**Title: The end of inquiry? How to overcome human cognitive limitations**

**Abstract**

What, if any, are the limits of human understanding? Epistemic pessimists, sobered by our humble evolutionary origins, have argued that some truths about the universe are perennial *mysteries* and will forever remain beyond our ken. Others have brushed this off as premature, a form of epistemic defeatism. In this paper we develop a conceptual toolbox for parsing different forms of cognitive limitation that are often conflated in the literature. We distinguish between *representational access* (the ability to develop accurate scientific representations of reality) and *intuitive* *understanding* (the ability to comprehend those representations). We also distinguish different modalities of cognitive limitation. If the scientific endeavor ever comes to a halt, will this feel like slamming into a brick wall, or rather like slowly getting bogged down in a swamp? By distinguishing different types and modalities of human cognitive limitation, we soften up the hypothesis of ‘cognitive closure’ and ultimate ‘mysteries.’ Next, we look at specific mechanisms and strategies for overcoming our innate cognitive limitations. For a start, we are not restricted by the limits of a single, bare, unassisted brain. One of the central features of human intelligence is the capacity for mind extension and distributed cognition. This enables us to radically extend our representational access, as witnessed by the history of science. Less obviously, scientists can extend their intuitive understanding as well. They do so by deploying different cognitive mechanisms which, importantly, are combinatorial and open-ended. In light of all these possibilities for extending the limits of understanding, we conclude that there is no good reason to suspect the existence of an outer wall of human comprehension, as several prominent epistemic pessimists have suggested.

Keywords: cognitive limitation; intuitive understanding; representational access; epistemic pessimism; new mysterianism; mysteries; cognitive closure; epistemic boundedness

[1 Introduction 3](#_Toc516146725)

[2 Biological limitations 5](#_Toc516146726)

[3 Kinds of limits 6](#_Toc516146727)

[3.1 Representational vs. intuitive limits 7](#_Toc516146728)

[3.2 Jumping from intuitive to representational limits 10](#_Toc516146729)

[4 Extending our representational reach 11](#_Toc516146730)

[5 Extending our intuitive reach 12](#_Toc516146731)

[5.1 A serious challenge: quantum mechanics 12](#_Toc516146732)

[5.2 Mapping across domains 15](#_Toc516146733)

[5.3 Analogies and metaphors 15](#_Toc516146734)

[5.4 Recursion and cumulation 18](#_Toc516146735)

[5.5 Wading through the swamp 19](#_Toc516146736)

[5.6 A thought experiment 21](#_Toc516146737)

[6 Conclusion 23](#_Toc516146738)

# Introduction

*“Nature initially arranged things her own way and subsequently so constructed the human intellect as to be able to understand her”* – Galileo Galileo in his *Dialogues*, 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 realize, after billions of years of unguided evolution. Among some thinkers, this line of thought has inspired pessimism about the epistemic prospects of the human race (Fodor, 1983; McGinn, 1993; Stich, 1990), and even led to a minor backlash against the naturalist worldview (Plantinga, 2011; Nagel, 2012; Boudry and Vlerick, 2014). Given our humble evolutionary origins, these epistemic pessimists have argued, we have no reason to suspect that (human) science will penetrate the deepest riddles of the universe. Indeed, it would be miraculous if the human brain were capable of any such feat. We are lucky that science has already advanced as far as it does, and we should not expect indefinite further progress. Some questions are doomed to remain “mysteries” (Chomsky, 1988). Just as the minds of other animals are closed to mathematics, polyphony or humor, some mysteries will never yield to human inquiry. To think otherwise is a blatant form of epistemic *hubris*.

However, not all those who embrace a purely naturalistic worldview share the epistemic pessimism of these so-called “New Mysterians” (Flanagan, 1992). According to Dennett (1991a; b) the pessimists have rushed to premature conclusions after only a “paltry canvassing of the opportunities” and have thus forfeited their intellectual responsibilities. Humphrey (1999, p. 218) has lamented the “continuing despondency” of the mysterians in the face of our advancing knowledge, and Flanagan (1992, p. 9) has speculated that they are motivated by a desire to “drive a railroad spike through the heart of scientism, the view that science will eventually explain whatever is natural.”[[1]](#footnote-2) In stark contrast to the conclusions reached by the new mysterians, but starting from the same evolutionary perspective on the human mind, these naturalists have developed a much more optimistic view of the epistemic prospects of humanity. If we take the evolutionary origins of the human brain as a starting point, these optimists argue, we should expect the world to be intelligible to us, precisely because we evolved *in* that world, and our survival depended on understanding it (Griffiths and Wilkins, 2015; Boudry and Vlerick, 2014). More fundamentally, if the universe were totally incomprehensible, we would not have evolved intelligence in the first place, or as Rescher (1990) put it: “A world in which intelligent creatures emerge through the operation of evolutionary processes must be an intelligible world” (Rescher, 1990, p. 65).

