Fundamental?

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It's family games night, and we're playing a guessing game. My mother - not a physicist - picks up a card and says, 'A fundamental particle.'

My father and I - both physicists - immediately begin talking. 'Quark! Gauge Boson! Electron! Neutrino!

She shakes her head, and we go on. 'Higgs Boson! Muon! Tau!'

Eventually we run out of time. My mother sighs. 'An atom,' she says, in a long-suffering tone.

Of course, atoms were always *intended* to be fundamental particles; the word 'atom' literally means indivisible. But 'fundamental' is a shifting goal-post in physics: when we say that something is fundamental, one of the things we mean is that it requires no further explanation, and we have a tendency to change our minds about that assessment. Indeed, many of science's most important paradigm shifts have been tied to alterations in our understanding of the fundamental.

Einstein is an obvious case, since the theory of special relativity can be thought of as following from the insight that simultaneity is not 'absolute,' i.e. fundamental [1]. Here, as in the example of the atom, something that was once regarded as fundamental became explainable in the context of a new theory. It also happens that something we once sought to explain comes to be regarded as fundamental, although this direction is less common. Aristotle famously believed that being at rest was the natural state for all objects, and therefore all motion demanded explanation [2]. His followers accordingly came up with ingenious ways of explaining phenomena like the parabolic motion of projectiles - for example, perhaps the air in front of the projectile becomes disturbed by its movement, and swirls behind the projectile, keeping it in motion [3]. Then, of course, Newton came along and revolutionised science by simply changing the explanandum. Unaccelerated motion became a natural state and all the convoluted explanations became superfluous [4].

Fundamental means we have won. The job is done and we can all go home.

Given these far-reaching consequences of our scientific attitudes to the fundamental, it is unsurprising that the question of whether or not something is fundamental often becomes a topic of vigorous debate - witness the long-standing argument about whether probabilities are fundamental [5]. Certain types of probabilities are clearly 'subjective,' meaning that they can be understood as a description of our own ignorance about the true facts of some situation, rather than as fundamental facts about the world [6]. But ever since the birth of probability as a formal field of mathematics, it has been accompanied by a vague, sometimes slightly incoherent idea that there exist two distinct types of probability [7], - so, for example, we find Laplace writing an essay in 1826 entitled *Concerning the Unknown Inequalities which may exist among Chances which are supposed to be Equal* [8] and Peirce in 1910 insisting that '(a) die has a certain would-be, (which is) a property, quite analogous to any habit that a man might have.' [9] In these locutions we recognise the beginnings of the modern concept of objective chances - fundamental, irreducible probabilities which appear in the laws of nature and are identified as properties of objects in the world.

Despite this promising start, at the beginning of the twentieth century things were looking black for objective chances: with the increasing sophistication of statistical mechanics making it possible to explain the probabilities of thermodynamics in statistical terms, it seemed likely that all our paradigmatic examples of probabilities would turn out to be subjective in character, and if quantum mechanics had not come along we might well have concluded that the notion of objective chance was just a confusion all along [10]. But quantum mechanics did came along, and quantum mechanics does not usually predict measurement outcomes with certainty: instead it assigns probability distributions. Furthermore, we have encountered a number of obstacles in attempting to come up with interpretations of the theory which say definite things about what is really going on at a microscopic level - for example, the contextuality theorems of Kochen-Specker [11] and Spekkens [12] tell us that it is not possible to come up with models for a reality underlying quantum mechanics where certain key structural symmetries of the mathematical formalism are preserved on the ontological level. So we can't easily account for the quantum probabilities in terms of subjective probabilities arising from our ignorance of some deeper theory, and therefore it seems natural to conclude that the laws of quantum theory are 'fundamentally probabilistic' [13–16]. In quantum mechanics, we have located those elusive objective chances at last [15, 17].

But there is something troubling about this narrative. Due to decoherence, quantum probabilities are effectively screened off from our everyday experiences [18, 19], so if it is true that quantum probabilities are objective chances, then our ancestors who came up with the concept of objective chance cannot ever have had any actual experience of what we now understand to be objective chance, so it seems nothing short of a miracle that they nonetheless managed to come up with a correct concept of objective chance.

Here is an alternative account: quantum mechanics came along, and try as we might, we could not find satisfactory explanations for the quantum probabilities. So we stopped trying, and began applying the term 'fundamental' to cover our lack of understanding. Conveniently enough the concept of fundamental, irreducible chances had been floating around in the collective consciousness for some time, so it was possible to invoke that term without anyone realising that a radically new and ill-defined concept was being introduced into science. The word 'fundamental' become a disguise for our confusion.

