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Imagination: A *Sine Qua Non* of Scientific Understanding

Michael T. Stuart
Center for Philosophy of Science
University of Pittsburgh

ABSTRACT

What role does the imagination play in scientific progress? After examining several new studies in cognitive science, I argue that the imagination plays a crucial, in fact, indispensable role. Namely, it is necessary for increasing scientific *understanding*, which is itself indispensable for science. After outlining this role, I sketch an epistemological account meant to justify it.

Blaise Pascal called the imagination that "deceitful part in man, that mistress of error and falsity." He said it was "all-powerful," and the "enemy of reason." Malebranche referred to our faculty of imagination as the "madwoman in the house," and many fictional and historical catastrophes can indeed cite specific over-active imaginations at their roots. It is imagination that leads Goethe's young Werther to his infamous sorrows, and it is behind the tragic ambition of Mr. and Mrs. Macbeth. We need only reference chapter eleven of *Mein Kampf* for an actual and much more terrifying instance of the imagination being used to justify evil actions. According to George Orwell, Hitler saw himself as "the martyr, the victim, Prometheus chained to the rock, the self-sacrificing hero who fights single-handed against impossible odds. If he were killing a mouse he would know how to make it seem like a dragon" (1940).

Yet the imagination is also a *positive* force in the human condition. To reverse the sexism of Pascal and Malebranche, we are lucky to be so imaginative. Without it we might have no goals at all, no ethics, no knowledge. In the context of scientific discovery, for example, tribute is paid to the imagination quite regularly. Francis Jacob, a Nobel Prize winning biologist, recently wrote:

> It was not a simple accumulation of facts that led Newton, in his mother's garden one day, suddenly to see the moon as a ball thrown far enough to fall exactly at the speed of the horizon, all around the earth. Or that led Planck to compare the radiation of heat to a hail of quanta. Or William Harvey to see in the bared heart of a fish the thudding of a mechanical pump. In each case they perceived an analogy unnoticed up till then. As Arthur Koestler pointed out, everything in this way of thinking seems different from that of King Solomon when he compares the beasts of his beloved Shulamite to a pair of fawns, or that of Shakespeare's Macbeth, when he sees life as "a tale told by an idiot, full of sound and fury." And yet, despite the very different means of expression used by the poet and the scientist, imagination works in the same way. It is often the idea of a new metaphor that guides the scientist. An object, an event, is suddenly perceived in an unusual and revealing light, as if someone abruptly tore off a veil that, till then, had covered our eyes. (2001, 119)

Jacob reminds us that no agglomeration of facts can give us the power over nature that science seeks, or the beauty and novelty of art. Dustin Stokes (2014) argues that even if Bach had known all there was to know about musical relationships, this still would not have been sufficient to compose *The Well-Tempered Clavier* (159-160). And this echoes Jacob's claim above; whatever is going on in scientific discovery, it is not merely the collection of facts. Other Nobel Prize winning scientists gesture to similar senses of imaginative artistry and its necessity in science (e.g. Einstein 1931, 97, 1934, 163; c.f. Holton 1996, Hadamard 1996).

However, it was common in the philosophy of science for a long time to hold that the imagination was not epistemologically relevant other than in the context of discovery. Its most ardent opponents were positivism (see de Regt 2009) and behaviourism (see Barsalou 1999). Partially thanks to the growing influence of science studies since the 1960s, many philosophers and cognitive scientists have reversed this trend, and now see the imagination as an important factor in the production of knowledge, and not just in the context of discovery. One reason for this change was the dissolution of an absolute distinction between the contexts of discovery and justification. Another is the recently emphasized role of the imagination in scientific thought experiments. René van Woudenberg, in his introduction to a special issue of *Metaphilosophy* on thought experiments, claims that "the imagination, perhaps surprisingly, plays an important role in the process of obtaining knowledge: knowledge of certain normative issues, of possibilities, of moral truths, of certain physical matters, of one's self, and more" (van Woudenberg 2006, 160).

To support such a claim, some philosophers have argued that because normative, modal and ethical truths are not accessible to empirical investigation, they must be the result of *mental* investigation (whether rational, as in Brown 2012, or naturalistic as in Nersessian 2007 or Miščević 2007). Considering possible worlds is one way the imagination might play a role in the divination of such truths. For example, the imagination is crucial in making the inference from conceivability to possibility, which is attacked and defended as a means (or mere guide) to modal knowledge. *Conceivability and Possibility* (2002), edited by Tamar Gendler and John Hawthorne, is 528 pages split between 14 essays focused entirely on evaluating the epistemological qualities of this inference.

Without privileging rationalism or naturalism, I would like to take a fresh look at the epistemological role of the imagination in science, specifically through the use of thought experiments. Assuming that they play some role, I want to find out the nature of that role, and the nature of the epistemic good produced. To do this, I am going to present some new results from cognitive science that ask what scientists and students of science learn from thought experiments, and how.

One problem with discussing the role of the imagination is that cognitive science studies rarely refer to the imagination in a general way. Instead it speaks of mental images or the creation of analogies or mental models. Something similar goes on in mainstream analytic philosophy, which deals with the imagination as something that tests modal propositions by seeing whether they are conceivable, or produces psychological states which obey special norms, and much else. (See Gendler 2013 for a representative sample of ways to characterize imagination). In order to connect empirical and epistemological issues, then, I maintain a very inclusive reading of the imagination, delimiting not much more than the mental ability to (re)present things on purpose to ourselves that are not now present via the senses. These (re)presentations need not be propositional or static (like an image), and to allow lots of space for rationalism, their content need not consist entirely of permutations of previous experience. If we like, we could add the requirement that the (re)presentations depart from the truth (following Stokes 2014), which is a reasonable requirement if we want to define the sort of imagination that goes into creating something truly new, but I do not think it is necessary at this level of investigation. Imagining a Boeing 747 at the bottom of the Mariana trench is no less an imagining if there is in fact a Boeing 747 there.