Both parties in this debate accept the purely natural origins of the human brain and all its faculties, as well as the mechanism that is (largely) responsible for them, but they end up with radically different conclusions about our epistemic prospects. How is this possible? In this paper, we introduce an enriched conceptual framework for thinking about the limits of human understanding, and we discuss specific strategies for overcoming our innate cognitive limitations. While the universe increasingly seems to throw up barriers to scientific understanding, over time we have also designed various strategies for overcoming these cognitive limitations. In light of the numerous mind-extension devices we have at our disposal, we argue that there is no reason to suspect that we will soon (or ever) reach an outer wall of understanding. This, of course, does not mean that, as a matter of fact, humans will sooner or later come to represent and understand everything there is to know about the universe. It merely means that we should not expect to ever arrive at some ultimate “mystery” that is resistant to any attempt at understanding. What is more, we will argue that such positive affirmations of ultimate “mysteries” are in fact far less modest than they appear.

In section 2, we briefly introduce the mysterian claim that our biological provenance entails cognitive closure. In section 3, we dissect the broad notion of cognitive limitation, by distinguishing between representational and intuitive limits. In section 4, we introduce the different ways of overcoming both kinds of limits and point out what this implies for our epistemic prospects.

# Biological limitations

Given that our minds are natural and biological organs with functional specifications and limitations, some aspects and properties of the world must lie beyond our ken. This, at least, is the line of reasoning developed by Fodor (1983), Chomsky (1988; 2014; 2005), McGinn (2000; 1994; 1993) and, to some degree, Pinker (1997). In the arguments of the new mysterians, analogies with other species play an important role. Just as dogs or cats will never understand prime numbers, polyphony, the rules of chess, or the properties of electrons, human brains must be closed off from *some* of the world’s wonders. If you think that human beings, alone in the natural world, are free from any such cognitive limitations, you buy into the myth of human exceptionalism. Jerry Fodor strongly suspects that this notion of “epistemic unboundedness”, or the assumption of unlimited cognitive capacities, is just “incoherent” (Fodor, 1983, pp. 122-123). And even if it is coherent, such hubris seems to grate against a naturalist outlook, in particular the notions of evolutionary gradualism and continuity. Darwin, after all, taught us that the difference between human beings and other animal species is but a difference in degree. For Noam Chomsky, therefore, the existence of human cognitive limits is an obvious “truism” for anyone who accepts the central facts of modern biology, namely that humans are “part of the organic world” (Chomsky, 2014). In particular, Chomsky (2000, p. 83) has argued that all human scientific activities are undergirded by a “science forming faculty” – loosely defined as those cognitive capacities that “enter into naturalistic inquiry.” This innate faculty constrains our epistemic scope: the answer to some of our inquiries about the world are out of reach and will always remain mysteries.

Even someone like Steven Pinker (1997), himself often accused of “scientism” and scientific imperialism (Wieseltier, 2013), is sympathetic to the pessimism of the new mysterians. Evolution by natural selection, according to Pinker, is an opportunistic and short-sighted *bricoleur*. It produces quick-and-dirty, satisficing solutions to adaptive problems in an organism’s environment. It is also a ruthless economizer, not endowing organisms with any more brainpower than is strictly needed for their survival and reproduction. It is too much to hope for that such as an opportunistic tinkerer would produce an organ – the human brain – that is capable of comprehending all the mysteries of the universe. 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).

But the argument from common biological ancestry moves too quickly. Our biological affinity to other species does not automatically imply that we suffer from similar cognitive limitations, differing only in degree. By way of analogy, consider the example of digital computers, or Turing machines. Digital computers are similar to, and indeed have historical antecedents in, Jacquard looms, adding machines, and pocket calculators. And yet, they 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 to such an extent that our cognition transcends 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.

# Kinds of limits

Mysterians 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. Most of them also seem to be talking about the limitations of a single and unaided human brain, while science is the collaborative enterprise *par excellence.* Finally, there is an important ambiguity in their thesis. Are they claiming that human beings will never possess the true scientific theory of some part of the world, or alternatively, that we will never *comprehend* that theory once we possess it? In other words, mysterians conflate various sorts of cognitive limitations, biases and challenges. If we want to think about human cognitive limitation, we need a better conceptual framework.

