpretation. Since changes in one part of a physical system can instantaneously induce changes in the system’s entire pilot wave, which in turn affects how particles will move, the de Broglie-Bohm version of quantum theory is decidedly non-local: a system’s pilot wave might easily extend through very large regions of space, or even the whole universe. It is also important to note that the theory makes precisely the same empirical predictions as orthodox quantum theory—given the latter’s empirical success if it didn’t the de Broglie-Bohm approach would be unviable. Consequently, there remains a sense in which the behaviour of individual particles in a given context remains inherently probabilistic.

If interest in the de Broglie-Bohm approach has been on the rise in recent years, interest the *many-worlds* interpretation—based on Everett’s work in 1957—has soared, partly but not wholly because it is currently favoured is cosmological circles. According to the many worlds theorists there is no collapse of the wave function when a particle is detected by a piece measuring apparatus. Rather, *all* the many potential trajectories which have a finite probability in the particle’s wave function are in fact realized, albeit in different worlds (or sub-worlds) which branch off from this one. Although the many-worlds view certainly solves the problem of explaining how a piece of measuring equipment *can* provoke the collapse of a wave function, the ontologically profligate manner in which it does so renders it implausible in many people’s eyes. Even if we are prepared to overlook that issue, the many-worlds view restores determinacy in a novel (and disturbing) fashion: no possible outcome of a physical interaction *fails* to be realized.[16]

Quantum Strangeness

The two slit phenomenon provides a striking manifestation of the sheer *weirdness* of the realm of the quantum. In this experimental setup a source is able to emit particles—electrons, let’s suppose—either singly, or in great numbers *en masse*. The source is aimed at a detector screen, and whenever an individual electron strikes the screen it registers as a small but visible white dot. In between the source and the screen there is a metal barrier with two narrow vertical slits, which can be opened or closed independently by the experimenter. If both slits are open and

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[16] For more on the many worlds interpretation see Vaidman (2014). Lewis (2016) provides accessible introductions to several of the leading alternatives to the Copenhagen interpretation.

electrons from the source arrive at the two slits *en masse*, almost immediately an interference pattern—in the guise of alternating illuminated stripes each consisting of many white dots—will appear on the screen, in the manner depicted in Fig. 11.2.

Remarkably, if the settings for the source are changed, and electrons are emitted only one by one, an interference pattern is still created on the screen, it simply takes longer to appear since the electrons are now arriving singly rather than in large numbers. If, however, the experimenters makes another adjustment to the settings and closes one of the slits leaving the other open, a quite different pattern emerges on the screen. Under these conditions *no* interference pattern is created; instead the electrons create a circular cluster-patter on the region of the screen behind the open hole. The same result occurs if an experimenter places a detector at one or both of the slits, with a view to finding out which slit an electron is passing through.

Put yourself in the position of a particle that has only just been emitted by the source. On average, the trajectory that you will take towards the screen will differ depending on whether one or two slits are open in the intervening barrier. But how at this point—before you have even begun your journey towards the latter—do you know how many slits are open? How do you know whether or not there is a detector at one of the slits? The interference patterns formed by water or sound waves are a straightforward consequence of the combined interactions which take place between myriad simultaneously existing particles. Such a process obviously cannot explain the interference pattern which gradually builds up when electrons are emitted one by one—so what does explain this effect?

Quantum mechanics can provide answers. An electron's trajectory is controlled by the wave function for the entire system, and the system's wave function when one slit is open is quite different from the wave function that exists when both slits are open. In the latter case parts of the wave function pass through both slits and the resulting ripples of probability interfere with one another. It is this interference structure in the wave function which is responsible for the interference pattern generated by electrons striking the screen—it is not difficult to see how this comes about since it is the wave function determines the probability of particles appearing at different locations on the screen.

On the Copenhagen interpretation, the electrons have no definite position from the time they are emitted from the source till the time they strike the screen. In contrast, for proponents of the de Broglie-Bohm approach the electrons always have a definite position throughout their journey, even if we only discover their location when they hit the screen; when both slits are open there is also a fact of the matter concerning which slit each electron passes through—even when we are not making any attempt to detect. On this view it is the guiding pilot wave of an electron that passes through both slits and is responsible for the creation of an interference pattern on the screen.[17]

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[17] What of the many worlds interpretation? On one view—see Deutsch (1997)—each of the different potential electron trajectories contained within the wave function correspond to actual outcomes in different worlds, and the interference pattern exists because of the ways the electrons in different worlds interact with one another.

