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ORIGINAL RESEARCH

Sharpening the tools of imagination

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Abstract

Thought experiments, models, diagrams, computer simulations, and metaphors can all be understood as tools of the imagination. While these devices are usually treated separately in philosophy of science, this paper provides a unified account according to which tools of the imagination are epistemically good insofar as they improve scientific imaginings. Improving scientific imagining is characterized in terms of epistemological consequences: more improvement means better consequences. A distinction is then drawn between tools being good in retrospect, at the time, and in general. In retrospect, tools are evaluated straightforwardly in terms of the quality of their consequences. At the cutting edge, tools are evaluated positively insofar as there is reason to believe that using them will have good consequences. Lastly, tools can be generally good, insofar as their use encourages the development of epistemic virtues, which are good because they have good epistemic consequences.

Keywords Epistemic tools · Thought experiment · Visualization · Models · Computer simulations · Metaphor · Metaepistemology · Epistemology of science · Epistemological consequentialism · Deontic epistemology · Virtue epistemology · Scientific imagination

1 Introduction

For Francis Bacon, scientific activity consisted of actions of the hand and actions of the mind. A scientist might spend one day carefully preparing a laboratory sample (with their hands), and the next day building a mathematical model to understand their observations (with their mind). The limits of these actions are just the limits of the human body and mind. "Neither the bare hand nor the unaided intellect has much

[1] For more on the connection between Bacon and imagination, see Corneanu and Vermeir (2012).

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power; the work is done by tools and assistance, and the intellect needs them as much as the hand. As the hand's tools either prompt or guide its motions, so the mind's tools either prompt or warn the intellect" (Bacon, 1620/2000, trans. Jardine and Silverthorne, 33). In other words, to overcome the natural limits of human minds and bodies, scientists use tools. The key idea is that tools of the mind (calculators, white boards, computer simulations, artificial intelligence, etc.) are *really tools* in the same sense that tools of the hand (forceps, pipettes, pumps, particle colliders, etc.) are tools. That is, tools of the mind "promote or regulate" the "motion" of the mind, by supplying suggestions and cautions that improve scientific reasoning.

Modern science is more complex than it was in Bacon's day, but it is easy to expand Bacon's insight to include other kinds of tools. For example, there are also *tools of the senses* (e.g., telescopes, microscopes, pressure and temperature sensors, etc.) and what might be called *tools of the voice* (journal publications, YouTube channels, press releases, etc.). And each set of tools can be further broken down into subgroups. Thus, tools of the senses can be split into tools for each of the senses, like tools of the eye (microscopes, telescopes, etc.), tools of the skin (thermometers, pressure sensors, etc.), and perhaps also tools of the non-human senses (magnetometer, Geiger counters, etc.). Likewise, there will be subgroups of tools of the mind, pertaining to the different kinds of mental actions that can be assisted by tools. These might include acts of calculation, logical inference, memory, and imagination (Peacocke, 2021). We might include more general kinds of mental action, like deciding and planning, but as these involve actions of imagination, memory, calculation, and logical inference, we will focus on these more specific actions instead.

Tools of the hand, mind, senses, and voice can be hard to distinguish. For example, a remotely operated rover on Mars that records and processes empirical data, which it sends back for public consumption, can be understood as all four kinds of tool. The scanning tunnelling electron microscope is usually a tool of the senses, but it has been used to move carbon monoxide molecules (a tool of the hand) to create a movie (*A Boy and His Atom*) which popularizes science (a tool of the voice), and explores data storage limits (a tool of the mind). Sometimes we can ignore these complications by focusing on *typical* uses of a tool. Thus, while a hammer can be used to explore new ideas, its typical purpose is to apply physical force.

Still, the problem of disentangling tools looks especially daunting when it comes to the sub-types of the tools of the mind. For example, computer simulations don't seem to have any *typical* purpose. They can be tools of the imagination in certain contexts (e.g., in exploring a new hypothesis) and tools of calculation in others (e.g., in approximating a solution to the Schrödinger equation). It also seems possible for a single tool of the mind to be a tool in several different senses at once. This is perhaps to be expected, since it is also true of mental actions, which can be, e.g., calculative imaginings or imaginative calculations. Despite this complication, it is possible to identify relatively clear examples of tools of imagination, and this will be done below.

Overall, the idea motivating this paper, inspired by Bacon's aphorism, is that all tools either *prompt* or *focus* action. Hydraulic pumps prompt motion and catalyzers prompt chemical reactions. Hammers and optical microscopes focus physical force or light. Tools of the mind prompt or focus *mental* action, by prompting us to think about new ideas or by refocusing our thoughts about existing problems in helpful ways.

Likewise, tools of imagination prompt or focus the imagination, so that we imagine more usefully.[1]

Section 2 will identify a number of tools of the imagination. Section 3 will argue for a particular way of characterizing tools of imagination as epistemologically good and bad, and then apply that framework to the tools of imagination discussed in Sect. 2.

2 Tools of the imagination

Imagination can be thought of as a character trait, a disposition, a cognitive process, or a mental state. It is not clear whether these can be interdefined (Stuart, 2019a). If this were possible, we could simply define the mental state of imagination as the output of any cognitive process (or act) of imagination, and we could define acts of imagination as nothing other than exercises of the character trait of being imaginative. However, it seems possible that the output of an act of imagination might sometimes be a belief or action, which are not imaginings. Likewise, it seems possible that exercises of the trait of imaginativeness might result in cognitive processes other than imaginings. This paper will focus on the cognitive process of imagination, and specifically, on the subset of cognitive processes that involve some conscious, intentional direction of the imagination. This is important because imagining is a cognitive process that can proceed consciously and intentionally, or unconsciously and automatically (Stuart, 2019a), and it is the intentional acts we want to focus on here, though it is likely that all of these include and profit from some unconscious processing as well. Finally, while the main focus will be intentional acts of imagination, we will also discuss the skill of imagination, as this allows us to talk about better or worse imaginations in general. Importantly, someone who is skilled at imagining can still imagine poorly in a particular case.

