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 grinding mirrors for a new telescope (with their hands), and the next day building mathematical models to understand their observations (with their mind). These actions inherit the limits of the human body and mind. “Neither the bare hand nor the unaided intellect has much 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, scientists use tools to overcome the natural limits of human minds and bodies. The interesting 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. Equally, then, tools of the mind "promote or regulate" the "motion" of the mind, by supplying suggestions and cautions that improve scientific reasoning.

Given the complexity of modern science, 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 tools of the non-human senses (magnetometer, Geiger counters, etc.). Tools of the mind will also admit of subgroups, pertaining to the different kinds of mental actions that can be assisted by tools. These will 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 the sub-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 aid the hand.

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]

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

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 section 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, though it is likely that all of these include and profit from some unconscious processing as well. So, 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 and 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 and 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 sounds worryingly vague: models alone are sufficiently diverse to prompt concerns that a single epistemological framework will not be able to capture them (Veit 2020), never mind the set of models *and* metaphors *and* visualizations *and* thought experiments *and* computer simulations. Still, 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 frames 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, 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 promoting 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).

As we have just seen, 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 and Fehige 2019). Letitia Meynell writes "Hardly any discussion about thought experiments takes place without mention of the imagination" (Meynell 2018, 498). James McAllister explains 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, 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, 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 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 may refer to particular or general experiences, but 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 images can be those which foster good imaginings.

However, unlike TEs, which seem mainly to be tools of imagination, visualizations are more flexible, serving as tools of memory, calculation, and logical inference-making. They can be powerful aides to memory (Shah and Hoeffner 2002; McCrudden, Magliano, and Schraw 2011; Fernandes, Wammes, and Meade 2018). They are also effective in guiding mathematical, scientific, and logical inference-making (Larkin and Simon 1987), as when a mathematician works through a proof in knot theory (Starikova and Giaquinto 2018). 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 (Stuart 2022; Sheredos and Bechtel 2020; Sheredos et al. 2013).

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 (Di Paolo, Noble, and Bullock 2000; Lenhard 2018; Arcangeli 2018; El Skaf and Imbert 2013; Chandrasekharan, Nersessian, and Subramanian 2013; Shinod 2021). For example, Johannes Lenhard classes both as types of "imagined experiment" that explore "hypothetical worlds" (Lenhard 2018, 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 and 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 and Knuuttila 2009; Knuuttila 2011a; 2011b). 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 2011a). 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 the same epistemology 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, 288). For Gaut, metaphor-making is a "paradigm of creative imagination" and also "an instance of creative imagination" (2003, 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, 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 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 primarily 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 and 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.

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[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.

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 to develop virtue or excellence. Thus, 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?

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 is 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 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 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 easy to adopt, 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, 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, 462).

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

[3] The work of David Gooding and Marco Buzzoni is especially coherent 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, 97). I thank an anonymous referee for pointing this out.

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. And 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; Krenn, Erhard, and Zeilinger 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, 39). The predictions agreed with experimental data up to five decimal places. "No one had produced anything like it" (Pais 1991, 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, Bote, and Verschure 2019; Gomez-Marin 2019; Cao and Rathkopf 2019).

3.2. Unknown (but foreseeable) direct *consequences*

In contexts with unknown but foreseeable consequences, we 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 common refrains. 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 or the equivalent amount of literal information, but they pack such a punch because of all the retrievable information they compress. 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 the problem 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 and 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, 506-7). 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, Abrahamsen, and Sheredos (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 consequences of using these kinds of visualizations are never known in advance. But they are used because it is hoped that they 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, Nersessian, and Subramanian 2013, 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 and Frigg 2020; Frigg and Nguyen 2020; 2016; 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 is the principles of generation, not the imagination (see also Kinberg and Levy 2022). In the present context, this is not to be lamented: even if we discard the Waltonian vocabulary of games of make-believe and props, the key point is 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. Thus, she claims that 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, 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 more 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, cautioning and prompting the imagination are not valuable on their own, but only insofar as they have good consequences.

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. Instead of their direct consequences, tools are 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 increasing the 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 aid in their development.

TEs are often 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, 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 tend to be in physics 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 and Gilbert 2000). This is true even, or especially, when students produce and resolve TEs that include errors (Reiner and 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, Bateman, and Uttal 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 and 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 training the scientist to be a good imaginer. For example, virtual and material models have been shown to increase a range of relevant skills in high school students (Dori and Barak 2001), university students in classrooms (Dori, Barak, and Adir 2003), and in laboratories (Kozma 1999; Kozma 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. And metaphors are connected with other tools of imagination, like visualizations (McAllister 2013) and models (Camp 2020; Levy 2020), so their mode of operation in these kinds of contexts could be similar: by constraining and simplifying (cautioning) while also guiding (prompting) the imagination in useful new ways, where "useful" is ultimately defined in terms of final epistemological consequences.

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. And they do this in several ways, but fundamentally, 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 open-ended problem-solving contexts, 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 good or bad in apparently different senses. 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: a consequentialist can claim 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.

I want to close with two open questions. Consequentialism defines good action in terms of how well valuable states of affairs are promoted. So, 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 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, like knowledge, understanding, problem-solving ability, truth, accurate predictions, etc., and even the very same episode might aim for a mix of epistemic desiderata. To make a prediction (based on what we have seen in ethics and epistemology), it is unlikely that the debate about good states of affairs will be resolved any time soon, and instead, we will have different forms of consequentialism, each of which champions a different notion of what the good states of affairs are. However, it is not out of the realm of possibility that philosophers of science could identify a hierarchy or taxonomy of epistemic goods that helpfully informs those in mainstream epistemology.

A second open question concerns how far the arguments given above 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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