Fundamental means we have lost. *Fundamental* is an admission of defeat.

It's certainly tempting to conclude that the word 'fundamental' refers to an attitude rather than a matter of fact. We question as deeply as we can, but eventually we grow tired, plant our flag in the ground, and say 'This, here, is the most fundamental thing,' - all the while acknowledging, at least in the back of our minds, that there will always be another generation of physicists who will insist on questioning further. And yet, if we are realists about science, we must surely believe that there is some endpoint to this process, some set of truly fundamental entities which will not need to be explained.

What do we suppose will be left over when all reasonable questions have been answered? The simplest answer is also the most ambitious: nothing.

The idea that the ultimate goal of science is to explain everything was first articulated by Spinoza [20,21], and was subsequently formalised by Leibniz in the form of the Principle of Sufficient Reason [21,22]. This is surely the grandest and most compelling vision of science that one could ever dare to contemplate: once our understanding becomes sufficiently advanced, we will see that the universe simply *could not have been otherwise*. It is an immensely attractive prospect, but also, surely, an impossible one, since it is very easy to conceive of a multitude of ways in which the world seemingly could have been different, and thus very difficult to imagine that our actual world could somehow be logically necessary. Even Leibniz ultimately needed a God to complete his vision - 'God,' of course, being the same sort of sticking-plaster concept as 'fundamental.'

And yet, vestiges of Leibniz's ideas live on in modern physics, not least in the current vogue for multiple universe theories in cosmology [23] and the interpretation of quantum mechanics [24]. There are certainly interesting theoretical arguments for these approaches, but in the background it is possible to detect a lurking secondary motivation: one day, with the help of these sorts of 'everything happens' theories, we might be able to do without arbitrariness altogether. There will be nothing fundamental left, except perhaps mathematics and logic.

A similar way of thinking gives rise to the common insistence that the initial conditions of the universe require explanation. For example, it is well known that to make thermodynamics work properly we need to invoke what is known as the 'past hypothesis,' which comes in many variants, but usually says something to the effect that the initial state of the universe was a particularly low entropy state [25]. Intuitively we feel that there is something unlikely about this special choice of initial state, and thus ever since the time of Boltzmann people have been attempting to argue away the unlikeliness, whether by appeal to anthropic arguments [26] or, more recently, by invoking cosmic inflation [27]. But is any explanation really needed here? It is by no means obvious that the initial conditions of the universe are the kind of thing which can or ought to be explained, but nonetheless we clearly all *want* an explanation. We are deeply uncomfortable with the idea that the universe must, on some level, be arbitrary.

Yet perhaps we will have to become more comfortable with arbitrariness. This does not mean we should give up on attempting to explain things and become anti-realists: it simply means we must demand greater clarity about what sorts of things need explaining and what sorts of explanations we are willing to accept for them.

When a coin is flipped a thousand times, it is always going to produce some sequence of outcomes, and any particular one of these sequences is fantastically unlikely - but some sequences demand explanation and others do not. In particular, if a sequence exhibits regularities that would allow us to make reliable predictions about some part of the sequence given knowledge of some other part of the sequence, we feel that those regularities demand an explanation: the coin landing on heads every single time would be an unlikely coincidence, or even a miracle, if there were no explanation for it.

But what precisely is it that needs to be explained? Is it the fact that the coin always lands *the same way up*, or is it the fact that it always lands on *heads*? Prima facie the question seems an odd one, because it is difficult for us to envision a physical mechanism which explains why the coin always lands the same way up without also explaining why it is always *that* way up. However, the situation is different for the universe as a whole. For example, what is it about the arrow of time that demands an explanation? Is it the fact that there *exists* an arrow of time, or is the fact that the arrow points *a certain way*? Of course it is the former. Assuming there is nothing outside the universe, asking why the arrow points this way rather than that is not even a meaningful question. The direction of the arrow is 'arbitrary' but it is not a puzzle that needs solving.

Generalising this point, as realists about science we must surely maintain that there is a need for science to explain the existence of the sorts of regularities that allow us to make reliable predictions - because otherwise their existence would be precisely the kind of strange miracle that scientists are supposed to be making sense of - but there is no similarly pressing need to explain why these regularities take some particular form rather than another. Yet our paradigmatic mechanical explanations do not seem to be capable of explaining the regularity without also explaining the form, and so increasingly in modern physics we find ourselves unable to explain either.