## Representational vs. intuitive limits

Our discussion will focus on cognitive limitations that are arise from the architecture of the human brain, and are thus specific to the human species. In other words, we are looking for alleged mysteries which, even though they may be perfectly accessible to another type of cognitive being, will forever remain beyond human reach. For the sake of completeness, we should note that we may also be under epistemic limitations arising from our spatio-temporal location in the universe, or from general computational or parametric principles. For example, some parts of the universe may be beyond our event horizon, and some problems might require more computational resources than are available in the universe. Fodor dismisses such limitations as merely “boring possibilities associated with parametric limitations of one sort or another” (Fodor, 1983, p. 121), which “even the most starry-eyed epistemic optimist” would be willing to accept (for a good overview, see Rescher, 2006).

The central question in this paper is a different and less “boring” one: do we suffer from any species-specific cognitive limitations, and what would they consist of? Here we should distinguish two different predicaments. In one scenario, there is a domain or aspect of reality which, because of some insurmountable cognitive or perceptual barrier, human beings will never be able to probe or penetrate. For our species, accurate scientific representations of this part of reality would be out of reach, even though it might still be accessible to other cognitive beings. In this scenario, human beings lack *representational access* to some 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 extension devices, see 4.1), but it is impossible for us to *comprehend* or *grasp* the relevant scientific theory of that part of reality. No matter how hard we try, we cannot seem to wrap our heads around it. Because of some species-specific cognitive limitation, these representations of reality will forever bewilder and baffle human beings. In this case, we suffer from an inability to develop *intuitive understanding* of a certain theory or representation (AUTHOR’S REF).[[2]](#footnote-3)

It should be clear that, at a first approximation, these are two completely different predicaments. Now let us try to define our notion of “intuitive understanding” a bit more carefully. An agent possesses intuitive understanding of some concept or idea if she manages to form an (accurate) internal representation of that concept in her mental workspace, and is able to perform basic mental operations on this mental representation (deriving inferences and predictions, analyzing its constituent parts, making comparisons with other representations). Intuitive understanding is less like an ability to do explicit calculations or to answer questions based on consulting external sources, and more like the deliverances of a well-trained neural network. It is like being able to shoot a free-throw or to anticipate a pass rather than being able to calculate the trajectory of a basketball.

A mathematical example will serve to illustrate the difference between representational access and intuitive understanding. Mathematicians have developed accurate formal representations of four-dimensional objects such as a tesseract, the 4D-equivalent of a cube. Based on this mathematical characterization, they can calculate the number of faces, edges and vertices of a tesseract, and describe other geometric properties, such as its various symmetries, its intersections with other figures, and its projections in two or three dimensions, etc.

But can mathematicians also intuitively represent a tesseract, in the way that we visualize a cube before our minds’ eye? In principle, our spatial imagination is limited to three dimensions, and we have no experience with higher-dimensional objects. Let us suppose, for the sake of the argument, that this cognitive barrier to understanding higher-dimensional objects is insurmountable: no human being will ever be capable of intuitively imagining a tesseract, in the way that all of us can ‘see’ a three-dimensional cube before our mind’s eye.[[3]](#footnote-4) In that case, human beings have *representational access* to the concept of a tesseract, but no *intuitive understanding*.

For the sake of clarity, we chose a well-defined abstract entity such as the tesseract to illustrate our distinction. But the point can be easily transferred to objects and entities in the natural world. Take the theory of general relativity. Physicists conceive of the universe as a four-dimensional space-time continuum that can be curved by the presence of matter and energy. That is, they possess theories and equations to characterize the way in which matter and energy interact with the space-time continuum. Among the predictions of general relativity is that time slows down in the vicinity of massive objects, that light passing close to a mass will be curved by its gravitational field, and that one twin making a space voyage close to the speed of light will be younger than his twin brother when he returns to Earth. Physicists can accurately model these relativistic effects and take them into account when making predictions, for example to calculate the location of a smartphone based on a GPS signal. It is clear that they have representational access to space-time curvature. Still, it remains to be seen if physicists can *intuitively* make sense of the strange phenomena of relativity theory. An even more challenging example is quantum mechanics, which we will discuss more extensively later on.

Remember that we are not talking about obvious parametric limitations (cf. Fodor’s point). Intuitive understanding of a phenomenon, as we define it, does not require that an agent develops an internal representation that is complete and fully detailed. For example, it is obvious that no human brain will ever be able to have a *complete* and fully detailed cognitive representation of the physical structure of the whole solar system as described by general relativity, or of a Helium atom as described by quantum mechanics. For our discussion, the question is not whether we can achieve such a *complete* understanding in our mental workspace, but whether we can develop an intuitive understanding of the basic physical principles and structures involved. In the case of a relativistic description of the solar system, this includes the principles of gravity, worldlines, speed of light, inertia, spacetime curvature... In the case of the structure of the atoms, this includes energy levels, hyperfine splitting, excited states, exchange forces… Our question thus becomes: is such an intuitive understanding possible, or is it ruled out in principle because of some insurmountable cognitive obstacle?

