



# The end of science? On human cognitive limitations and how to overcome them

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Received: 25 October 2019 / Accepted: 4 January 2020  
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## Abstract

What, if any, are the limits of human understanding? Epistemic pessimists, sobered by our humble evolutionary origins, have argued that some parts of the universe will forever remain beyond our ken. But what exactly does it mean to say that humans are ‘cognitively closed’ to some parts of the world, or that some problems will forever remain ‘mysteries’? In this paper we develop a richer conceptual toolbox for thinking about different forms and varieties of cognitive limitation, which are often conflated by the so-called ‘new mysterians’. We distinguish between *representational access* (the ability to develop accurate scientific representations of reality) and *imaginative understanding* (immediate, intuitive comprehension of those representations), as well as between different modalities (hard vs. soft) of cognitive limitation. Next, we look at tried-and-tested strategies for overcoming our innate cognitive limitations, drawing from the literature on distributed cognition and cognitive scaffolding’. This allows us to distinguish between the limits of bare brains vs. scaffolded brains. Most importantly, we argue that this panoply of mind-extension devices is combinatorial and open-ended. In the end, this allows us to turn the table on the mysterians: for every alleged ‘mystery’, they should demonstrate that no possible combination of mind extension devices will bring us any closer to a solution.

**Keywords** New mysterianism · Cognitive closure · Epistemic boundedness · Imaginative understanding · Representational access

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## Introduction

“Nature initially arranged things her own way and subsequently so constructed the human intellect as to be able to understand her” – Galileo Galilei in *Dialogue Concerning the Two Chief World Systems*, 1632

“And how awkward is the human mind in divining the nature of things, when forsaken by the analogy of what we see and touch directly?” – Ludwig Boltzmann in *Nature*, 1895

Human brains are the product of blind evolution. They evolved to deal with practical problems impinging upon survival and reproduction, not to unravel the mysteries of the universe. This, remarkably, is what human brains themselves have come to discover, after billions of years of unguided evolution. Are there any limits to what human inquiry might achieve, and if so, what parts of reality must forever lie beyond our ken? In spite of the spectacular successes of modern science, a number of philosophers and scientists have expressed pessimism about our epistemic prospects (Fodor 1983; McGinn 1993; Stich 1990). Given our humble evolutionary origins, they argue, we have no reason to suspect that we will ever penetrate the deepest mysteries of the universe. Some questions are doomed to remain what Noam Chomsky called “mysteries” (Chomsky 1988). Indeed, some philosophers have argued that, from the perspective of evolutionary naturalism, we have no reason to trust the deliverances of our own brains at all, and we should conclude that the naturalist worldview is self-defeating (Plantinga 2011; Nagel 2012; but see Boudry and Vlerick 2014).

In stark contrast to the pessimism of these so-called “new mysterians” (Flanagan 1992), some naturalists regard the fact of our evolutionary origins as a reason for optimism about our epistemic potential. Given that humans evolved in the natural world and that our survival depended on understanding that world, we should expect it to be intelligible to our brains (Griffiths and Wilkins 2015; Boudry and Vlerick 2014). Indeed, we would not have evolved big and metabolically expensive brains in the first place if these had not rendered the world intelligible to us. As Nicholas Rescher puts it: “A world in which intelligent creatures emerge through the operation of evolutionary processes must be an intelligible world” (1990, p. 65).

How should we resolve this conflict? In this paper, we introduce a richer conceptual framework for thinking about cognitive limitations, and we discuss specific strategies for extending the reach of our minds. Given the panoply of mind-extension devices at our disposal, we argue, it is unlikely that science will ever come to a screeching halt, or that we will reach an outer limit of understanding. Indeed, we argue that the mysterian position, though ostensibly inspired by the virtue of humility and the danger of hubris, is in fact far less modest than it appears.

In the first section, we briefly discuss the mysterian thesis that the biological provenance of human intelligence entails cognitive closure from certain aspects of reality. Next, we analyze different forms and modalities of cognitive limitation

(representational vs. imaginative, bare brains vs. scaffolded brains, hard limits vs. soft limits). Finally, we discuss different strategies for overcoming our innate cognitive limitations, using quantum mechanics as a case study.