We saw earlier that in advocating a dynamic conception of matter Leibniz mocked the ancient atomists and their followers in the mechanical tradition for holding that the "whole cause of cohesion in bodies may be interweaving of certain shapes such as hooks, crooks, rings projections and, in short, all the curves and twists of hard bodies inserted into each other." If the competing interpretations of the two slit experiment clearly demonstrate anything it is that Leibniz was right: interactions in the micro-realm are governed by mechanisms that are quite unlike anything dreamt of by the ancient atomists. Equally, they also go far beyond anything dreamt of by dynamists such as Newton and Kant.

There is a further implication of quantum theory that is very relevant so far as the nature of physical interactions is concerned: it is now widely agreed that the theory is fundamentally and irreducibly *non-local*. In this context a theory is *local* if it rules out action at a distance influences of any kind. In practical terms, for theories of the local sort if an event E1 exerts an influence on event E2 some distance away, then the effect of E1 will invariably be mediated by a process which passes through the intervening space—whether it be in the manner of a bullet moving from gun to target, or ripples crossing a pond. Since according to Einstein's special theory of relativity nothing can travel faster than the speed of light, it is natural to assume that all transmissions or influences between spatially separated events must occur at either light-speed or sub-light speed. This locality constraint is difficult to square with the much-discussed phenomenon of quantum entanglement. Present purposes will be served by a simplified schematic outline of this subtle effect.

Electrons have a quantum property known as "spin", a form of angular momentum (which, confusingly, does not involve electrons actually rotating). Spin can exist in any spatial orientation, but for present purposes we can restrict our attention to just two of these, which we can label *spin-up* and *spin-down*. Quantum mechanics tells us that it is possible for two electrons to interact in such a way that their spins are thereafter correlated—or "entangled"—in a distinctive way, at least until one or other of them interacts with something else.

Viewing matters from the perspective of the Copenhagen interpretation, when a pair of entangled electrons X and Y comes into being each of them has a 50% chance of being spin-up or spin-down, and their spin-states exist in a superposition until one or other of them comes into contact with a suitable detector. As a consequence, prior to a measurement being taken neither electron possesses a determinate spin. However, if at some point in time electron X encounters a suitable detector and is found to have spin-up, then a measurement conducted on electron Y a moment later will find that it has spin-down; if on the other had X turns out to have spin-down, then Y will be measured as having spin-up. Measuring X's spin results in an *instantaneous* collapse of the wave-function that had hitherto encompassed both particles, and this collapse is such that Y is guaranteed to have an opposite spin-orientation to X. Entangled particle-pairs are connected in this sort of way irrespective of how far apart they happen to be.

More generally, Ismael and Schaffer provide this usefully succinct characterization of the phenomenon: "The components of a system in an entangled state behave in ways that are individually unpredictable, but jointly constrained so that it is possible to forecast with certainty how one component will behave, given information about the measurements carried out on the other(s)" (2016). It was Schrödinger who first wrote of particles related in this way as *entangled*, and he found it problematic: "Measurements on separated systems cannot directly influence one another—that would be magic" (1935, 16). Einstein famously characterized this mode of interaction as "spooky action at a distance" and he too was less than happy with it.[18] He thought it likely that the relevant phenomena could be explained by a purely local theory, but never succeeded in finding one. More importantly, since the 1980s there has been a succession of increasingly sophisticated experiments that all point in one direction: to quantum entanglement's being a real physical phenomenon.[19] For Raymer this outcome "is a highly curious even shocking result. It brings home the truly revolutionary nature of quantum physics" (2017, 139).

So far as Einstein is concerned, it is perfectly understandable why he was far from welcoming with regards to quantum non-locality. It certainly does not sit easily with his special theory of relativity's ban on faster than light causal transmission. More significantly, with his general theory of relativity Einstein had successfully eliminating Newton's action at a distance gravitational force, and explained gravitational effects in terms of purely local fields. By so doing Einstein vindicated—or so it initially seemed—one of the main tenets of both the ancient atomists and the scientific revolution's mechanical theorists: the long-influential conviction that the only way things can only influence one another is by touching one another. Einstein was fully aware of the significance of such an achievement.