## Jumping from intuitive to representational limits

Representational access describes a relation between the world and our (scientific) representations of it, whereas intuitive understanding describes a relationship between our representations and our minds. It is important to distinguish between these two types of cognitive limitation, because in many pronouncements of mystery or closure, it is unclear exactly what form of limitation is intended, and often different cognitive limitations are conflated.[[4]](#footnote-5) McGinn, for instance, characterizes his thesis as one of “epistemic inaccessibility” (McGinn, 1993, p. 4), the impossibility of “convert[ing] the problem into regular science” (p. 40). About the mind-body problem, McGinn has written that “the correct *theory* is inaccessible to the human intellect” (1994, p. 145, our emphasis). But then McGinn proceeds to offers arguments that only bear on the psychological difficulties human beings experience when trying to *grasp* the relevant scientific theories. Throughout, he uses experiential and phenomenological language to describe the state of perplexity and bewilderment of those who contemplate the problems. For instance, he writes that the mind-body connection is “numbingly difficult to make sense of,” that we suffer from a “feeling of intense confusion,” and that “[t]he head spins in theoretical disarray” when we try to think about it (McGinn, 1993, pp. 27-28). But as we previously argued, intuitive closure does not entail representational closure. It is perfectly conceivable that we succeed in forming a scientific representation of some domain of the world, without being able to understand our own representation on an intuitive level (AUTHOR’S REF).

Noam Chomsky’s account of “mysteries” also seems to vacillate between representational and intuitive limits. According to Chomsky, there are certain problems in science which have perfectly natural answers, but those answers will forever remain inaccessible to our “science forming faculty” (Chomsky, 2000, p. 82). In other words, no scientific progress whatsoever can be made 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 without comprehension. It is conceivable that we can developed accurate representations about some part of reality without being able to wrap our heads around them. It is not clear whether this would qualify as a “mystery” in Chomsky’s sense.

# Extending our representational reach

It is undeniable that the human mind has certain biological specifications and limitations. The question is: what are our prospects for overcoming them? It is instructive to have a look at perceptual limitations first, as our cognitive predicament is partially analogous to it. Human senses cannot directly detect UV-light, ultrasound, X-rays, radio waves, CO2 molecules, gravitational waves, and so forth. But as our very awareness of all these phenomena attests, these are merely the perceptual limits of an unassisted human. To enhance our perceptual limits, we have developed X-ray film, Geiger counters, radio satellites, spectroscopy, gravitational-wave detectors, and so forth, all of which translate physical phenomena that are not directly observable into some format that is accessible to our human senses. Perceptual limitations of unassisted human eyes and brains are real and verifiable, but they do not set the limits of human observation. If we think about our observational limits, we have to take into account not just our biological senses, but also all the possible perceptual extensions that we can develop.

In the same way that technological instruments have drastically expanded our perceptual range, other forms of technology have broadened the class of things we can *represent*. Ever since the invention of writing, and possibly language itself, human beings have been using “external memories,” vastly extending the storage capacity of our naked brains. Indeed, according to the “extended mind” hypothesis (Clark and Chalmers, 1998), the human mind literally extends beyond the skin/skull boundary, encompassing notebooks, computers screens, maps, file drawers, and so forth. Modern physics in particular shows how mathematics can extend our representational reach. Whether in the form of equations or computer models, mathematics be seen as a mind-extension technology, enabling the representation of things that our unaided minds would never be able to represent. Similarly, probability theory and statistics are tools for extending and correcting our naturally poor understanding of chance and probability.