## The new mysterians

If our minds are biological organs fashioned by evolutionary processes, as indeed they are, they must have certain functional specifications and limitations. This, according to the new mysterians, means that certain thoughts and ideas lie beyond our ken. Just as dogs or pigs will never understand prime numbers, polyphony, the rules of chess, or the properties of electrons, the human brain must be closed off from *some* of the world's wonders. Most mysterians believe that their thesis is just a straightforward corollary of the evolutionary worldview of modern science. Anyone who accepts the central facts of modern biology, writes Noam Chomsky, must admit that the existence of human cognitive limits is a "truism". In particular, Chomsky has argued that all human scientific activities are undergirded by a "science forming faculty" (2000, p. 83)—loosely defined as those cognitive capacities that enter into scientific inquiry—which constrains our cognitive reach. It is an inevitable fact of biology that some aspects of the natural world must remain out of our mind's reach, and hence will always appear mysterious to us.

Pinker (1997) has spelled out the evolutionary reasons for this pessimism in a bit more detail. Evolution by natural selection, explains Pinker, is an opportunistic and short-sighted tinkerer. It tends to produce quick-and-dirty, satisficing solutions to adaptive problems in an organism's immediate environment, as opposed to optimal and generic solutions that work in every environment. It is also a ruthless economizer. If our ancestors didn't need to understand the universe at large to spread their genes, it would be profligate for natural selection to have given us the brainpower to do so. As Pinker rhetorically asks, "if the mind is a system of organs designed by natural selection, why should we ever have expected it to comprehend all mysteries, to grasp all truths?" (Pinker 1997, p. 563).

The arguments of Jerry Fodor, another philosopher in the mysterian camp, have a more general scope, and are not tied to specific evolutionary considerations. All finite cognitive systems have a certain "endogenous structure," according to him, which constrains the kind of representations that it can process. Because the human brain is just such a system, there are bound to be "thoughts that we are unequipped to think" (1983, p. 125). For Fodor, cognitive closure is not just a predicament of minds that evolved through biological evolution, but of *any* cognitive system. The notion that some cognitive systems are characterized by "epistemic unboundedness" is dismissed by Fodor as "just incoherent" (Fodor 1983, pp. 122–123).

Colin McGinn, finally, has treated the subject of human cognitive limitation most extensively, and he was the one to coin the term "cognitive closure" (1993, 1994). According to him, the human mind is cognitively closed to the answers to certain problems, not because those problems are inherently more difficult than solvable scientific problems, but because the particular structure of our minds obstructs

understanding of their answers. In McGinn's view, our minds can only process representations in combinatorial fashion. He calls this the CALM-conjecture, which stands for 'Combinatorial Atomism with Lawlike Mappings'. According to the CALM-conjecture, humans understand the world by analyzing it in terms of a set of primitive elements and their 'lawlike' interactions. But some problems, McGinn claims, simply cannot be grasped in this fashion. "Conscious states", in particular, "are not CALM-construable products of brain components" (McGinn 1993, p. 37). McGinn calls his position "transcendental naturalism", because he thinks that the problems in question "transcend" our cognitive capacities, even though their correct solutions are in fact perfectly natural. It's just that our minds are not suited to the job.

## Kinds of limits

But what exactly does it mean to be cognitively "closed" or "limited"? There seem to be a number of ambiguities in the position of the mysterians. First, they typically present the question of cognitive limits in stark and black-or-white terms. Either we are capable of solving a problem or the answer will forever elude us. Either we have cognitive access or we are blocked from it. But there are other possibilities. For example, our inquiries into the world may encounter a situation of gradually diminishing returns, without ever quite coming to a full halt. Second, mysterian arguments are focused on the limitations of a single and unaided human brain. But how about a collection of human brains working together, aided by various artefacts and cognitive scaffolds? Third, it is unclear whether the mysterians are claiming that human beings will never possess the true scientific theory of some part of the world, or alternatively, that we may well develop such a theory but we will never *grasp* it? In short, mysterians conflate various sorts and modalities of cognitive limitation. In the following sections, we will treat those points separately, thus developing a richer conceptual framework for thinking about human cognitive limitation.

## Representational and imaginative limits

Arguments about cognitive closure and mysteries often conflate two different predicaments. In one scenario, there is a domain of reality which, because of some insurmountable cognitive or perceptual barrier, we will never be able to probe or penetrate. Other creatures with different cognitive abilities might be capable of developing accurate representations about this part of reality, but for our species, they are inaccessible. In this scenario, we suffer from *representational closure*, which means that we lack *representational access* to a part of the world.