Imagination can be imagistic, but it need not be. It is also typically taken to be an important (or necessary) component of creativity (Gaut, 2003; Hills & Bird, 2019; Stokes, 2014). Given the importance of creativity in science, we will focus on acts of imagination that attempt to produce something novel (Sheredos & Bechtel, 2020), since this is generally taken to be a feature of creative acts or creative individuals. Finally, imagination tends to be free to a degree that belief is not, at least in the sense that imagining that *p* does not commit us to believing that *p*.

Tools of the imagination include thought experiments, visualizations, computer simulations, models, and metaphors. Each of these have been used in science (and elsewhere) to prompt imagination in new directions, and to guide imagination in a way that avoids error and dead ends. This might sound worryingly vague: models alone are sufficiently diverse to prompt concerns that a single framework will not be able to capture all their epistemic features (Veit, 2020), never mind the epistemic features of models, metaphors, visualizations, thought experiments, *and* computer simulations. Still, I hope to show that there are real epistemological insights that can be gained, even at this general level of discussion.

2.1 Thought experiments

Thought experiments (TEs) are widely and explicitly framed as tools. Thomas Kuhn characterizes them this way in his seminal 1977 paper, writing that "the historian, at least, must recognize them as an occasionally potent tool for increasing man's understanding of nature" (Kuhn, 1977, p. 240) because "thought experiment is one of the essential analytic tools which are deployed during crisis and which then help to promote basic conceptual reform" (263). For Kuhn, TEs are tools that assist the mind in times of theory change by facilitating conceptual change.

But this is not all they can do. In *Intuition Pumps*, a book about TEs, Daniel Dennett portrays TEs as useful tools for reasoning in general. He introduces the book with a lament about our mental weaknesses when it comes to reasoning through difficult problems: most of us are "not calculating prodigies," and we are "a little bit lazy." Still, "We can use thinking tools, by the dozens. These handy prosthetic imagination-extenders and focus-holders permit us to think reliably and even gracefully about really hard questions" (Dennett, 2013).

TEs can be understood, not just as tools of the mind, but more specifically as tools of imagination. The first line of the *Stanford Encyclopedia of Philosophy* entry on TEs tells us that "Thought experiments are basically devices of the imagination" (Brown & Fehige, 2019). Letitia Meynell writes "Hardly any discussion about thought experiments takes place without mention of the imagination" (Meynell, 2018, p. 498). James McAllister claims that whether a scientist trusts TEs or not will depend on whether they view imagination as an important, necessary, or dangerous "tool to apprehend reality" (McAllister, 2012, p. 26). Peter Swirski writes that TEs "are the best cheap tools for imagining and evaluating states to see if they're worth pursuing" (Swirski, 2007, p. 85; emphasis removed). Unlike the other tools we will discuss, TEs appear to be *essentially* tools of imagination.

Still, we might wonder whether TEs might not be better described as tools of some other kind. A brief process of elimination assuages this doubt. First, TEs do not seem to be tools for calculation. Indeed, it is the absence of explicit formal and numerical manipulation that seems to make something a TE as opposed to a mathematical inference or logical argument. TEs also do not seem to be *mere* tools for logical inference. John D. Norton argues that TEs can always be reduced to logical arguments and that their epistemic power is always equal to the epistemic power of their underlying arguments (Norton, 1996, 2004). But, as Hayley Clatterbuck argues, "On Norton's view, it is mysterious why thought experiments are uniquely good tools for arriving at their conclusions while their argument analogues may not be" (Clatterbuck, 2013). In other words, TEs may sometimes suggest or be (partially) justified by arguments, however, they are not "mere" arguments, because they require imaginative particulars to give additional content (and perhaps direction) to the mental performance of the argument. This is what makes TEs more cognitively powerful than mere arguments, and also explains how they can go wrong in special ways. For example, we tend to give "extensive latitude" to the creators of TEs who direct our imaginations, and we trust the creator of a TE to employ a fictional scenario that is typical of the phenomena being investigated. When creators of TEs abuse this trust, negative consequences can arise other than invalidity (Norton, 2018). Finally, it doesn't seem that TEs are tools of memory. They usually refer to particular experiences, but these need not be events we have experienced ourselves, and in general, their typical purpose is not to help us remember something that we already know, but rather to go beyond existing experience and knowledge. Thus, TEs are principally tools of imagination and not some other kind of tool of the mind.

2.2 Visualizations

It is common to claim that diagrams and visualizations engage and assist the imagination. The etymological connection between "image" and "imagination" suggests an intuitive link. Richard Swedberg writes that "A theorizing diagram should…be able to trigger your visual and theoretical imagination" (Swedberg, 2016). Norton Wise warns that images in science can be "much too powerful" and "likely to lead to the deceptive excesses of imagination rather than the calm reflection of reason" (Wise, 2006). And there are those who argue that imagination should be centrally identified with mental imagery (Kind, 2001; Nanay forthcoming), which makes it natural to think that good scientific images will be those which foster good imaginings.