Most importantly, perhaps, human cognition can also extend to *other* minds, as in Giere’s theory of “distributed cognition” (Giere, 2002), Tomasello’s account of the cultural origins of human intelligence (Tomasello, 2001), and various models of cumulative cultural adaptations (Henrich, 2015; Richerson and Boyd, 2005). Modern science is the epitome of such a collaborative cognitive endeavor, in which minds extend to other minds and pool their cognitive resources (Boudry and Pigliucci, 2016; Longino, 2015), enabling them to collectively develop representations that would be unattainable to each individual human mind (Campbell, 1997; Goldman, 1999; Thagard, 2012). The mind of a scientist extends “horizontally,” to the brains of her academic colleagues, but also “vertically,” to minds of scientists of past generations, as was driven home by Newton in his famous phrase: “If I have seen further it is by standing on the shoulders of giants.”[[5]](#footnote-6)

Is there a limit to this representational access to reality? In the past few decades, growing computer power has enabled increasingly detailed modelling of complex systems. No single scientist can hope to understand the details of all the significant processes in complex nonlinear systems such as planetary climates, so our models must be constructed and evaluated by large collaborations. The best understanding of the physical systems and even our models are distributed throughout the scientific community. Of course, with complex systems, progress in understanding becomes increasingly expensive, and the whole communities’ ability to build and validate better models faces increasing resource costs. But there is no discrete limit in sight to the level of complexity we can represent with our theories and models. By continuing to use mind-extension technologies, and distributing our representations of the world across many different people, human beings can expand their representational horizon further and further.

# Extending our intuitive reach

## A serious challenge: quantum mechanics

Representational access does not entail intuitive understanding. It is one thing to extend our representational access to the world, but can we also enhance our intuitive understanding? Our definition of intuitive understanding emphasizes immediate availability of a reasonably accurate mental picture and fluid performance of skills such as approximate predictions and comparisons—like tossing a ball rather than calculating a projectile trajectory. For this type of understanding, it seems more difficult to pool cognitive resources. Groups of human brains can surely collaborate on a complex theory that would be out of reach for each of them working in isolation, but groups of brains have not reached the level of interconnectedness that would justify our attributing some sort of collective understanding to them. Some people have speculated that, with the arrival of the internet, humanity will develop a sort of super-brain or global consciousness (Kurzweil, 2010; Heylighen and Bollen, 1996), but for the sake of the argument, we will assume that intuitive understanding cannot be distributed over groups of people, but must be attributed to single human brains. If no single scientist intuitively understands a certain theory, then neither does a group of them. People can help each other to grasp some bizarre phenomenon on an intuitive level, but at the end of the day, intuitive understanding is something that happens (or not) in their *own* minds.

To explore the limits of intuitive understanding, we will mainly use the example of quantum physics, which probably poses the most daunting challenge for the human mind, and which seems more counterintuitive than even relativity. After all, general relativity is still a classical theory. While it is hard to comprehend a curved 3+1-dimensional spacetime where matter/energy density and local curvature are nonlinearly coupled to one another, classical mechanical state descriptions retain strong conceptual ties to an everyday picture of moving objects. Physicists learn to think about general relativity while remaining anchored in the easily visualizable background of classical mechanics. Quantum mechanics is, notoriously, 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)[[6]](#footnote-7)

Some of the difficulties in intuitively understanding quantum mechanics are due to features such as superposition and the fundamental role of randomness. 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. In contrast, the most common approach to quantum mechanics describes states as “wave functions,” or, more generally, vectors in a Hilbert space. State vectors are superpositions of eigenvectors 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 numbers. The magnitude squared of these 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 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. Every available way to do quantum mechanics is far removed from folk physics and associated notions of intuitive access.

Just as in the case of general relativity, physicists clearly have representational access to quantum phenomena. It is worthwhile to ask: how much progress can we make toward a more intuitive picture? To address this question, let us look at the most important strategies for extending our intuitive reach.

## Mapping across domains

Fodor has argued that there are “constraints on the class of beliefs that the mind can entertain” (Fodor, 1983, p. 125). Because any kind of cognitive system has an “endogenous structure,” there are bound to be “thoughts that we are unequipped to think” (1983, p. 125). But is this endogenous structure rigid and unchangeable, like a prison of understanding? With regards to intuitive understanding, cognitive psychology teaches us that the innate “endogenous structure” of our minds consists of a number of “intuitive ontologies,” cognitive systems for dealing with various sorts of entities: physical objects, living beings, agents, abstract categories. Each of these ontological categories (Boyer and Barrett, 2005; Boyer, 2000) is associated with a number of core inferential principles for dealing with the class of objects in question. In the case of physical bodies, for example, this includes the principles of cohesion, continuity and contact. In the case of the living world, this includes hierarchical taxonomy and essentialism.

If these intuitive ontologies were fixed and informationally encapsulated, that would be the end of the story. The limits of our imagination would coincide with the limits of the intuitive ontologies which evolution has endowed us with. But this is not the case. We can train our minds to apply the core principles of one cognitive system to the set of entities of another system, thereby enriching or overriding our intuitive grasp of the world. Carey and Spelke (1994) have called this process “mapping across domains.” Importantly, this process of mapping across domains is open-ended and combinatorial. It allows us to redeploy our innate set of intuitive ontologies in a wide variety of novel combinations, thereby radically extending our intuitive reach (AUTHOR’S REF). The most important form of mapping across domains is the use of metaphors and analogies. Let us explore those in some detail, and see if this strategy can help us to wrap our heads around quantum phenomena.