Adopting a longer historical perspective sheds a different light on these developments. During the centuries-long reign of Newton's theory of gravity the majority of physicists had no trouble at all in accepting that the workings of the universe were governed by an action at a distance force, and nor did leading philosophers, most notably Kant. Since only a decade or so separates the arrival of Einstein's general theory of relativity—and the ensuing demise of Newtonian gravity—from the advent of quantum mechanics and entanglement, the undisputed reign of locality in modern physics was really rather brief.[20]

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[18] The two particle form of entanglement was introduced by Einstein et al. (1935) paper "Can Quantum Mechanical Description of Physical Reality be Considered Complete?", but non-locality had worried Einstein for longer. As Cramer (2016, §6.2) relates, in the 1927 Solvay conference Einstein introduced his "bubble paradox". On the orthodox view, there are circumstances in which a photon's wave function will take the form of an expanding sphere; the sphere will continue to expand until there an interaction with another particle, at which time the entire wave function instantaneously vanishes. Einstein asked how the parts of the wave function at some—potentially considerable—distance away from the detection even "know" they should disappear at precisely this instant?

[19] Particularly relevant here, since they close-off various loopholes in previous tests, are the recent results reported in Hensen et al. (2015) and Giustina et al. (2015).

[20] For helpful and encouraging comments on earlier drafts my thanks to Galen Strawson and Shyam Iyengar.

Appendix: The Standard Model

Our current best theory of matter is known as the *Standard Model of Particle Physics*, which takes the form of a quantum field theory (QFT). This field theory originated in work done on quantization of the electromagnetic field in 1926–1927 by Born, Heisenberg, Jordan and Dirac, and was gradually extended to cover other forces and fields over the next half century or so. The Standard Model received a noteworthy—and much publicized—confirmation when the Higgs boson was discovered at CERN in 2013.

According to the Standard Model all material things are composed of three families of particles: quarks, leptons (e.g. electrons and neutrinos) and force carrying bosons (such as electrons and muons). Hadrons are particles made up of multiple quarks: the *baryons* have three quark constituents—e.g. the protons and neutrons familiar from chemistry fall into this category, whereas the generally short-lived *mesons*—such as the pion—are composed of just two quarks. QFTs are so-called because their fundamental ingredients are entities known as *quantum fields*, and particles tend to be viewed as nothing more than patterns of activity within these fields—with different species of particle being associated with different types of quantum field. From the perspective of QFT the universe consists of a number of different overlapping quantum fields each of which extends through all of space.

The Standard Model provides an account of three of the known four forces in nature. These are the *strong force* which binds the quarks, the *weak force* responsible for the transformation of massive quarks and leptons to lighter particles, and the more familiar *electromagnetic force*, which has a potentially infinite range. As for the force-carriers, here is what CERNs introductory guide to the Standard Model has to say:

> Three of the fundamental forces result from the exchange of force-carrier particles, which belong to a broader group called "bosons". Particles of matter transfer discrete amounts of energy by exchanging bosons with each other. Each fundamental force has its own corresponding boson—the strong force is carried by the "gluon", the electromagnetic force is carried by the "photon", and the "W and Z bosons" are responsible for the weak force. Although not yet found, the "graviton" should be the corresponding force-carrying particle of gravity. The Standard Model includes the electromagnetic, strong and weak forces and all their carrier particles, and explains well how these forces act on all of the matter particles.[21]

In some respects this conception of the physical world is radically revisionary with respect to our common sense ways of thinking. One would never guess just by looking at it (or touching it) that a lump of rock consists of trillions and trillions of vibrations taking place in invisible fields. It is also natural to assume that a region of empty space—a cubic metre midway between two galaxies, say—is truly empty. According to the Standard Model even the emptiest region of space is in fact filled

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[21] https://home.cern/about/physics/standard-model.

with the quantum fields which—due to quantum uncertainties—continually generate extremely small, very short-lived ("virtual") particles in large numbers.

However, so far as the nature and role of *forces* are concerned, the picture drawn here may seem to be reassuringly familiar. At the most fundamental level, we are told that the world is being held together by forces. In its attractive mode the electromagnetic force ensures that positively charged protons and negatively charged electrons remain bound within atoms. It is electromagnetic repulsion between the electron "shells" surrounding atoms which prevents our feet from falling through floor. And in the case of the quarks composing protons and neutrons, the strong force binding them is *so* strong that the quarks in question can never be separated from one another. Given that we are all acquainted with the nature of force from our own experience, it seems that our experience—in this respect at least—is providing us with a reliable guide to the nature of reality.

In fact, drawing this reassuring conclusion would be premature. The impressive empirical successes of the Standard Model—the prediction of the Higgs boson is by no means the first of these—have convinced most physicists that the theory accurately reflects some important aspects of the way the world really works, but there remain plenty of unresolved problems.