In the second scenario, we do have representational access to a certain domain of reality (possibly with the help of mind extensions, see the section "[Bare senses and bare brains](#)"), but it is impossible for us to *comprehend* the relevant scientific theory describing that part of reality. No matter how hard we try, we just can't wrap

our minds around it. Because of some species-specific limitation to our imagination, this part of reality will forever bewilder and baffle us. In this scenario we suffer from *imaginative closure*, which means that we lack *imaginative access* to the correct representation of some part of the world (Vlerick and Boudry 2017).<sup>1</sup>

We need not give an exact definition of “imaginative closure” to see that we are dealing with two quite different predicaments. Representational access describes a relation between the world and our (scientific) representations of it, whereas imaginative access describes a relationship between our representations and our minds. By way of illustration, consider a tesseract, which is the four-dimensional equivalent of a cube. Mathematicians have developed accurate formal representations of tesseracts, from which they can derive the number of faces, edges and vertices, and describe other geometric properties, such as various symmetries, intersections with other figures, and projections in two or three dimensions. But this does not mean that mathematicians can *imagine* what a tesseract looks like, in the same way that all of us can visualize a cube before our mind’s eye. Mathematicians clearly have *representational access* to the concept of a tesseract, but one may well doubt if they have *imaginative access*. In a similar way, it is indisputable that physicists have representational access to space-time curvature, since even the GPS devices in our smartphones depend on scientific representations about this aspect of the world. They cannot, however, effortlessly imagine what it is for a 4-dimensional space-time continuum to be curved by a massive object in the same way they imagine an apple falling from a tree.

In the writings of the new mysterians, however, it is unclear exactly what form of limitation is intended, and often the two seem to be conflated.<sup>2</sup> McGinn, for instance, characterizes his thesis as one of “epistemic inaccessibility”, which means that it is impossible to “convert the problem into regular science” (p. 40). About the mind–body problem, McGinn claims that “the correct *theory* is inaccessible to the human intellect” (1994, p. 145, our emphasis). But then McGinn proceeds to offer arguments that only bear on the psychological difficulties which we experience when we try to understand the mind–body nexus. We experience a “feeling of intense confusion” when we contemplate the matter, and our “head spins in theoretical disarray” (McGinn 1993, pp. 27–28). In other words, the mind–body nexus is “numbingly difficult to make sense of”. But as we previously argued, imaginative closure does not entail representational closure. It is perfectly conceivable that we succeed in forming a scientific representation of some aspect of the world, but then

<sup>1</sup> In our previous work (Vlerick and Boudry 2017) we called these predicaments, respectively, “representational closure” and “psychological closure”. We have now decided to opt for a slightly different terminology, because the adjective “psychological” was too broad for our purposes.

<sup>2</sup> In his original formulation, McGinn wrote that “A type of mind M is cognitively closed with respect to a property P (or theory T) if and only if the concept-forming procedures at M’s disposal cannot extend to a grasp of P (or an understanding of T)?” (McGinn 1989, p. 350). By adding these parenthetical asides, McGinn suggests some rough equivalence, or a mere terminological difference. But there is a crucial difference between the claim that we cannot form a representation of some property P, and the claim that we cannot understand or grasp the representation itself.

fail to achieve an intuitive grasp of our own representations (Vlerick and Boudry 2017).

Noam Chomsky's account of "mysteries" also wavers between representational and imaginative closure. According to Chomsky, there are certain problems in science which have perfectly natural answers, only those answers will forever remain inaccessible to the "science forming faculty" of our species (Chomsky 2000, p. 82). In other words, no scientific progress whatsoever can be made toward demystifying those mysteries. But in his latest publication on the subject, Chomsky characterizes mysterianism as dealing with "phenomena that fall beyond human *understanding*" (Chomsky 2014, our emphasis). There is a possibility that Chomsky overlooks: scientific progress that leaves behind human comprehension. It is conceivable that we develop an accurate theory of some part of reality without being able to wrap our heads around it.

For example, it is not clear how the mysterian argument applies to quantum mechanics. On the one hand, it is undeniable that scientists have obtained representational access to the quantum world, with current scientific theories about this part of reality leading to extremely accurate predictions. On the other hand, quantum phenomena are notoriously hard to make sense of, even for quantum physicists (see "A case study: quantum mechanics" section). Would McGinn and Chomsky claim that humans are "cognitively closed" to the quantum world? If so, this deflates the thesis of mysterianism, since it allows that we may well develop accurate scientific descriptions of domains to which we are allegedly "closed" such as the mind–body nexus, just as we have already developed accurate scientific theories about the quantum world. If not, then the sense of bewilderment we experience when we contemplate the mind–body problem can only be very weak evidence for cognitive closure, since bewilderment in the face of counterintuitive theories far from everyday experience is nothing new in science.