## Analogies and metaphors

Analogies and metaphors allow us to understand something new, unfamiliar or alien in terms of something we already know. They work by highlighting structural similarities between a source domain and a target domain, and transferring our understanding from the former to the latter. Many everyday analogies are “near analogies,” which means that source and target domain are relatively close, but scientific breakthroughs are often made by the use of “distant analogies,” in which the boundaries of intuitive ontologies are crossed (De Cruz and De Smedt, 2010). Some authors have argued that metaphors often play a formative role in the development of new scientific theories (Brown, 2003), but in the context of our argument about extending our intuitive reach, we can remain agnostic about this argument. Representational access to the world may or may not be mediated by metaphors, but even if metaphors only play a secondary role in theory development (or none at all), they may still facilitate intuitive comprehension of that theory *once* it bas been developed.

Metaphors can be seen as interfaces for making scientific theories and concepts digestible to its human consumers. They only work for us because our minds have a certain “endogenous structure,” to put it in Fodor’s terminology, and because we have a certain range of prior experiences to draw from as possible source domains. If extraterrestrial beings invent science, we may expect them to arrive at theories that are conceptually equivalent to relativity or quantum mechanics or evolution, but we should not expect them to rely on the same metaphors (if they are capable of metaphorical thinking at all).

Metaphors and analogies are used in every domain of science, but when it comes to sheer incomprehensibility, as pointed out, quantum mechanics has the most daunting reputation. Since the early days of quantum physics, however, metaphors have been used extensively to make sense of what seems 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 modern 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 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.[[7]](#footnote-8) 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.

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.

Naturally, every analogy is imperfect in some way: atoms are only superficially like the solar system, and different physical states are not really stacked on top of each other.[[8]](#footnote-9) Different analogies and metaphors can be used to form an intuitive understanding of quantum phenomena. Some provide only a partial understanding, others are just temporary scaffolds to reach a higher level of understanding. For our argument, we do not need to assume that any given metaphor provides a perfect understanding of quantum phenomena. To soften up the limits of intuitive understanding, it suffices that metaphors allow us to get *some* intuitive purchase on otherwise incomprehensible phenomena.

## Recursion and cumulation

One important thing to notice about metaphors is their combinatorial possibilities, and the possibility of recursion. 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).

The recursive nature of metaphors and analogies can be gleaned from the fact that many of our most abstract concepts are rooted in metaphors and analogies, which are in turned based on more basic analogies, all the way down to our most fundamental everyday concepts (George Lakoff and Johnson, 1980; G. Lakoff and Johnson, 1999). Gentner & Jeziorski (1993) have argued that higher-order cognition is the product of our capacity for analogical thinking. Given the combinatorial possibilities of metaphors and analogies, it becomes very difficult to delineate the limits of our intuitive understanding.

## Wading through the swamp

Pronouncements about mysteries and cognitive closure typically evoke the image of suddenly hitting an impenetrable outer wall of understanding, hard-wired into our biological constitution and impossible to overcome. We reach an ineffable mystery and stare forever in blank incomprehension. But considering the possible technologies for mind extension – both representationally and intuitively – such hard and impenetrable limits of understanding seem unlikely. Somehow we always seem to be able to work our way around a mystery, to probe it from different angles, to partially understand it by comparing it to something else that we already understand.

If there really is a limit to intuitive understanding, it is unlikely that it will feel like slamming up against a wall. It is more likely that we will just experience increasing difficulties in our attempts to comprehend some representations. More and more cognitive effort is exerted, with ever diminishing returns. Max Planck, one of the pioneers of quantum mechanics, envisaged exactly such limits: “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).[[9]](#footnote-10) 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 brick wall. As you sink deeper in a swamp, you have to exert more and more effort to keep forging ahead, but there is no discrete point at which further progress becomes impossible.

Developing intuitions while learning a difficult theory such as quantum mechanics proceeds similarly. Ideally, physicists would like their quantum skills to become second nature, the way an expert automobile driver comes to feel the car as an extension of their body, directing it with little of the explicit attention to detail needed when they were first learning to drive. Due to resource limitations such as the brevity of life, even experienced physicists who teach quantum mechanics to others will never internalize their calculations about quantum phenomena to such a degree. Nonetheless, they can improve their intuitive understanding as they go along, albeit at an increasing cost in time and effort. If they face a limit in intuitively grasping quantum mechanics, it is swampish rather than like facing a hard wall.