However, unlike TEs, which seem mainly to be tools of imagination, visualizations are more flexible. They can be powerful aides to memory (Fernandes et al., 2018; McCrudden et al., 2011; Shah & Hoeffner, 2002). They are also effective in guiding mathematical, scientific, and logical inference-making (Larkin & Simon, 1987), as when a mathematician works through a proof in knot theory (Starikova & Giaquinto, 2018). Of course, even in cases where diagrams are being used to assist the power of memory or logical inference making, their success as tools may be mediated by the way they facilitate the imagination. But this is not necessarily so: visualizations need not be mediated by or taken up in the imagination.

Nevertheless, visualizations are often produced and consumed in ways that increase the power of imagination. For example, images that represent complex systems can be reproduced in imagination, and this is often helpful in working out the solution to a problem, even when resources for externalizing representations are available. For example, in the context of solving a problem many scientists manipulate visualizations they have seen in papers and textbooks in their minds to think about what might be going on in a particular system (Sheredos & Bechtel, 2020; Sheredos et al., 2013; Stuart, 2022).

Even when a diagram is not reproduced and explored internally in the imagination, it might still be imaginative. For example, some artists have total aphantasia (i.e., the inability to produce sensory imaginings). Still, they use and create external visual images (sketches, drawings, paintings, etc.) to explore ideas in an imaginative way that they cannot do inside their own minds.

2.3 Computer simulations

Computer simulations have been compared with TEs by a number of authors (Arcangeli, 2018; Chandrasekharan et al. 2013; Di Paolo et al., 2000; El Skaf & Imbert 2013;

Lenhard, 2018; Shinod, 2021). For example, Johannes Lenhard classes both as types of “imagined experiment” that explore “hypothetical worlds” (Lenhard, 2018, p. 484). Rawad El Skaf and Cyrille Imbert write that both TEs and computer simulations are used to “unfold” the content of imaginary scenarios (El Skaf & Imbert, 2013). While some argue that TEs and computer simulations work via logical inferences (Beisbart, 2018), others stress the exploratory, imaginative nature of each. Insofar as computer simulations are like TEs, the arguments given above to justify the inclusion of TEs as tools of imagination can be extended to computer simulations.

Still, the differences between TEs and computer simulations are large enough to justify a more extended discussion. Lenhard argues that while TEs use intuition and imagination and require epistemic transparency (i.e., every step should be understandable for a TE to work properly), computer simulations allow for opacity and massive iteration. Despite this, he argues that “simulation experiments, like thought experiments, are a method of exploring hypothetical models.” Simulation experiments “present a new and surprising methodological twist to find out or determine the conclusions that follow from our assumptions…Simulation experiments explore new possibilities that automated calculations open up” (Lenhard, 2018, 494–5). Here, it seems that computer simulations are tools that assist the imagination of scientists, though they employ logical and computational means as part of their process.

Like visualizations, computer simulations are not necessarily tools of imagination. They can be tools of calculation or logical inference-making, for instance. Nevertheless, they can be tools of imagination. Indeed, some scientists claim that “we should not trust imagination to play any epistemic role in science… it would be better to offload our imaginative duties to computer models” (quoted in Stuart, 2019b). This is only possible if they serve the same imaginative function. In sum, TEs and computer simulations are similar enough to count them as occasionally serving the same purpose: empowering the imagination.

2.4 Models

Several philosophers argue that models should be understood as artefacts, or epistemic tools (Alexandrova, 2008; Boon & Knuuttila, 2009; Knuuttila, 2011). The idea is to think about models *as tools* that are “built by specific representational means and are constrained by their design in such a way that they facilitate the study of certain scientific questions, and learning from them by means of construction and manipulation” (Knuuttila, 2011). Tarja Knuuttila rejects an epistemology of models based on representational fidelity, citing examples of models that are “imaginary,” that is, models which do not attempt to say anything about a particular system but instead explore possibilities (Knuuttila, 2021).

If we can frame models as tools, why think of them as tools of imagination, and not some other kind of tool? Certainly, models can be tools of calculation, as in mathematical models. But some models, especially toy models, scale models, and material models that employ visual elements, seem plausibly to be tools of imagination. This is especially true if Fiora Salis and Roman Frigg are correct that models and TEs can be captured by a single epistemological framework that is focused on how they marshal imagination (2020).

As with computer simulations, there are important differences between models and TEs. For example, Michael Weisberg argues that some models (e.g., those employing ordinary differential equations in biology) cannot be imagined (2013). Still, this is consistent with *some* models being tools of imagination. And, as Brian McLoone points out, Weisberg's argument seems to assume that imagination is imagistic (2019). If that is so, Weisberg is certainly right that we cannot imagine, e.g., a continuous population of rabbits in an imagistic way. But given a more abstract notion of imagination that is not limited to mental imagery, models can still function as fictions explored in imagination for scientific purposes.

2.5 Metaphors

Metaphors traditionally have a close connection with imagination, and they are often portrayed as a device or tool. Berys Gaut writes that "a good metaphor doesn't so much prompt thought, as guide thought…and its standard of success isn't the volume of thought it causes to gush from us, but the quality of that thought (2003, p. 288). For Gaut, metaphor-making is a "paradigm of creative imagination" and also "an instance of creative imagination" (2003, p. 284). For Arnon Levy, scientific metaphors "engage the imagination. They are a type of figurative device, imposing an imaginative description on a real-world target" (2020, p. 292). They frame a target of investigation "by imaginatively juxtaposing it with a familiar subject matter. In this way it highlights certain properties and makes accessible certain patterns of reasoning" (294). Levy places metaphors on a continuum with models, in the sense that metaphors and models are both instances of surrogative reasoning, though metaphors are more opaque, and typically arise earlier in the history of an investigation into a phenomenon. If this is right, then the arguments given above suggesting that models are tools of imagination can be applied to metaphors.