### **Bare senses and bare brains**

When mysterians are talking about the cognitive limits of our species, are they referring to the limitations of an isolated human brain, or of human brains with various scaffolds and extensions? To highlight the difference, it is instructive to have a look at the limits of human perception. There are a range of physical processes and phenomena that we cannot detect with our bare senses: UV-light, ultrasound, X-rays, radio waves, CO<sub>2</sub> molecules, gravitational waves, and so forth. But of course this is not the end of the story. In order to extend the range of our senses, scientists have developed X-ray film, Geiger counters, radio satellites, spectroscopy, gravitational-wave detectors, and so forth. All this equipment translates physical phenomena into some format that is digestible by our human senses. So are we perceptually 'closed' to UV light? It depends on whether we take into account extension devices.

Just as technology has drastically extended the range of our senses, it has also extended the class of things we can *think*. With the invention of writing, for example, we have vastly expanded the storage capacity of our naked brains.<sup>3</sup> When it comes to understanding the universe, mathematics and statistics have proven to be fantastically successful cognitive scaffolds. For instance, no scientist would be capable of modeling a complex nonlinear system like our planetary climate with their bare brains, but they don't need to, because they have mathematical models and computers to do the heavy lifting.

Perhaps even more importantly, human minds can also be scaffolded by *other* minds. In cases of mutual scaffolding, a network of human brains can achieve a form of collective understanding that is greater than the sum of its parts. Giere (2002) called this phenomenon “distributed cognition” and Dennett (2017) “distributed comprehension”. Many minds working together can understand what none of them would be able to understand on its own. Indeed, according to scholars of cultural evolution, this ability to pool our cognitive resources is the secret to our success as a species, since it allowed for the emergence of cumulative cultural design that is smarter than any human agent (Henrich 2015; Richerson and Boyd 2005; Tomasello 2001). While this collaborative intelligence predates science, probably by tens of thousands of years, modern scientific institutions are the most impressive examples of it (Boudry and Pigliucci 2016; Longino 2015). As a group, scientists can understand much more about nature than any of them would be capable of individually (Campbell 1997; Goldman 1999; Thagard 2012). Continuing the metaphor of mind extension, we can say that the mind of a scientist extends both “horizontally” (contemporary academic peers) and “vertically” (scientists of past generations), a point that was expressed forcefully by Isaac Newton: “If I have seen further it is by standing on the shoulders of giants”.<sup>4</sup> The idea that understanding can only be situated at the level of individual reasoners, according to Dennett, is nothing more than a prejudice arising from the cultural ideal of the “intelligent designer, the genius who has it all figured out” (Dennett 2017, p. 324).

The deeply collaborative nature of science shows that the focus of mysterians on the cognitive limits of a single, isolated human brain misses the point. It is probably true that no single scientist understands all the details involved in the discovery of the Higgs boson or gravitational waves. But collectively, the scientific community does possess such an understanding. It is far from clear if there is any limit to what collective human intelligence can achieve. Progress at the cutting edge of science can become increasingly expensive, demanding ever-increasing cognitive, technological and institutional resources. But there is no discrete limit in sight to what we can collectively represent and understand. By continuing to use and develop

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<sup>3</sup> According to the “extended mind” hypothesis in philosophy of mind (Clark and Chalmers 1998), the human mind literally extends beyond the skin/skull boundary, encompassing notebooks, computer screens, maps, file drawers, and so forth. But one does not need to embrace this radical philosophical view to appreciate how artefacts “extend” the reach of our minds.

<sup>4</sup> Letter to Robert Hooke, February 5, 1675: <https://bit.ly/2hIzhle>.

mind-extension technologies, and by distributing our knowledge across many different people, human beings can expand their cognitive horizon further and further.

### Hard limits and soft limits

Pronouncements about mysteries and cognitive closure typically evoke the image of suddenly hitting an impenetrable wall, of reaching a discrete limit hard-wired into our biological constitution. We hit upon an ineffable mystery and stare forever in blank incomprehension. But considering the various possible technologies for mind extension, such a hard limit seems unlikely. In the history of science, we have somehow always seemed to be able to work our way around a mystery, to probe it from different angles, to try to partially understand it by comparing it to something else we already understand.