My preliminary conclusion after looking at results in cognitive science is that one important and mostly overlooked use of scientific thought experiment is to create *understanding* as opposed to knowledge. Even though explaining how thought experiments increase scientific understanding would partially address the "primary philosophical challenge" of thought experiments (see Brown and Fehige 2011), many writers focus on the ability of thought experiments to provide new knowledge, empirical evidence or empirical information. Still, increasing understanding is just as epistemologically interesting as providing new knowledge, and in the second half of this paper I will suggest an account that attempts to ground the ability of thought experiments to produce new understanding in the human imagination.

Let us now turn to results in cognitive science. Kosem and Özdemir have recently claimed that "imagery is an indispensable component of scientific reasoning" (2014, 887), and many others agree (e.g., Brown 2006; Clement 1993, 2008, 2009; Gilbert and Reiner 2000; Klassen 2006, Lattery 2001; Reiner and Burko 2003; Reiner and Gilbert 2004). Add to this the claim of Gooding (1992, 285) that "Visual perception is crucial because the ability to visualize is necessary to most if not all thought experiments." Still, it is not immediately obvious how we should go about investigating this component of reasoning. One way is to consider important cases in the history of science. Stephens and Clement (2012) argue that even though such an exercise may be helpful, it is not enough to discern the cognitive mechanisms that underlie imagistic mental reasoning of the type we find in scientific thought experiments. They write:

> It is difficult to analyse the mental processes that allow a scientist to generate and run a thought experiment during an investigation by using historical data because the original thought process can easily be buried under many changes and refinements the author carries out before publishing a thought experiment. Also, for many thought experiments it is hard to know whether they were originally part of a discovery process or created after the investigation to convince others. (2012, 160)

Historical details can only take us so far; we must also study thinking agents in real-time. I will summarize the results of several such studies here. First I will look at studies done on thought experiments in science education, and then I will consider studies of the way thought experiments are spontaneously invented in scientific problem-solving.

Reiner and Gilbert (2000) discuss thought experiments in textbooks by first cataloguing which thought experiments appear where, and for what purpose. Then they compare the original and textbook presentations of famous thought experiments. They conclude that thought experiments help students and scientists understand scientific concepts. What does it mean for a thought experiment to help us understand something? They cite Stephen Toulmin (1972) in explicating what they mean by understanding a concept in terms of being able to use it. A concept of any kind is capable of use, and therefore understood, if two criteria are met: if it is intelligible, in that the user knows what it means; and if it is fruitful, in that it enables the user to achieve a goal or to identify new possibilities.

I highlight this characterization of understanding because most of the below-mentioned studies are easily brought under its framework. Scientists and their students must be able to use new concepts, otherwise they serve no purpose. And one cannot use a new concept without knowing what it means, or in other words, without the concept being intelligible. Intelligibility is not always so easy to achieve, especially in abstract disciplines like science, and we will see that thought experiments are sometimes capable of affording this desideratum. Also, if one understands a concept, one can achieve something with it. Thought experiments help us explore the consequences of adopting certain concepts, and see how conceptualized phenomena interrelate, and this opens up new possibilities for theorizing, modeling, and constructing experiments.

Building on this simple framework, Reiner and Gilbert argue that thought experiments in science textbooks (as opposed to in scientific peer-reviewed literature), are not used effectively. In scientific literature, most thought experiments are presented in the following way: We begin with a scenario or problem-statement. We create an imaginary world to help us explore the scenario or problem. We "set up" or "design" a thought experiment in this world, which we then "run" and "observe." Finally, we draw a conclusion about the initial problem or scenario. This presentation-style spurs members of its audience to make new connections on their own. On the other hand, textbook presentations are only "mental simulations," where the conclusion of the thought experiment is given first, and then the imagined scenario is introduced, which lends credence to the conclusion. In a mental simulation, students do not vary variables in their minds; they simply follow along a text (Reiner and Gilbert 2000). This is counterproductive for achieving Toulmin's two conditions. If you do not perform the thought experiment or otherwise establish the conceptual connections for yourself, a scientific concept or theoretical structure will have diminished meaning for you, or have no meaning at all. It is also less likely that you will see all or any of the ways to use the concept and make it fruitful.

Velentzas, Halkia and Skordoulis (2007) look at textbooks as well, and they show that what James R. Brown calls "constructive" thought experiments (Brown 1991, 36), i.e., those that provide evidence for or establish a theory, are preferred by textbook authors to what Brown calls "destructive" thought experiments (Brown 1991, 34), which function like counterexamples. The thought experiments used most commonly in physics textbooks are Einstein's train, Einstein's Elevator, and Heisenberg's Microscope. Perhaps this is because constructive thought experiments like these show students how their everyday experiences can translate into modern day physical theory, which motivates them to learn (2007, 365ff.). In other words, they "build bridges between students' knowledge and everyday experience and the new or modified concepts and principles which have to be learned" (359). Building such bridges would certainly help to make a new concept intelligible and useable for a student. One way to interpret the results of this study is that destructive thought experiments are not as useful for building bridges. However we will see below that destructive thought experiments are indeed successfully used for this purpose, and therefore something else must be responsible for the popularity of constructive thought experiments in science textbooks.