It is in this context that we naturally turn to objective chance. The claim that quantum particles just have some sort of fundamental inbuilt tendency to turn out to be spin up on some proportion of measurements and spin down on some proportion of measurements does indeed look like an attempt to explain a regularity (the fact that measurements on quantum particles exhibit predictable statistics) without explaining the specific form (the particular sequence of results obtained in any given set of experiments). But given the problematic status of objective chance, this sort of non-explanation is not really much better than simply refraining from explanation at all.

Why is it that objective chances seem to be the only thing we have in our arsenal when it comes to explaining regularities without explaining their specific form? It seems likely that part of the problem is the reductionism that still dominates the thinking of most of those who consider themselves realists about science [28]. The reductionist picture tells us that global regularities like quantum statistics must be explained in terms of fundamental properties of individual particles, and objective chances fit into this reductionist ontology because it seems to make sense to think about them as properties of the objects that exhibit the probabilities, as in the propensity interpretation of probability [5]. But moving away from the reductionist picture would give us many more options, including some which are likely more coherent than the nebulous notion of objective chance.

So seems that we are in dire need of another paradigm shift. And this time, instead of simply changing our attitudes about what sorts of things require explanation, we may have to change our attitudes about what counts as an explanation in the first place.

Consider the following apparent truisms. The present explains the future, and not vice versa; properties of parts explain the properties of the whole, and not vice versa. There are of course *practical* reasons why explanations satisfying these requirements are of particular interest to us: we want to know how to do things in the present in order to bring about desired future events, and we want to know how to construct things by combining parts to produce a desired whole. But the notion of the Fundamental, writ large, is not supposed to be about our practical interests. In our standard scientific thinking the fundamental is elided with ultimate truth: getting to grips with the fundamental is the promised land, the endgame of science.

In this spirit, the original hope of the reductionists was that things would get simpler as we got further down, and eventually we would be left with an ontology so simple that it would seem reasonable to regard this ontology as truly fundamental and to demand no further explanation. But the reductionist vision seems increasingly to have failed. Instead of building the world out of a single type of fundamental particle, we have been required to hypothesise so many fundamental particles that the hourglass ran out before my father and I could finish listing them. The mathematics, too, is becoming increasingly complex: Newtonian mechanics requires only high school mathematics, whereas the mathematics of string theory is challenging even for postgraduate mathematicians. We physicists are fond of mathematics, so we have mostly taken this in our stride, but perhaps we should be more worried. Perhaps we should take it as a sign that we have been swimming against the current all this time: the messiness deep down is a sign that the universe works not 'bottom-up' but rather 'top-down,' with the laws of nature governing the whole of history at once, akin to the Lagrangian formulation of classical physics [29].

After all, what is beginning to become clear within modern physics is that in many cases, things get simpler as we go *further up*. Our best current theories are renormalisable, meaning that many different possible variants on the underlying microscopic physics all give rise to the same macroscopic physical theory, known as an infrared fixed point [30, 31]. This is usually glossed as providing an explanation of why it is that we can do sensible macroscopic physics even without having detailed knowledge of the underlying microscopic theories [31]. But one might argue that this is getting things the wrong way round: the laws of nature don't start with little pieces and build the universe from the bottom up, rather they apply simple macroscopic constraints to the universe as a whole and work out what needs to happen on a more fine-grained level in order to satisfy these constraints. Presumably at least some features will be left underdetermined by the global constraints, and that is where the arbitrariness comes in, but there is nothing wrong with this as long as the arbitrary features are of the harmless kind. To return to the coin-flipping example, one might in a univeral context hypothesize that it's simply a law of nature that the coin must always land the same way up - whether it lands heads or tails is not fixed by any of the laws of nature, but that doesn't matter, because it was the existence of the regularity and not the specific form that we particularly needed to explain.

If this is correct, it is no wonder that when we do quantum physics we find it difficult to say anything definite about how things are on a microscopic level: most of the time there simply *is* no fact of the matter about how things are on a microscopic level, because the universe is efficient, and doesn't bother answering questions when it doesn't need to. To ensure the satisfaction of the macroscopic constraints, there's usually no need to decide how things are on a microscopic level - except of course when human experimentalists start wiggling smaller and smaller things and demanding answers.

So maybe it really is the case that there is no endpoint to this process of questioning nature: as we build bigger and bigger particle accelerators to probe ever more deeply, the universe will be forced to invent deeper and deeper levels of reality that exist only to answer our questions. But these levels of reality won't be getting us any closer to what is truly fundamental - how can they be 'fundamental' if most of the time they're not even there? Thus from this perspective, it may actually turn out to be correct to say that atoms are more fundamental than quarks, bosons, electrons, neutrinos and the like. In the end, we might even decide that atoms have been fundamental particles all along.

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