If there really is a limit to human knowledge (representational or imaginative), it is therefore unlikely that it will feel like slamming up against a wall. Another possibility is that science will gradually slow down, as researchers spend ever increasing resources against ever-diminishing returns. Max Planck, one of the pioneers of quantum mechanics, envisaged such limits when he wrote that “with every advance [in science] the difficulty of the task is increased; ever larger demands are made on the achievements of researchers, and the need for a suitable division of labor becomes more pressing” (quoted in Rescher 2006, p. 51). Perhaps this division of labour cannot continue indefinitely, but still there is no clear point at which it must come to a halt. Reaching the limits of human knowledge—to use a contrasting metaphor—might be compared to gradually getting bogged down in a swamp rather than slamming into a wall. As you sink deeper, you have to exert more and more effort to keep forging ahead, but there is no discrete point at which further progress becomes impossible.

## Extending our cognitive reach

### A historical perspective

It is undeniable that, in a lot of respects, human beings have already transcended the innate cognitive limitations of their brains. Even mysterians will not deny that we can now observe UV light and ultrasound, or that we understand the mechanism of global warming with the help of mathematical models. How far can such mind extensions take us? That, *pace* the mysterians, is virtually impossible to tell. First and foremost, since we cannot know beforehand what sort of cognitive (and perceptual) extensions we may develop in the future, we also cannot make definitive pronouncements about the hard limits of human representational access. Secondly,



when it comes to imaginative access, we have to consider the open-endedness and flexibility of human cognition.

By way of analogy, consider digital computers. Computers are similar to, and indeed have historical antecedents in, Jacquard looms, adding machines, and pocket calculators. And yet, digital computers radically transcend the capacities of their homely predecessors. Indeed, because Turing machines are universal computers, there is a sense in which they are key to understanding *all* natural processes as combinations of rules and randomness (Edis and Boudry 2014). In a similar way, human cognition and culture may depend on suites of tools that extend our reach in such a radical way that our cognitive powers transcend those of our fellow animals. We should consider the possibility that other animals exhibit cognitive closure in much the same way that an adding machine has rigid computational limits, while human cognition is indefinitely extensible in the way a universal computer is limited only by tasks that demand infinite resources.

In order to see the danger of drawing premature inferences about cognitive limitations, imagine that extraterrestrial ‘anthropologists’ had visited the earth around 40,000 years ago to write a scientific report about our species and its cognitive prospects.<sup>5</sup> Suppose that some mysterians among their lot had argued as follows:

Millions of years of evolution on this planet have equipped the minds of these creatures to deal with macroscopic objects and environments characterized by low gravity and travel at slow speeds. None of these earthlings have ever traveled close to the speed of light, spent time in the vicinity of truly massive objects, or experienced quantum phenomena. Because conditions on the surface of this planet happen to approximate zero-curvature geometry and the classical limit of quantum mechanics, evolution by natural selection has hard-wired this local ecology into their brains. Alas, this means they have no innate capacity for understanding simple things like space-time curvature or wave functions. As long as their biological constitution remains the same, these unfamiliar physical domains will forever remain beyond their ken.

But those extraterrestrial anthropologists would have been dead wrong. Even though our biological constitution did not alter significantly since 40,000 years ago, we did manage to develop a scientific understanding of non-Euclidean geometry and space-time curvature, not to mention state vectors in Hilbert spaces. We have succeeded in unraveling the phenomena of modern physics by using various tools and strategies to extend our cognitive capabilities and our perceptual limits, by developing the indefinitely extensible language of mathematics, and above all, by pooling our cognitive resources.

Bearing in mind that representational access does not entail imaginative understanding, it is still possible for mysterians to retreat to a weaker position. It is one thing to have an accurate scientific theory of the quantum world or the mind–body nexus, but it is another thing altogether to comprehend such a theory. As we already pointed out, however, if mysterians are merely claiming that some theories will be

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<sup>5</sup> This thought experiment was earlier used in an essay for *The Conversation* (Boudry 2019).

very difficult to understand once we have obtained them, their position becomes far less interesting, because this sort of situation is already familiar from modern physics. Moreover, it is not clear if our imaginative understanding will encounter any hard limit either. Consider that many scientific theories which we are familiar with now also struck people as bizarre and counterintuitive when first proposed. In his book on the counterintuitive nature of science, Robert McCauley has expressed this point:

When first advanced, the suggestions that the earth moves, that microscopic organisms can kill human beings, and that solid objects are mostly empty space were no less contrary to intuition and common sense than the most counterintuitive consequences of quantum mechanics. (McCauley 2000, pp. 69–70)

Because we have grown accustomed to these older theories, they have lost something of their original shock value. But this provides reasons for optimism. If we have become better at making sense of empty space and the principle of inertia, we may also become better at comprehending space-time curvature and non-locality. Indeed, this argument provides grounds for what we may call an “optimistic meta-induction” about the history of science. Ideas and theories that once seemed bizarre and incomprehensible may gradually yield to a more intuitive understanding. For instance, experts in general relativity today can acquire a more intuitive feel of time dilation, space-time curvature and higher dimensions, after years of exposure to such theoretical notions (Goldberg 1984; Mermin 2009). To conclude, let us now briefly apply these ideas to the case of quantum mechanics, which has perhaps the most daunting reputation for being impossible to make sense of.