While metaphors seem useful as tools that assist imagination, they need not be used this way: metaphors could be used simply for aesthetic effect. However, their ability to evoke aesthetic experiences might be mediated by their effect on the imagination (Camp, 2017, 2020). And in any case, it hard to find examples of scientific metaphors functioning primarily as tools for aiding memory, calculation or logical inference-making. This suggests that they are perhaps best understood as tools of imagination.

To summarize the last few subsections, it seems appropriate to think of TEs, visualizations, computer simulations, models and metaphors as occasionally being tools of imagination. The motivating idea is that they empower the use of imagination (by prompting or guiding it), which is useful in science insofar as imagination is useful in science. A skeptical reader might want to reject that one (or more) of these tools is really a tool of imagination, in which case they are free to focus only on the tools they agree are used to assist imagination. Still, given the close connection between them, if we accept that one is, it seems likely that all are. For example, Maxwell's demon is a TE that is often expressed visually. Sometimes it is simulated in computers (Skordos & Zurek, 1992), and it is used as a metaphor in computer science and elsewhere (Canales, 2020). All of these seem to be different modes that the same tool of imagination can take, and the same epistemological approach could be used for all of them.[2]

The concept TOOL OF THE IMAGINATION allows us to treat TEs, visualizations, computer simulations, models and metaphors together, epistemologically. But this is only a useful thing to do if the framework of tool-use can provide concrete descriptive or normative insights. The next section will argue that it can.

3 Epistemology of tools of imagination

Tools can be evaluated as better or worse in a number of ways. It might be helpful to consider a clear, non-scientific example. Isao Machii is a swordsperson who can slice through a pellet fired from a bb gun. This is a complex action that is at least partially intentional, that we can describe as more or less successful. There are at least three ways to explain its success: (1) The swordstrike was good because it had good consequences. E.g., it was good in the sense that the pellet was cut in two. It would have been better if the halves of the bullet were identical in mass, but slicing it in two is better than not slicing it at all. (2) The swordstrike was good because it was done in a way that respects the principles of good swordstriking, e.g., the body was moved in the most efficient way to generate power, speed and precision. In this sense, the swordstrike may have been good whether it sliced the pellet in half or not. (3) The swordstrike was good because it was performed by a master swordsperson, e.g., it manifested the master swordsperson's virtues of elegance, grace, and judiciousness.

These three ways of evaluating an action suggest three ways of evaluating tools. On the first, a good tool increases the quality of the consequences of an action. For example, a good sword is just whatever sword enables us to more reliably slice flying pellets without injury. On the second, a good tool is one that assists the user in respecting the duties that govern a specific kind of action. For example, a good sword helps the swordsperson to transfer their weight efficiently, to generate power, to focus on the strike, etc. On the third, a good tool assists the user in developing virtue or excellence. For example, a good sword is one that helps the user cultivate elegance, grace and judiciousness in swordplay.

These three positions reflect three general frameworks for evaluating actions. They're most recognizable in their ethical form, as consequentialism, deontology and virtue ethics, but they also appear as consequentialist, deontic, and virtue epistemology. We can employ them to define epistemologically good mental acts, including acts of imagination, and correspondingly, epistemologically good tools of imagination. However, we cannot simply use all three frameworks, since they can yield contradictory answers about whether a specific tool is good or bad. So, which, if any, of the frameworks should we adopt for acts (and tools) of scientific imagination?

[2] Different tools of imagination can subsume one another and work together in interesting ways. For example, TEs can include visualisations and metaphors. Simulations can include visualizations. Visualizations can sometimes be thought of as TEs. This helpfully complexifies the analysis to more accurately reflect scientific practice, but it does not suggest that any of these tools is not a tool of imagination. I thank an anonymous reviewer for raising this point.

In previous work using qualitative methods, I asked this question of scientists and noted that the three different ways of evaluation seem to be deployed in a way that depends on the relationship between the scientist and the imagining in question (Stuart, 2022). When an imagining took place in the past, scientists tend to evaluate it based on its consequences. They do not say that a past imagining was good because the person who imagined it had a good imagination, or because they followed some rules that govern all good scientific imaginings. For example, it seems good that Maxwell imagined a demon, and bad that Heisenberg imagined a gamma ray microscope, even though a priori, we might have thought it would have been the other way around (Stuart, 2016).

Scientists seem to evaluate imaginings a bit differently in the context of an on-going exploration of a problem-space where the solution is still unknown and several options are available. Here, scientists tend to evaluate imaginings in a deontic way, such that one imagining might be better than another insofar as it presents a more accurate as a representation of the target system, or insofar as it coheres better with background knowledge. But this is only because scientists do not yet have access to the consequences of the imaginings in question. As a result, they employ rules and guidelines, though in a flexible way, always willing to break them if they believe that doing so will have good consequences. This is one reason why scientists are reticent to prescribe specific rules to imagine by: because breaking rules might have the best consequences.

Finally, when asked about imaginings that might happen in the future, or imaginings in general, scientists tend to switch to a virtue theoretic framework, such that, in general, scientists should ideally strive to develop a good imagination, or at least to know how to compensate for a poor one. This appears to suggest that it is good for scientists to have good imaginations, independently of the consequences. However, on further analysis, it seems that scientists only take up the virtue theoretic framework instrumentally. That is, we should not understand them as being committed to virtue theory as an account of the fundamental source of epistemic value for imagination, but rather as only being committed to it insofar as it tends to have good consequences.

Employing this tripartite framework grounded in consequentialism, a relatively straightforward epistemological account of tools of imagination emerges: Tools of the imagination are good when they improve the consequences of imaginings. This idea is quite general, and that is why it is able to unite such a broad set of tools, including models, metaphors, TEs, visualizations and computer simulations.