This study inspires several more papers by Velentzas and Halkia. In the first (2011), they discuss Heisenberg's Microscope "as an example of using thought experiments in teaching physics theories to students." They begin by citing Alexander Koyré, who claims that thought experiments "help scientists to bridge the gap between empirical facts and theoretical concepts" (Koyré 1968). They agree, and argue that while Heisenberg's microscope thought experiment is not generally well regarded by physicists (either at Heisenberg's time or now), the thought experiment is still quite useful for introducing the uncertainty principle in quantum mechanics, which they taught to 40 high school students in grade 11 using the thought experiment. Here is how: first they introduced some important concepts from quantum mechanics, and then let the students work through the thought experiment mostly on their own. What does it mean to conduct a thought experiment "mostly on one's own"? Their methodology is somewhere between an interview and a class. Through Socratic question and answer, the students were allowed to work through their guesses, and if they went too far off track, they were gently guided back. Velentzas and Halkia recorded the sessions in order to code and analyze them, and administered a test two weeks later for comprehension. They concluded that many students could and did learn the uncertainty principle from the thought experiment. And not merely for the case of gamma rays and microscopes; they appreciated the principle independently of any considerations of specific measuring apparatuses.

Next they turned to General Relativity (2013a). In this paper the authors concluded that thought experiments in General Relativity make it possible for students to "grasp physical laws and principles which demand a high degree of abstract thinking, such as the principle of equivalence and the consequences of the constancy of the speed of light to concepts of time and space" (3026). They found this achievement more surprising than in the case of the uncertainty principle, because students have very strong folk intuitions which seem to interfere with understanding General Relativity. For example, students generally do not understand the concept of "inertia," imbuing what looks like magical power to it. They also assume that their intuitive concept of time could not be wrong; that space is empty and separate from time; that observers may have a point of view, but that this has no bearing on physical laws since there is always a higher frame that we can escape to which makes visible the *real* answer (Arriassecq and Greca 2012).

However the authors did manage to convey the difficult concepts of General Relativity to the students successfully, letting them work through thought experiments like Einstein's elevator and train. They recorded the sessions and analyzed them, and then administered a test two weeks later for comprehension. They succeeded, and concluded that thought experiments are used "both for clarifying the consequences of physics theories and for bridging the gap between the abstract concepts inherent in the theories and everyday life experiences" (3027).

Finally, in their (2013b) the authors turned to Newton's Cannon. As in the above two cases, the authors got the students to work through the thought experiment on their own, and to see that projectile motion and orbital motion are governed by the same laws. The authors claim that Newton's thought experiment "can act as a bridge which enables students to correlate the idea of the 'downward' motion of objects drawn from their everyday experience with the same objects' motion 'to the center of the Earth'" (2623). To make this possible, students had to see the Earth from above, and extend their knowledge of regular projectile motion to a scale large enough to replicate suborbital and orbital motion. This allowed them "to link the motion of a projectile as it can be observed in everyday situations with the possible case of a projectile that can move continuously parallel to the ground in a context where the whole Earth is visible" (2623).

The metaphor of "bridging" is common to all of these studies, and continues to be invoked below. I think it is significant because it relates to Toulmin's second condition. When a bridge opens, new territory becomes accessible. The territory was already there, but we did not have access to it. A concept is not *fruitful* if it does not make possible new and identifiable uses of the concept, and one way that we do this is by connecting the concept via "bridges" to existing concepts and experience. Such activity can open a means of access.

Velentzas and Halkia conclude that thought experiments are useful in science education because they help students learn to apply difficult scientific concepts. But there are two other interesting conclusions they draw in their (2013b). One is that thought experiments are pedagogically superior to computer simulations, because only in a thought experiment is it completely up to the student to see how the outcome of the imagined scenario results from the parameters. A computer simulation where the earth is seen from above and the student can program in different projectile velocities and subsequently see how these changes affect the motion of a projectile, was useful and certainly better than merely calculating consequences of Newton's laws for the students. But in these cases the student takes a passive role by setting the parameters and waiting to see what happens. In a thought experiment, students mentally "set" the parameters, and then in addition have to figure out what will happen. And instead of trusting to the algorithms of a computer, students must provide some reason to believe the system will evolve as it does in their imaginations. Also, talking through imaginary scenarios enables teachers see where a student stands with respect to their comprehension of the theory. Therefore the authors conclude that there is good evidence that thought experiments will not be replaced by computer simulations in the near future, at least in the classroom.

This is related to their second important conclusion, that "in any experiment, the manipulation of ideas is more important than the manipulation of materials" (2638). That is, "hands on is less important as compared to minds on" (Duit and Tesch 2010). Presumably the authors mean that manipulating laboratory equipment is pedagogically less useful to a student who does not grasp the deeper meaning behind these events. And with respect to the goal of increasing scientific understanding, this is something worth stressing.

Now that we have discussed some of the findings of thought experiments in science education, let us look at how thought experiments originate *in situ*.

In "The Symbiotic Roles of Empirical Experimentation and Thought Experimentation in the Learning of Physics," Reiner and Gilbert argue that in the course of solving empirical problems, subjects often construct and run thought experiments spontaneously. They conclude that "the process of alternating between these two modes—empirically experimenting and experimenting in thought—leads towards a convergence on scientifically acceptable concepts" (2004, 1819). In other words, thought and empirical experiments appear in conjunction, and this is for the best, because together they enable us to go from "seeing" a physical phenomenon to "knowing" about it (1820). What leads them to this conclusion?

In their study, Reiner and Gilbert asked students to analyze a physical mechanism that behaved in an unexpected way. Two heavy wheels were set next to one another into a base, and each was free to spin. If one was made to spin quickly, the other would do nothing. But as it slowed down, the other would begin to spin and speed up, until the first came to a complete stop. When the second wheel began to slow down, the first would start spinning again. The reason for this behaviour was a set of hidden magnets contained in the wheels. Given a list of the materials out of which the mechanism was built, the students were asked to figure out what was going on. Different sets of students all followed a similar methodology: first they began by identifying the various physical mechanisms in a general way using concepts like force, acceleration, weight, direction, and so on. They used these to construct various (mental or physical) models that could capture what they observed in the mechanism. Then they abstracted their models further into what the authors called a "representational space," where the relationships between features of the mechanism were represented, often with the help of pen and paper. Finally, they created and used imaginary worlds to test their models using thought experiments.