In the case of the wall-like limits envisaged by the new mysterians, we would expect little individual variation in cognitive abilities. Some people may be better at understanding difficult subjects, but all of us are bound by the same hard-wired biological limitations. New mysterians are talking about “mysteries” for the human species at large, not just for particular individuals or groups. In the case of swampish limits, however, we would expect to find more individual variation. Some people who are unusually smart or imaginative and have received extensive training, may be able to progress further than others. With increasing resources devoted to the task, we should see some improvement in capabilities, even though the costs might eventually become prohibitive.

In the history of science, such individual variation is precisely what we observe. Most members of the human species will never understand quantum mechanics or population genetics or even heliocentrism, but some will. ­Given sufficient education and training, some people are capable of wrapping their heads around parts of these notoriously counterintuitive theories, forming approximate images and partial mental representations. And some exceptionally gifted individuals will be pioneers of understanding, blazing the trail for others. As Planck noted, however, it is undeniable that that our scientific theories have become more intuitively challenging, and fewer and fewer people are able to comprehend them. The low-hanging fruit has long been harvested by our predecessors, and the remaining problems in science will prove to be very challenging indeed.

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 order to see what metaphors, analogies and visual representations can accomplish in terms of mind extension, it is instructive to look back at the history of science. Being immersed in our modern scientific environment, we tend to forget how bizarre some ideas and theories were when initially proposed. To us, they have lost some of their original shock value, because we have grown accustomed to them. In his book on the counterintuitive nature of science, McCauley makes this point obliquely:

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)

This suggests, indirectly, that both scientists and the public at large have become better at wading through the swamp. And this 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 have gradually yielded to intuitive understanding. This process of familiarizing continues today. Experts in general relativity today, after years of exposure and familiarity with the subject, have acquired a more intuitive feel of time dilation, space-time curvature and higher dimensions (Goldberg, 1984; Mermin, 2009). Much the same can be said of quantum mechanics.

## A thought experiment

In order to see the danger of drawing premature inferences about cognitive limitations, it is instructive to contemplate the epistemic prospects of humanity as they might have appeared before modern science. Imagine that extraterrestrial observers had visited the earth around 15 000 BCE and tried to assess our cognitive potential. They would have noted our modular brain organization, our capacity for meta-representation, our linguistic skills and logical reasoning, our gregarious nature and capacity for communication, and so forth. But they would also have noted our hard-wired intuitive ontologies: our folk physics, folk biology, etc. Suppose that some mysterians among those extraterrestrial visitors had followed this line of reasoning:

Evolution on this planet has equipped the minds of human beings to deal with environments characterized by low gravity, travel at slow speeds, and macroscopic objects. None of these earthlings has ever traveled close to the speed of light, spent time in the vicinity of truly massive objects, or explored quantum phenomena. Because conditions on the surface of the earth 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 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 extraterrestrials would have been wrong. Even though our biological constitution did not alter significantly since 15 000 BCE, we did manage to develop a scientific understanding of non-Euclidean geometry and space-time curvature, not to mention state vectors in Hilbert space. We have succeeded in understanding 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 by deploying a range of metaphors and analogies to recruit our intuitive understanding. In other words, we have gained representational access (we have the science and it works) as well as enhanced our intuitive understanding (we understand the science better and better).

This thought experiment should be a counsel for prudence when it comes to speculation about cognitive limits, whether representational or intuitive, and bold pronouncements of eternal “mysteries”. Even when it *seems* that a cognitive system is bounded or limited in a particular way, as it would have seemed to extraterrestrial visitors around 15 000 BCE, it is almost impossible to foresee all the possible ways in which minds can extend their limits. It is therefore imprudent to admit defeat or to draw pessimistic conclusions that later turn out to be premature.

# Conclusion

As we argued before (AUTHOR’S REF) representational limits do not follow from intuitive limits. It is conceivable that human beings succeed in accurately *representing* some aspects of the world, by way of collective scientific labor powered by various other mind extensions, but then fail to wrap their heads around the representations themselves.

By distinguishing these 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 epistemic prospects. Not only have scientists gained representational access to many exotic aspects of the universe, as witnessed by our impressive predictive and technological successes, but they have also slowly gained an intuitive understanding of even the most bizarre theories. By bending, twisting, stretching, and pumping up our imagination – all metaphors in their own right, naturally – it is possible to acquire an intuitive understanding of phenomena that our minds have not been designed by evolution to understand.