Before turning to examples, it is helpful to remember why scientists transition between consequentialist, deontic and virtue theoretic language when it comes to evaluating imaginings. When the consequences of using a certain tool of imagination are foreseeable, the right tool can be prescribed with confidence. At the cutting edge, however, consequences are not always foreseeable. In this case, the best advice is to use certain kinds of tools, for example, tools that are like those which have worked in the past. Finally, when speaking about contexts in which the consequences are not at all foreseeable, e.g., in pedagogical contexts, scientists recommend tools that help facilitate or develop epistemic virtues. Though, doing so is valuable only for its good consequences.

We therefore have three contexts of interest, in which tools are evaluated in apparently different ways: known consequences of tool-use, unknown but foreseeable *direct* consequences of tool-use, and unknown but foreseeable *indirect* consequences of tool-use. We will structure the more detailed discussion of the epistemology of tools of imagination around these three contexts.

3.1 Known consequences

In contexts where the consequences of using a certain tool are given (e.g., because we are talking about a past use of that tool), "good" tools of imagination will be those which have good epistemic consequences.

If Kuhn is right that TEs mediate scientific revolutions by motivating new concepts, then a good TE is just one that has that effect. If there were rules for producing such TEs, the rules ought to be followed. The key point, however, is that such rules should not be followed for their own sake, but rather for the good consequences that following them has. Of course, since Kuhn, many more functions for TEs have been identified, such as illustrating theoretical claims, controlling variables, exemplifying properties, explaining, making intuitions accessible, identifying counterexamples, and making conceptual connections. Given the natural intuition that tools are better insofar as they help us achieve our goals, a good TE can be understood as one that helps scientists to achieve any of these intended goals.[3]

An example might be Einstein's chasing the lightwave TE, which is epistemologically interesting insofar as it was instrumental in helping Einstein to develop special relativity (Norton, 2013). It is not celebrated primarily because *Einstein* imagined it, nor because it respects some universal rules for good imagining. Rather, it is celebrated primarily for the way it helped Einstein develop special relativity, and perhaps secondarily to the extent that it helps physicists and students grasp Einstein's ideas. The TE is good because of its good consequences. Another example might be the set of TEs that Darwin presents in Chapter 5 of the *Origin of Species*, which together provide a useful exemplar for how to think about the evolution of complex phenotypes. These were "good" to the extent that they helped to convince people of Darwin's theory, but also because they made his style of thinking more intuitive, which increased the ability of students to learn and use it. "Bad" TEs can likewise be defined in terms of their consequences. Norton writes that Szilard's version of Maxwell's demon caused "long-lived confusions" and engendered "mischief and confusion" (2018, p. 461). It is "the worst" TE at least in part because of its bad consequences, which spread due to the fact that it legitimated a bad exemplar and distracted scientists from more fruitful ideas (2018, p. 462).

Visualizations are also evaluated as better or worse insofar they have had better or worse epistemic consequences. Minkowski diagrams, Feynman diagrams, free body diagrams, cladograms, phylogenetic trees, mechanistic diagrams in biology, and

[3] The work of David Gooding and Marco Buzzoni is especially conciliant with this idea. For example, Gooding writes that the success of a TE is at least partially a measure of how well it is able to spread in a discipline (Gooding, 1992), and Buzzoni characterizes the quality of (empirical) scientific TEs at least partially in terms of whether they "would lead to the consequences that they predict" (Buzzoni, 2008, p. 97). I thank an anonymous referee for pointing this out.

structural formulae in chemistry all had good consequences, both for students and for science. When we evaluate a diagram from the past, it is natural to focus on its consequences. A diagram can have "objectively" good epistemic properties (representational accuracy, clarity, informativeness, etc.), but if it misleads scientists, it will be evaluated negatively. And if a certain diagram was rejected in science, but later came to be appreciated for facilitating progress, the original verdict will be overturned. The opposite can also happen, as with anatomical diagrams of the human body that were inspired by the work of Galen around the time of Vesalius. These tended to ignore the actual anatomy of the body, and instead depict how our internal organs *should* look, if Galen were correct, despite the fact that real anatomical information was increasingly available. For example, the traditional "frog-like" figures that can be found in both German and Persian manuscripts, or others from the same period which portrayed the uterus as having six or seven chambers, to cohere with the Galenic idea of the uterus having seven cells (Gurunluoglu et al., 2013). These diagrams were valued as guides for students and the wider public, but from our current standpoint we must say that these were bad diagrams because they mislead the imaginations of those interested in anatomy.

Computer simulations are often evaluated, both individually and as a whole, in terms of their consequences. Particular simulations, like those that approximate solutions to the Schrödinger equation, are credited with making entire new fields possible, in this case, quantum chemistry. Some seem clearly designed to do what the imagination might have done in the past, like explore a problem space for solutions. For example, scientists are now using computer simulations to combine representations of laboratory equipment to create new experimental configurations. This used to be done on a whiteboard with the imagination, and it is now being outsourced to artificial intelligence algorithms. The outputs are judged to be good if they produce viable experimental set ups in a time that is shorter than it would take humans to do the same (Krenn et al., 2016, 2020).

Models, as well, have been evaluated in terms of their consequences for science and for imagination. For example, Bohr's model of the atom was celebrated for its consequences, and this was in some sense, *despite* its content. According to Peter Vickers, it "was able to explain in detail the pattern of spectral lines which had long been associated with hydrogen. That is, the theory was able to explain why hydrogen emits and absorbs light at only certain specific frequencies. But better than this, in a short period of time the theory succeeded in not only explaining the phenomena it was, in some sense, designed to explain, but in making successful predictions and explaining new phenomena" (Vickers, 2013, p. 39). The predictions agreed with experimental data up to five decimal places. "No one had produced anything like it" (Pais, 1991, p. 149, quoted in Vickers, 2013).