The authors claim that what emerges is an instance of the move from perception to knowledge, and "how concepts emerge out of touching and seeing. [This move] forges links between the bodily and the mental, between the physical and the cognitive, faculties." The authors delimit four main steps in this emergence. First, “sensory interaction with the physical set-up in the experiment triggers knowledge associated with memories of sensations.” Second, “knowledge associated with sensations is spontaneously represented in pictorial representations.” Third, those “representations are used for communication, their meaning shared across situations, across subjects, used for conceptual negotiation.” And finally, the “representations are used for running experiments in thought. The results of these thought experiments are used to refine the set-up of the physical experiment” (2004, 1831).

Notice the cyclic nature of the process. Perception, memory and tacit knowledge feed into the creation of new representations, which are communicated and negotiated using models and thought experiments, and then tested. The results of the tests cause more representations to be created, which feed into more models and more tests. Experience does not justify the results of the imaginary experiments any more than the imagination justifies the results of physical modeling or experiment. The two cognitive achievements are symbiotic.

Another paper I want to look at is Kosem and Özdemir (2014). This study asks what students use thought experiments for, and they determine several answers by collecting three groups of subjects, each with a different level of expertise in physics. They produce trials to find out what types of thought experiments would spontaneously be invented and for what purposes.

The problems they asked students to solve were usually difficult ones drawn from dynamics or mechanics. The first group was made up of doctoral graduates. The second was university undergraduates, and the final group was high school students in grade 12. The total number of thought experiments invented by each of the three groups was basically equal.

In terms of the means of the thought experiments, each student either modified an object in an imaginary scenario (for example, the size of a car), or a variable (its velocity). When they modified the object, they did so either to match a familiar case, like the way they felt when riding a bus, or a simpler case, for example, by dissecting a problem into several smaller, easier problems. When they modified a variable, they either eliminated or minimized the variable’s value to eliminate its influence altogether, which helped them focus on the relationships of other variables, or they increased the value of a variable to make its effect on the system more obvious.

In general, changing the problem to a more familiar case by modifying the object was the most common type of thought experiment strategy used by the undergraduate and high school groups. Modifying the variables was used quite often by the doctoral group, and very seldom by the others.

In terms of purpose, there were several. Sometimes a subject would have an intuition, which they explored with a thought experiment. This use was labelled “prediction.” Other times a subject might have an independent reason for believing something, which they chose to illuminate with a thought experiment while trying to report or justify it. This was labelled “explanation.” Other times the thought experiment completely played the role of a proof. The undergraduates used thought experiments as a proof more than any of the other groups. The high school students and doctoral graduates very rarely used thought experiments as a proof. Across all three groups, however, by far, “the most frequently observed purpose of using a thought experiment is for ‘explanation’” (882). That is, “to communicate ideas, or exemplify the solution” (879).

Finally I would like to discuss two studies of expert scientists working in vivo. First, Trafton, Trickett and Minz (2005) ask if scientists use the imagination to manipulate mental representations. They conclude that they do. They argue that scientists create what Clement later calls “overlay simulations” (2009) between external and mental representations. That is, they compare and align mental and external representations, checking for fit or feature-similarity. The authors found that the scientists manipulated spatial representations more often in their heads than they did using computer screens (2005, 97).

In a second study, Trickett and Trafton (2007) built on these results, arguing that scientists spontaneously invent "small-scale" or "local" thought experiments (867) in times of "informational uncertainty" (843). Scientists perform thought experiments in such conditions to "develop a general, or high-level, understanding of a system" (844). The authors focus on the data analysis phase of research, in which scientists must negotiate uncertainty to see what information the data presents, and interpret it. Employing "what if" reasoning helps scientists test out alternate interpretations of their facts, fill in holes in their data, and see how the data fits with existing research questions and background theories. They predict that thought experiments "will be used by experts when they are working either outside their immediate area of expertise or on their own cutting edge research—that is, in situations that go beyond the limits of their current knowledge" (867).

To summarize so far: if the empirical results I have mentioned are on the right track, there is a great deal that is philosophically interesting here. In almost every one of these articles, one of the main conclusions is that thought experiments are important because they bridge conceptual/theoretical knowledge to kinaesthetic or kinematic knowledge. And even when this is not an explicit conclusion, all of the above results are consistent with it. What does this tell us about the epistemological role of thought experiments in science? If we separate the action of bridging existing instances of knowledge from the action of creating new instances knowledge, we see that thought experiments are often instances of the first kind of action, whether or not they can also be properly characterized as instances of the second. And the thought experiments we examined in this chapter were more often than not used to explore or interpret conceptual solutions to problems, communicate ideas, or model scenarios, than they were to provide concrete solutions to problems. That is to say, the initial performance of a thought experiment usually increases understanding by exploration rather than producing new knowledge. In fact, Özdemir (2009) argues that students learn to shy away from using thought experiments as evidence in physics as they mature, although they do not shy from using them to communicate and explore. It is possible that this trend maintains itself in the professional careers of scientists everywhere.

It is also important that all of the above studies produce results that support the idea that thought experiments create understanding in one of the two ways mentioned at the start. Velentzas and Halkia showed in the course of three studies that students used thought experiments to bridge empirical knowledge and theoretical structures. Gilbert and Reiner saw a symbiotic relationship between thought and empirical experiments, which were performed in a way that "negotiated concepts" through communication and exploration, which made a student's concepts and models intelligible to him or herself, and also to his or her fellows. Stephens and Clement argue that thought experiments "appear to have considerable value as a sense-making strategy" (2006, 1). Kosem and Özdemir found that the most common use of thought experiments across different groups was to "communicate ideas or exemplify a solution." Trafton, Trickett and Mintz found scientists employing thought experiments to compare, align and manipulate representations, especially for communication. In all these cases, it has been emphasized that if we do not make sense of a theoretical structure, we cannot use it.