In light of all the possible ways (and combinations of ways) to expand our intuitive reach, we should be wary of affirming that some aspects of the world will never make sense to the human mind. Mysterians have been mostly interested in the mind-body problem or the nature of causation rather than quantum mechanics, but the point applies more generally. If, for example, you want to claim that the mind-body nexus will forever baffle human reasoners, you have to demonstrate that no possible combination of metaphors, mappings, thought experiments and analogies will lead us any closer to understanding this presumed mystery. That is a taller order than the new mysterians have acknowledged (Dennett, 2017). The same point applies to the question of representational limits. In order to demonstrate that we are representationally closedto some part of the universe, you need to show that no possible combination of mind extensions (future technology, advanced mathematics, etc.) and collaborative arrangements between scientists can bring us any closer to representing certain parts of the world. This, ironically, is far from the ideal of epistemic modesty promoted by the new mysterians.

Our experience with the world thus far also provides circumstantial evidence against wall-like closure. In its recent history, physics has made considerable advances modelling domains that are far removed from everyday experience, using counterintuitive but learnable theories. Its limitations, so far, appear to be swamplike, involving simple resource limits rather than some form of conceptual inaccessibility. Perhaps, by some cosmic accident, our brains and our scientific institutions have thus far been peculiarly suited to understand the way the world works even in circumstances relatively far from the environment we evolved in and we may still encounter wall-like limits in the future of scientific inquiry. But the more likely possibility is that with our indefinitely extensible box of cognitive tools, our abilities are more like that of a universal computer than an adding machine. Except for tasks that demand infinite resources, nothing need be in principle beyond our sciences.

Of course, 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 represented and some theories never fully comprehended. To assume otherwise would be epistemic hubris indeed. But, if our arguments about mind extensions are correct, the end of human inquiry will feel more like getting bogged down in an increasingly dense swamp rather than suddenly slamming into a brick wall. There is no reason to assume that there any “mysteries” out there which will forever lie beyond our ken. In light of the history of science, and the myriad possibilities for extending our minds, any such pessimistic pronouncements remain premature.

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1. For a discussion of the problem of 'scientism' and the limits of science itself, as opposed to the limits of human inquiry in general, see AUTHOR’S REF. [↑](#footnote-ref-2)
2. In previous work (AUTHOR’S REF) we called these predicaments, respectively, “representational closure” and “psychological closure”. After some reflection, we have decided that “psychological” as a construct is too broad to contrast with “representational”. Bear in mind, however, that “intuitive” in this context has nothing to do with ‘gut feelings’ or unreflective ‘instincts’, but with *intuitive apprehension*, i.e. the mental ability of an agent to grasp or understand a given representation. This is admittedly still vague, but it will suffice to disentangle the different strands in the literature of the new mysterianism, and to soften up the thesis of cognitive closure. [↑](#footnote-ref-3)
3. In fact, there is a range of techniques for pictorial or schematic representations of multidimensional objects. For instance, mathematicians can project the "shadows" of a tesseract, in the same way in which three-dimensional objects project a shadow on a two-dimensional surface. They can also visualize how a tesseract moves ‘through’ our three-dimensional world, analogous to the way in which a cube can pass through a two-dimensional surface. Another strategy to get an intuitive feel of 4D objects is to use the colour spectrum as the extra dimension. [↑](#footnote-ref-4)
4. 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 huge 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. [↑](#footnote-ref-5)
5. Letter to Robert Hooke, February 5, 1675: http://digitallibrary.hsp.org/index.php/Detail/Object/Show/object\_id/9285 [↑](#footnote-ref-6)
6. It is curious that mysterians have not explored quantum mechanics as a possible example of a cognitively closed domain. This might perhaps be attributed to the fact that quantum mechanics is notoriously demanding, to the extent that even confidence that it presents a mystery might be hard to come by. [↑](#footnote-ref-7)
7. Δ*x*Δ*p* ≥ ℏ/2 is really Δ*x*Δ*k* ≥ ½ for waves in general, combined with the de Broglie relationship of *p* = ℏ*k*. [↑](#footnote-ref-8)
8. Sometimes misleading metaphors can lead the public and even scientists astray Boudry, M., & Pigliucci, M. (2013). The mismeasure of machine: Synthetic biology and the trouble with engineering metaphors. *Studies in History and Philosophy of Biological and Biomedical Sciences*, 44(4), 660-668. doi:http://dx.doi.org/10.1016/j.shpsc.2013.05.013.. But even if we decide to get rid of some bad metaphors, we have no choice but to replace them with new and better ones. [↑](#footnote-ref-9)
9. Planck’s point applies to both what we call representational and intuitive limits. [↑](#footnote-ref-10)