This suggests a straightforward argument for the view that models are evaluated, in retrospect, for their good consequences. If we portray models, as some philosophers do, as tools for generating hypotheses, then good models are those that generate good hypotheses. Such tools should be considered as tools of imagination because hypothesis-generation is traditionally something done by the imagination. The process of building models of phenomenon can be seen as a careful, guided way to do the same, but which often achieves better results (Alexandrova, 2008). Insofar as a model enables the generation of good hypotheses, it is a good model. Whether this is so for a given model is best appreciated after the hypotheses have been tested. Tania Lombrozo considers empirical evidence for a similar conclusion, arguing that "we can shift from thinking about models as epistemically valuable to the extent they accurately describe or approximately resemble the world to instead considering their epistemic value in terms of their role in supporting the acquisition of true beliefs. A *model* can be false, but a downstream consequence of *engaging in the process of modeling* can be the production of true beliefs" (2020, 245; original emphasis).

Metaphors are likewise evaluated in terms of their consequences. It was good that William Harvey imagined the heart as a mechanical pump, not principally because it was a categorically good thing to imagine, or because it manifested Harvey's epistemic virtues. Rather, it is principally appreciated because of the fact that it led to a revolution in the understanding of human anatomy, circulation, and medicine (Jacob, 2001). Stuart and Wilkenfeld (2022) give several examples of metaphors that had good epistemic consequences, in the specific sense of increasing the quality of scientists' representations of the world and their abilities to manipulate those representations. Scientists themselves also perform similar evaluations, when sufficient time has passed after a metaphor's introduction. For example, the metaphor of the brain as a device that codes and decodes information was extremely influential. But now scientists are beginning to worry that it is having bad consequences on neuroscience. They recognize that metaphors like this one can freeze concepts and hinder critical discussion (Brette, 2019). In particular, this metaphor has put science in "epistemic danger" (Brette, 2019) because "the code" is treated variously and confusingly as either the stimulus provided by the researcher or an ontological object in the brain (Arsiwalla et al., 2019; Cao & Rathkopf, 2019; Gomez-Marin, 2019).

3.2 Unknown (but foreseeable) direct consequences

In contexts with unknown but foreseeable consequences, we should expect scientists to define better and worse tools of imagination in terms of how likely they are to increase the good consequences of imagining.

Here are two refrains common in the philosophical literature. First, TEs, visualizations, computer simulations, models and metaphors are idealized or simplified. Second, each of these are quite information-dense. It is interesting that both statements can be true at once: each of these tools packages content in a way that is simpler to digest and easier to use than physical systems of interest themselves or the equivalent amount of literal information, but they pack such a punch because of the large amount of information they contain. In striking the right balance between simplicity and information density, a good tool of imagination constrains the imagination in some ways (which makes things simpler), while providing a lot of information and freedom to work with that information, allowing scientists to see things in new ways and break constraints that are no longer useful. These affordances of tools of imagination are the reason why they are used even when the exact consequences of using them are not foreseeable: It is hoped that building a model or running a simulation or exploring a metaphor will help to focus the imagination and/or break old constraints that are no longer useful, which are good things to do insofar as they lead to new knowledge, understanding, etc.

When faced with novel problems, physics students invent TEs in very regular ways: they break problems down into parts, and they simplify each part, by reducing certain variables to zero, or inflating other variables, to isolate or minimize the causal effects of each component and make them more visible (Kösem & Özdemir, 2014). Why are these good ways to focus imagination via TEs? Because those kinds of tricks have worked in the past. They employ TEs that constrain their imagination (e.g., to focus only on certain, simpler aspects, one by one) and prompt them in new directions (e.g., to try on different perspectives which might help them better understand the properties of the system described in the problem). More generally, we can assume that good TEs in this sense will be ones that strike the right balance of constraining imagination and freeing it, and the reason this is done, in general, is to solve a given problem.

With respect to visualizations, Letitia Meynell adopts a Waltonian perspective and notes that diagrams play an important role as props for imagination, which are helpful when confronting ideas that are unintuitive from an everyday perspective. Good images help to direct our attention to which principles of generation (rules for manipulating imaginary content) are salient, and also encourage the free play of imagination by allowing viewers "to find their own paths" through the image (Meynell, 2018, pp. 506–507). Similarly, Stuart and Nersessian (2019) identify interactive diagrams in science that help biologists see the structure of computational models as they change their code. These help the scientists to imagine the structure of their models more accurately, so they have a better idea of what their code is doing to the model as they change it. These visualizations are employed, not for their own sake, but instrumentally, for their good consequences. Bechtel et al. (2018) point out a number of ways that biologists use diagrams, from representing proposed mechanisms, creating anchors on which to build computer models, and drawing broader connections to elements in surrounding networks. Each has its own affordances. The exact consequences of using these kinds of visualizations are never known in advance. But they are used because it is hoped that the consequences will be good enough to justify the time spent creating and engaging with them. A large and evolving set of contextual conventions exists to increase this possibility, but no convention is sacrosanct.