Let us turn to some considerations of these results. First, are these less-than-knowledge producing roles that we have just discussed *epistemological*? The answer is "yes." If these roles produce understanding as opposed to knowledge, we are able to draw on the quickly expanding resources in the philosophy of understanding, a subfield of epistemology. Understanding was of course rejected as a topic of serious study in the philosophy of science around the time of the logical positivists, because it was associated with a psychological and subjective *feeling* (especially by Hempel; see de Regt et al 2009, 3-5; de Regt 2009, 22-24). This feeling might be an outcome of good science and provide clues concerning what should be investigated next (see Lipton 2009, Grimm 2009, Thagard and Stewart 2011), but it might also be categorically irrelevant and even misleading (see Ylikoski 2009). Leaving the positivist-era characterization behind, I want to consider something more robust, even though there is no currently accepted definition for this more robust sense of understanding in philosophy.

As with "thought experiment," a vague but useful term, we can also say interesting things to differentiate understanding from other epistemological states in the absence of a satisfactory definition. For example, understanding is a relation that obtains between a subject and an object, produced by means of some third thing, where that third thing is often a model, an experiment, a theory, a thought experiment or an explanation. One way to know if we have increased understanding is to ask about abilities. When we understanding something, we can use it in new ways. We can relate what is understood to new and old knowledge, and abilities we already had. Thanks to these abilities, we often come to see the world in a new way. Advances like these may be associated with an "aha!" moment, but they are much more than that experience: they are genuine cognitive achievements. This is why I continuously return to Toulmin's characterization of what it takes to be able to use a concept. If we look at the thought experiments used in the aforementioned studies and in the history of science, we see that almost *all* thought experiments make some concept(s) intelligible and usable, and so provide understanding in Toulmin's sense. In fact, I think it is plausible that all of the often cited thought experiments in science, such as Schrödinger's Cat, Heisenberg's microscope, Einstein's Elevator and Train, EPR, Galileo's Falling Bodies, Stevin's Prism and Darwin's Eye, provide this sort of understanding by connecting theoretical structures to experience or kinaesthetic representations. If thought experiments all perform this function, this would be no obstacle to their also in addition serving as evidence for or against theoretical claims. That is, they can provide both understanding and knowledge, although it is understanding I am interested in here.

How might thought experiments provide both knowledge and understanding? First, I hope it is clear that the same thought experiment can have several different uses at different times or for different people. For example, Schrödinger's cat was once used to attack the Copenhagen interpretation of quantum mechanics, and now it is used to introduce physics students to superposition. One might argue that we have here two different thought experiments, but surely it is the same imagined scenario drawing on similar underlying assumptions, even if it is used for a different purpose in the two cases. If this is correct, the same thought experiment is at one time used by experts as an argument against a theory, and later by teachers and students for pedagogical reasons. Now, I ask: is it possible that the same thought experiment can play more than one epistemic role, for the same person *at the same time*?

I think they can. Thought experiments like Heisenberg's microscope, Schrodinger's cat, Einstein's elevator and others, are simultaneously used by scientists to make sense of difficult new theoretical structures, which increases scientific understanding by helping scientists connect abstract theoretical structures either to experience or to previously unconnected parts of theory. In addition to serving this purpose, many of these thought experiments simultaneously or derivatively use this new understanding to attack, subvert, popularize or explain a theory or theoretical interpretation. The application of new understanding often results in new knowledge.

There is a complementary idea present in the work of Hans Radder on laboratory experiments (1996), and Sören Häggqvist for thought experiments (1996). (And Häggqvist's idea was later developed by Tim de Mey in his 2003). The idea is that the *performance* of an experiment is different from the *application* of the result of the experiment to theory. These two actions are often conflated in general discussions of scientific experiments. What I am arguing is that the performance of a good thought experiment yields understanding, while the application of the results of that experiment yields knowledge.

What is novel here is that thought experiments are almost always significant for scientific understanding and not merely for knowledge. This idea has some nice consequences. For instance, it explains why many of the more famous thought experiments appeared in the later stages of their respective scientific revolutions. This is because they were meant to make sense of a new theoretical structure that had been introduced during the course of the revolution. If this is the case, the thought experiment could not have shown up earlier. The new quantum formalism was mathematically complete and more or less empirically adequate by 1925, and Schrödinger's cat was not born until a decade later. Similar relationships obtain between Maxwell's demon and the statistical-mechanical interpretation of heat, Einstein's train and General Relativity, the clock in the box and quantum mechanics, and many others.

This idea also helps to explain the role of thought experiments in the rhetoric of science. If you can provide an intuitive interpretation of a theory, this can be a way to get others to accept that interpretation, and therewith, the theory. If I am convinced of the Copenhagen interpretation of quantum mechanics, it is necessary that I am also convinced of quantum mechanics. Likewise, for those who oppose a new and competing theory, the first reaction is often to look for counterexamples, cases where the theory does not apply or that the theory cannot explain. And searching for counterexamples is itself an attempt to explore the connection between the new theory and the world, and show that the proposed connection cannot be made, or that it can but that we find either the physical or theoretical correlate implausible.

This also explains the prevalent place of thought experiments in science textbooks and websites which aim to describe in general outline how this or that modern scientific theory works. Thought experiments help students take the steps their intellectual ancestors took in order to understand a theory. They also provide high-level connections in an easy way. Even if someone does not understand the difficult theoretical structures invoked by a theory, they might grasp the relationship between those structures to the everyday or laboratory world of experience via a thought experiment. If half-way understanding promotes the causes of science, it is better than no understanding at all.