## A case study: quantum mechanics

### The counterintuitive nature of the quantum world

While it is hard to comprehend a curved 3 + 1-dimensional spacetime continuum, general relativity is still a classical theory. Physicists learn to think about general relativity while remaining anchored in the easily visualizable background of classical mechanics. Classical states can be described as a list of physical variables, or a point in an appropriate phase space—hence even at a high level of abstraction, classical physics retains a connection with intuitively available pictures such as projectile motion. Quantum mechanics, by contrast, is much further removed from everyday physical intuitions—as expressed by Richard Feynman, who remarked that “I think I can safely say that nobody understands quantum mechanics” (2017, p. 129).<sup>6</sup>

Some of the difficulties in intuitively understanding quantum mechanics are due to features such as superposition and the fundamental role of randomness. The most

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<sup>6</sup> It is curious that mysterians have not explored quantum mechanics as a possible example of a domain to which we are cognitively closed. This might perhaps be attributed to the fact that quantum mechanics is notoriously demanding, to the extent that even confidence about its status as a mystery might be hard to come by.

common approach to quantum mechanics describes states as “wave functions,” or, more generally, vectors in a Hilbert space. State vectors are superpositions of eigenvectors of mathematical operators corresponding to physical observables. A typical quantum state, therefore, represents multiple possible measurable results; indeed, quantum mechanics only predicts probability distributions for experimental outcomes. This inherent randomness is conceptually challenging, and probabilistic thinking is already intuitively difficult for most people, including physics students (Bao and Redish 2002). But the difficulties run deeper. The components of quantum state vectors—the coefficients multiplying the appropriate eigenvectors—are complex rather than real numbers. The magnitude squared of these complex numbers give the probabilities, while the relative phases produce the notoriously counterintuitive quantum interference phenomena. Quantum states, therefore, represent not probabilities but *probability amplitudes*, a concept that is unique to quantum mechanics. Conceptually, quantum states are far removed from pictures—such as those of projectiles—that are rooted in folk physics.

Moreover, our understanding of quantum mechanics very heavily depends on mathematics, and the mathematical degrees of freedom in describing the quantum realm are such that even the fundamental objects representing physical states are not completely settled. For example, it is possible to do quantum mechanics without state vectors, and hence without probability amplitudes. The same information can be represented through real-valued functions in classical phase space known as “Wigner functions,” which are conceptually closer to probability distributions except that they can take on negative values (Zachos et al. 2005). Physicists do not even attempt to reach agreement on a “true” picture of a quantum state; our representations function pragmatically as mathematical devices to generate the probability distributions subject to experimental tests. So every available way to do quantum mechanics is far removed from folk physics and associated notions of imaginative access.

In that case, how much progress can we make toward understanding quantum mechanics on an intuitive level? To address this question, let us look at the most important strategies for extending our imaginative reach.

### Mind-stretching through metaphors

Metaphors and analogies allow us to understand something new, unfamiliar or alien in terms of something we already know. It is a form of “mapping across domains” (Carey and Spelke 1994), in which we apply the core principles of one mental category to the set of entities of another, thereby enriching or overriding our grasp of the world. In particular, metaphors work by highlighting structural similarities between a source domain and a target domain, and transferring understanding from the former to the latter. Just as in any other domain of science (Brown 2003), quantum physicists have extensively relied on metaphors to make sense of what has seemed incomprehensible at first. Max Planck’s notion of a “quantum” uses our everyday experience with discrete bundles or packages of matter. J. J. Thomson’s model of the structure of the atom uses the image of a plum pudding, with negative electrons

distributed in a positively charged atom “pudding”, while Ernest Rutherford’s model draws an analogy with the structure of the solar system, with electrons going around the nucleus in orbit (Brown 2003, pp. 74–99). In current versions of quantum mechanics, these analogies have been largely superseded, but metaphors drawn from everyday experience continue to recruit the intuitive imagination of physicists and lay people alike. The central concept of quantum “superposition” is a metaphor exploiting our spatial imagination, which invites us to think of quantum states as discrete entities stacked on top of each other. Quantum “entanglement” draws an analogy with strands or ropes that are inextricably intertwined with each other.