Simulations are also used to "enhance the scientific imagination," especially in science education, where computer simulation is "a tool for extending human cognition by overcoming the limits of mental simulation" (Landriscina, 2017). Developing this idea, Chandrasekharan, Nersessian and Subramanian argue that simulations will eventually replace TEs in science (2013). This argument presupposes the idea that TEs and simulations serve at least some of the same functions, such that one could replace the other. Modern science requires mental modelling, which can be done using TEs or computer simulations. Simulations, according to Chandrasekharan, Nersessian and Subramanian, are often more appropriate, given the complexity of the models it can handle, the amount of data they can process, and the fact that they work with variables instead of concrete imagined particulars. "Just as no scientist studies the stars with the naked eye anymore, no one would use TEs to probe the complex phenomena studied by contemporary science" (Chandrasekharan et al., 2013, p. 257). While they argue that computer simulations are better tools, they do not count TEs out: they envisage a different use for them, a more preparatory, exploratory one. In sum, computer simulations can be good in the same sense as TEs: by helping to constrain and prompt the imagination in ways that we think are likely to have good epistemic consequences.

One way to understand models as tools of imagination is to apply the Waltonian framework (see e.g., Toon, 2012; Frigg, 2010; Salis & Frigg, 2020; Frigg & Nguyen, 2016, 2020; Levy, 2015). Here, models will be portrayed as props in a game of make-believe, with the objective of discovering what else holds in the fictional world of the model. Like TEs, models can be judged as better or worse depending on how well they prompt and constrain the imagination. Salis and Frigg argue explicitly that the same Waltonian epistemological framework can capture both models and TEs (2020). The Waltonian account makes explicit reference to the prop (the model) and principles of generation as constraining devices, and Salis has since developed this view, discussing in more detail some of the particular constraints that are applied (Salis, 2020).

However, the Waltonian account is not accepted by everyone. For example, Stacie Friend (2020) claims that what really does the epistemological work in the models-as-fictions view are the principles of generation, not the imagination (see also Kinberg & Levy, 2022). In the present context, this is not to be lamented: we can discard the Waltonian vocabulary of games of make-believe and props and retain the key point, that tools of imagination like models can be good in the sense that they employ a good set of constraints, which are good in the sense that they help to focus the imagination in a way that has good consequences. Why should we consider discarding Walton's view? Friend argues that it only explores models as *prescriptions* to imagine, and allows that the entire process of reasoning with models can be independent of any actual imaginings. Attention must be paid "to the way in which concrete imaginings play a role in elaborating fictional truths about models and selectively exporting them to beliefs about the real world" (2020, p. 125). So, Friend does not reject the idea that models could be tools of imagination, but rather laments that more hasn't been done to take the role of imagination seriously in how models help human scientists achieve their aims.

There is also a Waltonian account of metaphors (Walton, 1993), which portrays metaphor-comprehension via imaginative engagement with make-believe. Here again, the vocabulary of principles of generation can be used, or replaced by a more direct consideration of constraints that focus imagination, to make sense of how metaphors focus imagination in ways that (it is hoped) have good consequences. But as with other tools of imagination, we should not limit our discussion to constraints. Tools, as Bacon pointed out, do not merely caution, they also prompt us in new directions. And again, this helpful cautioning and prompting of the imagination accounts for the deontic value of tools of imagination, though it must be remembered that the deontic value is parasitic on the anticipated good consequences that a given tool will have.

3.3 Unknown (but foreseeable) indirect consequences

When scientists don't have a particular problem in mind, tools cannot be evaluated in terms of their direct epistemic consequences. Still, tools of imagination can be better or worse insofar as they train the imagination, in a general way, that tends to have good consequences. Thus, instead of their direct consequences, tools can be valued for the indirect consequences they can have on an agent. Here, we expect scientists to define better and worse tools as those that are helpful for developing epistemic virtues which may be manifested in acts of imagination, like intuition, patience, conscientiousness, open-mindedness, humility, intellectual courage, prudence, and intellectual determination. Creativity and imagination have also be classified as virtues (see Stuart, 2022), and in this case, tools of imagination could also aid in their development directly.

TEs can be used to train fruitful imaginations. In a paper about TEs, Tamar Gendler reminds us of "the therapy people engage in to overcome neuroses. People who are afraid of public speaking *imagine* themselves speaking before an audience over and over until they become comfortable with the idea; people who are afraid of flying in airplanes *imagine* themselves being safely able to do so until their adverse reactions begin to fade." Through repeated TEs, such a person might "find themselves able to fly on a plane fearlessly" (Gendler, 2004, p. 1160). Gendler focuses on the effect such training has on belief, but agents in these situations might develop courage as well, which is valuable to the agent insofar as it helps the agent get where they want to go.

In science education studies, TEs are characterized as useful for prompting students to increase their grasp of difficult concepts, measured by their ability to explain things in their own words or solve novel problems. These abilities may be taken as proxies for their level of understanding (Stuart, 2017). But working through TEs also develops epistemic virtues like imagination, intuition, determination, and logical thinking skills. Gilbert and Reiner (2000) argue that TEs work best for students when they are presented in an open-ended way. A theoretical conclusion must emerge from a TE: it should be explored and tested by the student in imagination, not given in advance, as they often are in science textbooks. Why is it good for TEs to be open-ended? Because it forces students to exercise and develop their skills, including creativity, imagination, intuition and problem-solving abilities (Reiner & Gilbert, 2000). This is true even or especially when students produce and resolve TEs that include errors (Reiner & Burko, 2003). This open-endedness is a good-making feature of virtue-oriented tools, and it is shared by visualizations, computer simulations, models and metaphors. All of these allow a certain amount of wiggle room in which students can play and explore, which is important for building scientific virtues.