Aside from pedagogy, this focus on understanding might also explain why humans are so drawn to thought experiments in general. In 2012 the website edge.org asked "What is your favourite deep, elegant, or beautiful explanation?" There were 192 contributors, including Richard Nisbett, Steven Pinker, Lawrence Krauss, Daniel Dennett, Freeman Dyson, Lee Smolin, Richard Dawkins, Brian Eno, and Douglas Coupland. 21 of these responses were thought experiments, and 8 more were kinaesthetic analogies of the type highlighted above. This is even more impressive if we take into consideration the fact that these (different) thought experiments were competing with explanations like the theory of evolution by natural selection, General Relativity, religion, the double helix, and mathematics itself. For some people, thought experiments have provided deeper, more elegant and/or more beautiful explanations than the most important explanatory theories produced in the history of our species. I suspect this is at least partly because they can play several epistemological functions at once.

This interpretation also sheds light on the role of thought experiments in scientific theory proliferation and “public marketing.” If a theory has been developed in great theoretical or mathematical detail, but has not yet caught the eye of the greater scientific community, perhaps it is time to try some thought experiments. These may assist in funding and public image, but also in smear campaigns against competitors. Late night infomercials on television encourage you to imagine yourself in some uncomfortable situation, from which only the Brand New Shining Product can save you. Thought experiments are powerful tools of advertisement that likewise appeal to emotion via the imagination. Recognizing this power illuminates a new danger in thought experiments that was hidden until now: High-level or general understanding is one of the goals of science. Since thought experiments can provide this, they might be used (intentionally or not) to deliver such understanding *falsely*. Heisenberg’s microscope is a potential example. While it does provide a way to understand and visualize the uncertainty principle, it has been criticized quite harshly for doing so in a misleading way (see, e.g., Roychoudhuri 1978).

This is an interesting issue, because general understanding, while a desiderata, might not always be achievable. Our cognitive limitations do not always match the limitations we find in theoretical structures. Perhaps it has already happened in science that we have abandoned a good theory for a rival that was more easily intuited and understood, although false. Physicist Paul Dirac “regards models, images, pictures not only as redundant, but as dangerous. As long as the formalism and experimental results dovetail, theoretical physics has achieved its task” (quoted in Yourgrau 1967, 866). The Aristotelian theory of motion including natural places for the five elements strongly appeals to the imagination, and this is surely one of the reasons it was dominant for so long. This is a new reason someone might be skeptical about the usefulness of thought experiments: some things *cannot* be imagined, and we may go astray by trying to do so, even with the best intentions. This is a problem that needs to be understood, and accounted for, although there is some reason to think it can be avoided. It is true that once we pass into the microscopic domain or higher dimensions we lose the ability to visualize properly (or at all), but this does not stop us from focusing on *aspects* of those systems that we *can* imagine. The entities that make up our world display a multitude of interesting properties, many of which stand in relations that can be visualized apart from the rest. Of course, the more complicated our theories become, the more careful we must be with our imaginary examples. Pursuing this question further will help us to map out the difficult grey area between good and bad uses of thought experiments in science.

Finally, if thought experiments provide understanding, they serve a function which is indispensable for the progress of human science. Without understanding, we cannot use our knowledge, and without knowledge there is nothing to understand. These two features of science can develop independently for a while, but not for long. Even with the greatest division of intellectual labour, one eventually reaches for the other. According to Peter Kosso: “knowledge of many facts does not amount to understanding unless one also has a sense of how the facts fit together” (2006, 173). He invites us to recall the Omniscienter from Pierre Dumal’s novel *A Night of Serious Drinking*, over whose chair it reads “I know everything, but I do not understand any of it.” Kosso suspects that “the Omniscienter has spent too much time gathering evidence and too little time thinking about it. He has taken the piecemeal empiricism too seriously and overwhelmed his science with observation. Too many data have left too little room for understanding. There are examples of knowledge without understanding in the physical sciences, and they are found in the most empirically dependent sciences or in any science at the time of new empirical discovery" (182).

To this end, Steven Weinberg remarks that General Relativity offers more understanding than does quantum mechanics, because the latter cannot easily be bridged to our other stores of knowledge. He sees the Copenhagen interpretation as a surrender to the incomprehensibility of the theory, throwing up our hands and asking for empirical accuracy only (Weinberg 1992, Kosso 2006, 184). If it is true both that we need to understand our theories, and that quantum mechanics is inherently difficult to understand, then we should expect a great deal of thought experiments in quantum mechanics, especially at the time when the theory was introduced. And indeed, this is the period most replete with thought experiments since the early mathematization of science with Galileo.

Many scientists explicitly seek connections between their theories and the world or other pieces of knowledge, which I have characterized above as a search for understanding. Ernst Mach remarked that there has to be what he called "coordination" between the variables of a theory and the aspects of the world to which it refers. The temperature reading taken from a thermometer must refer to something real, not to another conceptual entity. And gesturing to the thing itself is often made more difficult with complex terms (see van Fraassen 2008). Reichenbach extended the problem, noticing that even the coordinating relation, if we could create one, would only be another abstract relation, which we would again need to coordinate (1965). Einstein remarked that if we want to talk about rigid bodies and their behaviour, we must first coordinate "experience[e]able objects of reality with the empty conceptual schemata of axiomatic geometry" (Einstein 1921). Einstein also spoke of the "ever-widening logical gap between the basic concepts and laws on the one side and the consequences to be correlated with our experiences on the other—a gap which widens progressively with the developing unification of the logical structure, that is with the reduction in the number of the logically independent conceptual elements required for the basis of the whole system" (1934, 165). In other words, scientists recognize the need for something to bridge the gap between our theoretical structures, including laws, concepts, equations and mathematical models, and the world. Further, he considers the possibility that as physics becomes more refined and united, it must make use of more and more abstract notions and relations to accommodate all its information by interrelating it. When this happens, the gap between theory and world grows larger.