Physics education at all levels draws heavily on such metaphors. Some are only used for scaffolding: students learn about the planetary model of atoms, but later they will confront its failures, moving on to Bohr’s variation on the planetary model, and then examining the Bohr model’s failures in order to motivate a proper quantum approach. Some metaphors continue to guide the way physicists work. For instance, the standard Hilbert space formulation of quantum mechanics draws on physicists’ experience with waves and vectors in many other areas of physics, even though infinite dimensional complex vector spaces can harbor mathematical oddities that cannot be anticipated through familiarity with the three-dimensional vectors of introductory courses. Such metaphors also help develop real intuitions—as they advance, students acquire intuitions about quantum phenomena, though they will never be able to dispense with the mathematics. A beginner has to trust the math, and carefully calculate to obtain even trivial results. An expert is often able to perceive, even if they can’t always articulate how, that something feels wrong about an erroneous conclusion. A beginner can do little more than trust a mathematical procedure; an expert will develop insight into quantum physics to a degree where they often, by doing back-of-the-envelope calculations and drawing on analogies with other domains of physics and mathematics, know what sort of result should be expected even before a detailed calculation is carried out. Indeed, such developed intuitions are vital for exploring physics beyond fully solvable textbook examples. Much of the research in physics pedagogy concerning quantum mechanics addresses ways to develop improved intuitions in students (Singh et al. 2006).

The Hilbert space formulation of quantum mechanics is dominant partly because of its richness in providing metaphors that exploit connections with non-quantum physics. Its apparatus of linear algebra and partial differential equations are familiar to students in many different physical contexts, and the easily visualized waves of everyday experience often provide direct insight into the behavior of quantum wave functions. Quantum scattering phenomena, for example, are very similar to ordinary wave scattering. The famous Heisenberg uncertainty principle is best approached as a property of waves, without anything especially ‘quantum’ about it.<sup>7</sup> Physicists do not just learn quantum mechanics as an abstract formalism; they develop a toolkit of metaphors and concrete visualizations that help with developing approximations and avoiding blind alleys in research.

<sup>7</sup>  $\Delta x \Delta p \geq \hbar/2$  is really  $\Delta x \Delta k \geq 1/2$  for waves in general, combined with the de Broglie relationship of  $p = \hbar k$ .

Alternative mathematical formulations of quantum mechanics, such as working with Wigner functions rather than vectors in Hilbert space, can further help develop this understanding. Few physicists learn about Wigner functions, and almost never at an undergraduate level, because the mathematical apparatus to deal with Wigner functions is not shared between many different domains of physics. But once mastered, the phase space formalism can be an anchor for developing fresh metaphors. Even though the predicted probability distributions remain the same, and therefore the different formulations are identical in physical substance, they provide different conceptual anchors and motivate varying intuitive approaches to problems. Varying mathematical approaches support different metaphorical scaffoldings to help physicists establish a feel for quantum mechanics.

When considering the limits of imaginative understanding, it is also important to note that metaphors and analogies can be recursive. Not only can we compare anything to anything, but a target domain of one metaphor can become the source domain of a different metaphor. For instance, Rutherford's model of the atom uses the analogy of the structure of the solar system, with planets (electrons) orbiting the sun (nucleus). But the heliocentric model was itself a relatively recent invention, which was intuitively hard to make sense of when initially proposed. Newton explained how planets can be orbiting the sun by using the thought experiment of a cannonball that is being shot horizontally on top of a large mountain (Newton and Cohen 2004). Indeed, many of our most abstract concepts are rooted in metaphors and analogies that are in turned based on more basic analogies, all the way down to our most fundamental everyday concepts (Lakoff and Johnson 1980, 1999).

Naturally, every analogy is imperfect in some way, and some may lead even scientists astray (Boudry and Pigliucci 2013). Atoms are only superficially like our solar system, and different physical states are not literally stacked on top of each other. But different analogies and metaphors can be used to overcome each other's limitations, or function as temporary scaffolds to attain a higher level of understanding. For our argument, we need not assume that any given metaphor provides a perfect understanding of quantum phenomena. It suffices that some metaphors allow us to get *some* intuitive purchase on otherwise incomprehensible phenomena. Even experienced physicists who teach quantum mechanics to others may never develop a complete intuitive understanding of quantum phenomena, forming only approximate images and partial mental representations. Nonetheless, they can improve their imaginative understanding as they go along. If they face any limit in trying to grasp quantum mechanics, it will be swamp-like rather than wall-like. This is all we need to soften up the radical thesis of imaginative closure. It is possible that in the future only a few people, and eventually no-one at all, will be able to wrap their heads around some scientific theories, but it is also possible that we will just become better and better at wading through the swamp. In any event, a hard cognitive limit such as envisaged by the mysterians seems to be an implausible assumption.