The theory does not incorporate either dark matter or dark energy, which remain mysterious. Also, the Standard Model has yet to incorporate gravity. As CERN note in their introductory guide: "… the most familiar force in our everyday lives, gravity, is not part of the Standard Model, as fitting gravity comfortably into this framework has proved to be a difficult challenge." This is nicely understated: the problem of reconciling quantum theory with general relativity remains unsolved, despite receiving the attentions of many of the best minds in physics over a period of many years.

Since no one yet knows what a viable quantum gravity theory will look like we are similarly ignorant as to the character of the theory which will succeed the Standard Model.

Also, as we have already seen, quantum theory poses notorious problems of interpretation, which all extend to the Standard Model simply because it *is* a quantum theory. Indeed, the Standard Model generates several new problems of its own. Quite what the best mathematical formulation of it will turn out to be remains controversial—there are a number of competing alternatives. Calculations using the theory tend to produce physically unrealistic infinities; although these have been partially tamed by "perturbation" techniques the suspicion remains that a better theory will not have this consequence. The Standard Model includes a large number of parameters that need to be determined experimentally—the theory provides no clue as to why these parameters have these particular values rather than others. Estimates for the energy of the vacuum derived from the Standard Model turn out to be enormously larger than the value predicted by GTR. Also, and significantly from a metaphysical standpoint, the basic ontology of the Standard Model is very much open to debate. Contemporary theorists remain divided on the question of whether the basic entities in QFTs are fields or particles—there are considerations which point in different directions.[22]

Given the current state of play little is very clear, but one thing does emerge with at least some clarity. Interpretations of the Standard Model in terms of particles consisting ultimately of excitations in fields which interact by exchanging other particles, do provide an account of the basic nature of reality which is intuitively appealing by virtue of being easily visualizable. It may even be that this a picture along these lines proves to be correct; but it is equally possible that it does nothing of the sort.[23]

We saw earlier that Einstein's relativity theories have implications for the nature of time that also impact on our understanding of forces. If, as many have concluded, in the light of Einstein we have no option but to conclude that we live in a four dimensional block universe, the future is as real as the past, and we can no longer view causes (or forces) as bringing their effects into existence. There is another important respect in which the nature of time and the nature of forces and causes are interrelated, one that is entirely independent of relativistic considerations.

Thanks to the work of Euler, Lagrange, Hamilton and others a comprehensive alternative mathematical framework for carrying out Newtonian mechanics was developed in the 18 and 19th centuries. On this alternative picture, the role of forces —both of the impact and action at a distance variety—is supplanted by global "variational principles" such as the principle of least action (in mechanics) or least time (in optics). Since these principles minimize (or maximize) properties of an object's *entire path* through space over an interval of time, they presuppose a four-dimensional view of nature according to which the future is no less concrete and real than the present.

Since in the case of classical mechanics the "Newtonian" and "Lagrangian" approaches are completely equivalent, we cannot draw any implications in that domain concerning the nature of time from the fact that the success of the Lagrangian methodology.[24] However, variational principles not only play a key role in all the main formulations of quantum field theories, they are also at the heart

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[22] For more on the difficulties confronting QFT see https://plato.stanford.edu/entries/quantum-field-theory/.

[23] Nima Arkani-Hamed, who has recently pioneered impressive new geometry-based ways of performing calculations in QFT makes the point thus: "… there are more and more people trying to explain quantum field theory in an accessible way … [but] they're explaining a point of view about the subject which is thirty or forty years old and which is almost certainly not going to be the way we think about it in the future. … the one thing that is almost certainly *not* going to be the case is that the story is that *The big deal is that there are those different fields and there are these particles that are excitations of the field*." Burton (2013), 377. See Wolchover (2013) for an accessible introduction to Arkani-Hamed's work on the amplituhedron, the higher dimensional geometrical entity underlying the new QFT methods.

[24] For more on variational principles and the metaphysical conundrums to which they give rise see Smart and Thebault (2013)—also see Chiang's (2002) sci fi story.

of many attempts to reconcile quantum theories with relativity. If this remains the case, and no alternatives to the variational approaches emerge, this could be taken as compelling evidence that nature is itself four-dimensional, and that global variational principles—rather than forces as traditionally conceived—have explanatory priority. This said, anyone who finds this conception of time unacceptable on metaphysical grounds will still have the option of holding that quantum theories should be interpreted only instrumentally, i.e. as useful tools for predictive purposes, rather than reliable guides to the nature of reality.[25]

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[25] For a recent defence of this approach to the realm of the quantum see Healey (2017).

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