There is also evidence that scientists have intentionally used thought experiments to bridge this gap. Heisenberg showed in 1925 that the matrix and wave-mechanical formalisms of quantum mechanics were mathematically equivalent. Still, Schrödinger was set on the wave mechanical interpretation, and Heisenberg on the particle interpretation. According to Marten Van Dyck, Schrödinger called Heisenberg's theory a "formal theory of frightening, indeed repulsive, abstractness and lack of visualizability." And "'Heisenberg's theory in its present form is not capable of any physical interpretation at all,' was another claim made at the same time" (2003, 81). In response, Heisenberg began considering whether an interpretation focused on the particle nature of atomic elements could be visualized, and specifically whether in-principle observables could be simultaneously measured. "This was a turning point for Heisenberg's theory, because it led him to propose a visualizable interpretation of quantum mechanics *through thought experiments* based on the limits of measurement. Heisenberg wrote out all his ideas in a letter to Pauli at the end of February [1927], in an attempt, *he said*, to 'get some sense of his own considerations' as he groped towards a consistent theory" (Beller 1999, 105; emphasis added). Kristian Camilleri writes, "Heisenberg's introduction of the imaginary gamma-ray microscope was not intended primarily to demonstrate the limits of precision in measurement. Though it certainly did this, its real purpose was to define the concept of position through an operational analysis. This becomes evident once we situate Heisenberg's use of imaginary gamma-ray microscope within the context of his concerns over the meaning of concepts in quantum theory" (2007, 179). Heisenberg's thought experiment was therefore a way to link the new theoretical structure to some empirical content, whether through operationalization or visualization, *for Heisenberg*, in dialogue with his peers.

And this goes for many of the physicists of the period. Mara Beller writes, "most physicists, Bohr and Heisenberg included, wanted more: some feeling of understanding, of illuminating, or explaining the kind of world that quantum formalism describes. The need for this kind of metaphysical grasp is not merely psychological but social as well—the power of a successful explanation and the power of the effective legitimation and dissemination of a theory are connected" (Beller 2002, 107). This supports the notion that understanding provided by thought experiments is important for many reasons, including pedagogy and popularization. But more importantly, it shows that scientists have been aware of this, and have used thought experiments for this purpose.

What have we learned so far? Thought experiments have many epistemological uses, many of which generate understanding as opposed to (or in addition to) knowledge. And the imagination plays some role in this. How does it work? Perhaps those who characterize thought experiments as mental models have an answer. Nenad Miščević (2007) argues that the power of the imagination results from its having evolved as a useful predictive tool with its roots in normal perception. Nancy Nersessian agrees, stating that "the perceptual system plays a significant role in imaginative thinking," which "makes sense from an evolutionary perspective" (2007, 136). While Nersessian does not claim that all the content that is manipulated by our mental models is perceptual or imagistic (142), she does "contend that a wide range of empirical evidence shows perceptual content is retained in all kinds of mental representations" (139). What grounds the epistemic use of thought experiments for Miščević and Nersessian is experience itself, and the usual cognitive and sensory faculties that provide empirical knowledge. Miščević and Nersessian are generally concerned with the primary epistemological challenge of thought experiments, which in most iterations concerns the production of new knowledge. Yet because understanding produced by thought experiments also relies on the imagination to "abruptly pull back the veil" and reveal fruitful connections between disparate phenomena, concepts and models, their justification of the outcome of thought experiments through mental or neural mechanisms might also be used to help explain the reliability of thought experiments conceived as producing understanding. Let us examine this claim.

The idea that we manufacture complex ideas from sensory experience via reason and imagination has its modern roots in British Empiricism. It is still well-supported empirically (see e.g., Prinz 2002) and is introspectively attractive. Nevertheless, there is something about the use of imagination in producing scientific understanding that seems left out of such a justification. Thought experiments as I have portrayed them above do not succeed because the imagination has its roots in perception. We might be right to trust *knowledge* claims based on what happens in imaginary scenarios because those scenarios are formed by cognitive faculties that are basically reliable. But in producing *understanding*, we do not need or want accuracy; we only need to create new bridges. There is no observation I can make that would explain to me the empirical significance of Einstein's equivalence principle. Einstein's elevator succeeds because the imagination takes us *away* from normal perception and gives us a new means of conceiving the world via new concepts, analogies and models. Since this use of the imagination is different from the one that generates new knowledge, we need a different justification for it. To provide one, I begin by considering the way that understanding gained by thought experiments is *constitutive* of the content of science.

To do this, I will set up an analogy. On the one hand we have the connection between perception and imagination, and on the other, the connection between the empirical content of the theoretical structures of science and thought experiments. I want to claim that perception can justify empirical claims, and the imagination can help us perceive. This is merely to suppose the arrow of influence from perception to imagination goes both ways. In other words, while we certainly *do* receive perceptual information which we convert into more and more complex representations by imagination, it is also the case that the imagination makes certain high-level acts of perception or cognition possible. Of course, without perception, we would have nothing to apply theoretical structures to, and so experience is still our main source of all knowledge.

There is support in cognitive science for such a view. For example, the now classic Miller and Cohen (2001) discusses “top-down processing”, which is “central in modern neuroscience” (Burchard 2011, 69). Top-down processing occurs when we first categorize or cognize things in broad strokes, and work through the details later. Those details are perceived as aspects of the more general idea, which means that the higher centers of our brain actually help to determine what we see. When top-down processing is operative, higher centers in the prefrontal cortex of the brain track and modify what happens in lower centers. When something new or difficult to identify is presented to a subject, top-down processing starts before recognition of the object is accomplished. According to Miller and Cohen (2001), the prefrontal cortex provides bias signals to lower brain structures. These bias signals guide the flow of neural activity along certain pathways. In other words, when we see something new, parts of our brain normally associated with conscious thought are already involved in categorizing and making sense of the thing as it is presented to us (see also Buschman and Miller 2007).