Like TEs, visualizations can be used to develop the capacities of scientists that are relevant to imagining well. To be a good tool of this sort is to guide the imagination in a way that develops these skills. John Gilbert writes that visualizing, especially visualizing in terms of models, plays a very important role in science. Proper visualizing requires a "metavisual capacity" that scientists must learn (Gilbert, 2005, 2008). The obvious way to acquire metavisual capacity is via interacting with the right sort of visualizations. What makes a visualization of the right sort? Barbara Tversky argues that effective visualizations in science represent the target system accurately and in a way that is easy to comprehend (Tversky, 2005). But as noted above with respect to TEs, virtue-developing visualizations require room for play. This is what new computer programs being deployed in chemistry classrooms aim to do, with software that allows students to create their own visualizations of molecules (Stieff et al., 2005). Another way that visualizations can be tools for virtue-development is by seeing them as enabling scientists to apply virtues that they already have to generate and evaluate models and explanations from a theory that would have been very difficult to use without the visualizations (De Regt, 2014).

Computer simulations can also nurture virtues that are relevant to effective imagining. Kozma and Russell (2005) argue that computer simulations assist students in developing "representational competence," which includes the ability to use, generate, adapt, compare, and evaluate representations. This competence is gained through a sequence of steps (or what Vygotski called "zones of proximal development") from simple isomorphic depictions from given viewpoints, to the inclusion of symbolic elements (e.g., arrows), abstraction away from particular viewpoints, and the inclusion of nonvisible information (e.g., causal information). Computer simulations build these abilities.

> Simulations allow users to select values for input variables from within suitable ranges and observe the results on output variables. With chemical simulations, users might change pressures in a gaseous system or concentrations of regents in a solution system and observe the impact of these changes on the species in the system. Simulations can be used to explore chemical systems or processes in order to derive or test possible underlying explanations or theoretical models. (Kozma & Russell, 2005, 137)

Simulations thus also make use of constrained, directed, active exploration. Some that do this are credited with increasing creativity directly (Betz, 1995; Gokhale, 1996).

Models, especially material and computer models that can be manipulated in an external way, are also useful for increasing scientifically relevant virtues. For example, virtual and material models have been shown to increase a range of relevant skills in high school students (Dori & Barak, 2001), university students in classrooms (Dori et al., 2003), and in laboratories (Kozma, 1999, 2003).

Metaphors also play important roles in science education, especially in causing students to look inwards and question their assumptions (Thomas, 2006), which is important for developing virtues like conscientiousness and self-awareness. Metaphors can help students and researchers to develop abilities that enable them to compress and decompress data and manipulate representations in useful ways (Stuart and Wilkenfeld, 2022), which are skills that are often manifested in scientifically good imaginings.

Overall, this framework can be used to evaluate any scientific tool of the imagination, in the following way. First, we determine the context of the tool being used by reference to the type of intended consequences (e.g., is it meant to solve a particular problem or train the imagination more generally?). Then we evaluate the effect the tool actually has in terms of whether it helps to achieve the intended consequences.

4 Conclusion

This paper argued that alongside tools of the hand, senses, mind and voice, it is sensible to refer to tools of the imagination. These tools plausibly include TEs, visualizations, computer simulations, models, and metaphors. Not every one of these is *always* a tool of the imagination, but insofar as they improve scientific imaginings, they can fruitfully be understood as tools of imagination. And tools of imagination are to be judged as better insofar as they increase the epistemic quality of acts of imagination. I argued that to understand "better and worse" uses of imagination, we should look to how scientists themselves evaluate imaginings. They do this in several ways, but fundamentally, it is done in terms of good and bad consequences.

Thus, we saw that tools can be evaluated in terms of (a) their past consequences on science, (b) how likely they are to have good future consequences in a given, ongoing problem-solving context, and (c) their expected indirect consequences via improving scientific agents and communities.

The arguments presented here provide a framework that helps us to understand how the same tool can be apparently good *and* bad. According to Richard Coll, there are metaphors in chemistry that are useful to researchers, but confusing to students (2006). This shows that a metaphor which might be praised for its good historical consequences, or useful instrumental value at the cutting edge, has less value as a training tool. This may seem like a conflict between epistemic frameworks but it isn't, since the consequentialist claims that the final value of the metaphor will always be evaluated from a future perspective in terms of *overall* consequences. Such a calculation will take into account its negative pedagogical consequences. The consequentialist can then provide normative recommendations: we should not employ that metaphor in teaching, to minimize its negative consequences. In general, we should identify the uses of a tool that tend to have good consequences and those that don't, and work to ensure that only the good consequences materialize. The same holds for tools of imagination: scientists should aim to avoid potential bad consequences of using a particular tool, whether direct or indirect.

We close with two open questions. A consequentialist account of imagination requires an answer to the axiological question of which states of affairs are valuable. "Traditional" views of scientific epistemology will argue that all epistemic aims are all subordinate to the aim of knowledge or truth. Khalifa (2017) gives arguments for this view. Others might be more pluralistic, or pragmatic, arguing that different aspects of science might wish to promote different kinds of epistemic goods, without requiring knowledge or truth to be fundamental. To make a prediction (based on what we have seen in ethics and epistemology), it is unlikely that the issue will be resolved any time soon, and instead, we should look forward to future debate between consequentialists who champion different notions of what the good scientific states of affairs are.

A second open question concerns how far the arguments in this paper may be extended. One might worry that too many things can be counted as tools of imagination, for example, analogies, jokes, examples, and pop-culture references could also be included. However, for each role that imagination plays in science, there may be tools that assist it, and there is no in-principle limit to what might count as such a tool. All possible tools of imagination could not be accounted for in one paper, so instead, a broad sample of tools were chosen. Probably too many. But this was done to support the idea that the framework could be extended as far as needed. And that might be very far.

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