## Discussion

### Epistemic modesty?

Mysterians often present their arguments as displaying appropriate modesty in the face of the cosmos and its mysteries. Would it not be the height of hubris to imagine that the human brain, a product of biological evolution just like any other organ, can unravel all mysteries and understand everything there is to understand about the cosmos? On closer inspection, however, their position is far less modest than it appears. Take McGinn's confident pronouncement that the mind–body problem is “an ultimate mystery [...] that human intelligence will never unravel” (McGinn 2000, p. 5). In order to secure this conclusion, McGinn needs knowledge about three different things: the nature of consciousness, the constitution of the human mind, and the reasons for the mismatch between the two.<sup>8</sup> In particular, following our framework, mysterians have to demonstrate that no possible combination of mind extensions (including all possible mind extensions which could be developed in the future) will bring us any closer to an understanding of consciousness. Not only is this a taller order than mysterians have acknowledged, but it also leads them into a paradox. In his pronouncement about the mystery of consciousness, McGinn is assuming more knowledge about consciousness than his own transcendental naturalism allows.

To some extent, McGinn has attempted to rise to the challenge with his CALM-conjecture. Phenomena like consciousness and the human self, according to him, have a “hidden structure” that defies description in terms of CALM-like properties. At this point, however, the CALM-conjecture remains a speculative proposal that bears little relation to state-of-the-art cognitive science. Indeed, as mysterians succeed in spelling out exactly what it is about the human mind that makes knowledge of certain mysteries inaccessible, they risk being hoisted by their own petard. As Dennett writes:

As soon as you frame a question that you claim we will never be able to answer, you set in motion the very process that might well prove you wrong: you raise a topic of investigation. (Dennett 2017, p. 374)

In any event, to claim that at the outset that human brains will *never* understand some problem, when scientific inquiry into that problem has only just begun, is far removed from the ideal of epistemic modesty championed by mysterians.

### Conclusion

By distinguishing between different forms and modalities of cognitive limitation, and exploring the different strategies for mind extension, we have arrived at a more optimistic assessment of our species' epistemic prospects. First, mysterians often talk about the limitations of a single, isolated brain, but such limits miss the point and are often trivial or uninteresting. Humans have developed a range of devices for extending not just the range of their senses, but also the range of their minds.

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<sup>8</sup> In this respect, a more consistent (and radical) form of mysterianism can be found in Kriegel (2003), who maintains a strict second-order ignorance about the reasons for our sense of mystery.

Second, imaginative closure does not entail representational closure. It is conceivable that human beings succeed in accurately *representing* some aspects of the world, but then prove unable to fluidly grasp these theories on an intuitive level. Third, mysterian arguments typically evoke the image of hitting a hard wall of knowledge, but there are other more plausible options. Given the flexibility of the human mind, and the myriad possibilities for mind extensions, it is more likely that we will encounter a scenario of diminishing cognitive returns. Reaching the end of scientific inquiry may feel less like slamming into a brick wall than getting bogged down in a swamp. Even when it comes to imaginative access, our prospects are not that bleak. By bending, twisting, stretching, and pumping up our imagination—all metaphors in their own right, naturally—it is possible to develop an intuitive understanding of phenomena that our minds have not been designed by evolution to understand.

Naturally, we can never completely rule out the possibility that human inquiry will one day come to an abrupt end. Some areas of reality may never be fully represented and some theories never fully comprehended. To assume otherwise would be epistemic hubris indeed. But in light of the remarkable history of scientific successes, and the myriad and open-ended possibilities for mind extension, any such pessimistic pronouncements remain premature.

**Acknowledgements** We would like to thank Manvir Singh in particular for making extensive comments on an earlier draft of this paper, thus lending his versatile mind to “scaffold” ours. We also wish to thank Daniel Dennett, Stefaan Blancke, two anonymous reviewers and several participants during a seminar at the Centre for Logic and Philosophy of Science at Leuven University, for offering useful feedback and constructive criticism.

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