Top-down processing is accepted by most cognitive scientists today. To help demonstrate the mutual dependence between perception and the imagination, on the one hand, there are many experiments which show that a subject’s visual cortex is actively engaged while they are imagining. This suggests that imagining is an activity derivative on perceiving. On the other hand, many experiments demonstrate that people who have lost their visual cortex due to injury, or who were born blind, can still imagine things vividly (Arditi, Holtzman, and Kosslyn 1988; Kerr 1983; Marmor & Zaback 1976; Nersessian 2007, 137). Likewise, patients who have damaged parts of their neocortex sometimes cannot see conceptualized objects, like, e.g., ducks. They can only see lines, shapes and patches of colour (Thagard 2010, 70). Also, if we approach an ambiguous figure with a certain interpretation in mind, this often determines what we see when we look at it. I take all of this as evidence that the imagination can play a constitutive role in determining the content of experience. Of course in a healthy individual, both directions of interaction mesh together, and so we should give up speaking as though one comes *before* the other. Bottom-up and top-down cognition are not step-wise, or even separable. Paul Thagard writes, “Because brains perform inferences using parallel activity of millions of neurons, perception can elegantly integrate both bottom-up and top-down information” (2010, 71). And “perception involves simultaneous parallel processing that combines top-down knowledge with bottom-up perceptual input” (2010, 100).

What else can we say about the constitutive role played by the imagination in perception and thought? Mark Johnson writes in *the Body in the Mind* that we can “connect up” (152) abstract mental structures with the contents of our sense perception using what he calls "schemata," which are "nonpropositional structures of imagination" (19). He says "Even our most simple encounters with objects, such as the perception of a cup, involve schemata that make it possible for us to recognize different kinds of things and events as being different *kinds*" (20). Johnson's schemata have been very influential in cognitive science, and after the idea was re-expressed in Lakoff and Johnson (1999), it has spawned a subfield of research. The basic idea is that through the imagination, we create schemata that give content to our beliefs, and structure perception and thought.

Nigel Thomas, a long time researcher of mental imagery, understands schemata as data structures in the brain that make possible perceptual experience of the world (Thomas 1999). Thomas understands schemata slightly differently from the Johnson-Lakoff school, but he admits that the views are compatible, and again the imagination plays a crucial role. Thomas argues that schemata are not things that we experience, although they are necessary for experience in general.

Finally, support for the fundamentality of imagination is not limited to cognitive science. Stokes (2014) argues from a philosophical perspective that imagination is necessary (although not sufficient) for the formation of new beliefs, desires, intentions, as well as for learning new concepts and skills (179-180). And Colin McGinn (2004) argues that imagination is necessary for all cognition, since it is necessary for grasping meaning.

If we grant the possibility that imagination can structure perception, we can complete the analogy to thought experiments. Whether or not the imagination functions at the most fundamental level with respect to conceptual content, as it does for the Lakoff-Johnson school and Thomas, there is certainly a sense in which we can understand the imagination playing this role at a higher level through thought experiments. Even if the imagination is not functioning at the level of guiding "biases" between my prefrontal cortex and my occipital lobe, we do occasionally use the imagination to explore and settle on what a difficult new concept means or variable represents, and in so doing, understand it by relating it to other concepts we already understand, increasing its empirical content, or becoming comfortable with it through repeated use. Instead of using the imagination to create a meaningful image of a duck from lines and colours and shapes, we use it to create a meaningful theoretical structure from our experience, the variables in the structure, and the relations between those variables.

Such mental bridge-building could take place on the conscious level, and take the form of a thought experiment (though it could take other forms as well). For Kant, the imagination was the link between the senses and the understanding. Every time we used a concept, we performed an action, or in Kant's words, created a schema, that linked a specific experience to our concept. I think something like this becomes very plausible if instead of linking individual sense experiences to individual categories, we consider linking experience as a whole (or in swaths) to the partially-interpreted theoretical structures of scientific theories via conscious use of the imagination. In this case, an action is also performed, which may sometimes take the form of a thought experiment, which connects theoretical structures to the world. The thought experiment can make these structures, which are usually developed in a formal mathematical way, meaningful and useable. No amount of mathematics or laboratory experimentation or computer simulation could tell us what exactly is the content of the principle of equivalence, the uncertainty principle, or Newton's laws, because no amount of formal manipulation or experience could explain a theoretical concept or relation. However, the imagination *can*, since it enables new connections to be forged between emotional, sensorial, memorial and rational elements. In fact, all high level theoretical structures will likely require some use of the imagination for us to understand them, even if it does not come by means of a thought experiment. And this implies that the use of the imagination in science cannot be justified by cognitive science or by philosophy. It is justified by always already being presupposed by both. That is why it is a *sine qua non* of scientific understanding.

I hope this characterization of the role of the imagination in thought experiments sheds some light on the common conclusions of the empirical studies I considered at the beginning, namely, that thought experiments increase scientific understanding by bridging theoretical structures with existing knowledge or experience. Thought experiments perform a myriad of functions, and they can perform more than one at the same time. One of their crucial functions is to provide understanding. And in those cases where novel understanding is produced, it is often due to creating a connection between some theoretical structure(s) of science and existing knowledge or experience, via an exercise of the imagination. We can now substantiate this idea by considering the imagination as a key component in building these bridges. Thought experiments are instances of the sort of conceptual exploration that is needed to understand scientific concepts, which is itself a necessary condition for the possibility of a working science. This argument, that thought experiments increase understanding by means of the imagination, which is fundamental to all theoretical understanding, suggests a novel way to justify the role of the imagination in creating scientific understanding, one that does not conflict with any of the existing accounts that aim to justify empirical knowledge produced by thought experiments.

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