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ARTICLE

Everyday Scientific Imagination

A Qualitative Study of the Uses, Norms, and Pedagogy of Imagination in Science

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Abstract
Imagination is necessary for scientific practice, yet there are no in vivo sociological studies on the ways that imagination is taught, thought of, or evaluated by scientists. This article begins to remedy this by presenting the results of a qualitative study performed on two systems biology laboratories. I found that the more advanced a participant was in their scientific career, the more they valued imagination. Further, positive attitudes toward imagination were primarily due to the perceived role of imagination in problem-solving. But not all problem-solving episodes involved clear appeals to imagination, only maximally specific problems did. This pattern is explained by the presence of an implicit norm governing imagination use in the two labs: only use imagination on maximally specific problems, and only when all other available methods have failed. This norm was confirmed by the participants, and I argue that it has epistemological reasons in its favour. I also found that its strength varies inversely with career stage, such that more advanced scientists do (and should) occasionally bring their imaginations to bear on more general problems. A story about scientific pedagogy explains the trend away from (and back to) imagination over the course of a scientific career. Finally, some positive recommendations are given for a more imagination-friendly scientific pedagogy.

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1 Introduction

Imagination is increasingly well-studied. Its nature, use, and development are being analyzed philosophically, historically, computationally, and scientifically in animals,[1] humans,[2] machines,[3] communities,[4] scientists,[5] and students of science.[6] There is no definition of imagination shared by all those who study it, but there is a shared conclusion: imagination is crucial for managing our cognitive interaction with the world.

Despite the increase in academic attention, no one has gone into a lab to investigate the specifics of *scientific* imagination—to find out the different ways it is used, and how it is used well. This might be appropriate if imagination did not play a large role in science. After all, scientists are supposed to "stick to the facts." But a moment's reflection reveals how important imagination is for the scientific enterprise. For example, all experiments begin with hypotheses generated by imagining different ways the world might be. Before testing them, we explore these hypotheses by imagining what else would be true if they were. When it comes time to experiment, we take the real-world system we are interested in and recreate it inside our minds, laboratories, or computers by imagining analogous systems that could be investigated. And even though our idealized experiments remove confounding real-world factors, we imagine that the natural world also instantiates the regularities observed in experiments in order to refine our theories. Different though they are, each of these uses of imagination is necessary for scientific progress.[7] If we want to understand science, we have to understand scientific imagination.

But scientific imagination is only now gaining attention. Perhaps this is a (delayed) consequence of the fall of logical positivism. The positivists introduced a distinction between the contexts of discovery and justification, according to which philosophers of science should focus only on what justifies scientific claims. On this view, *how* scientists arrive at a claim does not matter: what matters is whether the claim is justified. Thus, if a scientist drank too much black coffee and made a big discovery while lying in bed waiting to sleep, this might be *psychologically* interesting, but it would not be epistemologically interesting. As long as justification is understood as a logical relation between a proposition and a set of independent empirical facts, there is no place in epistemology of science for states of mind or mental activities. "The boundary between context of discovery (the *de facto* thinking processes) and context of justification (the *de jure* defense of the correctness of these thoughts) was [at that time] understood to determine the scope of philosophy of science" (Schickore 2018).

In the second half of the 20th century, however, the distinction between the contexts of discovery and justification, as well as the propositional view of scientific theories, crumbled. The thinking processes of scientists became legitimate topics of epistemology (see, e.g., Darden 1991; Hoyningen-Huene 1987; Nersessian 1984, 1992; Thagard 1984), and philosophers of science could now pursue cognitively informed epistemology of science by taking

[1] Jensvold and Fouts (1993), Savage-Rumbaugh and McDonald (1988), and many of the entries in Mitchell (ed.) (2002) focus on primates, including monkeys, chimpanzees, gorillas, orangutans, macaques, and bonobos.
[2] For children, see, e.g., Lillard (1993), Walker-Andrews and Harris (1993), Weisberg et al. (2013). For adults, see, e.g., Piaget (1981), Byrne (2005), Kosslyn (1994), Pylyshyn (2002).
[3] See, e.g., Hamrick et al. (2017), Weber et al. (2017), Pascanu et al. (2017), Mahadevan (2018), Chen (2018).
[4] See, e.g., Castoriadis (1987), Hart-Brinson (2016), Strauss (2006), Taylor (2002).
[5] See, e.g., Nersessian (2008), Chandrasekharan and Nersessian (2015), Trafton et al. (2005), Clement (2009).
[6] See, e.g., Stephens and Clement (2012), Özdemir (2009), Velentzas and Halkia (2011, 2013a, b).
[7] For a more detailed defense of the claim that imagination is necessity for science, see Stuart (2017).

into account how scientists actually reason. Uncovering the ways that imagination contributes to the scientific project is a natural step in this direction.

The idea of studying scientific imagination using empirical methods is not new. For example, there are a number of studies concerning how imagination is used in science education. These typically have the following structure: a social scientist enters a science classroom, and tests students by giving them questions that require imagination. The students are then distracted or assisted in various ways, and conclusions are drawn about the role of imagination. For example, Gilbert and Reiner (2000) focused on thought experiments, which are tools of reasoning that require imagination. They show that these assist students best when they are open-ended, and worst when the students are given the conclusion at the beginning. In a series of articles, Velentzas and Halkia (2011, 2013a, b) showed that thought experiments can help students understand difficult concepts when they proceed through open-ended discussion. Kosem and Özdemir (2014) showed that students of different levels (secondary school, undergraduate and graduate level) all spontaneously created thought experiments at a similar frequency to deal with difficult problems, but they used them in different ways: younger students used thought experiments to support their arguments, while graduate students used them more frequently to communicate their ideas. This is useful data for the epistemology of scientific imagination. But we also need data on working professional scientists. As far as I know, there are only two studies that focus on this group, and they do not focus on imagination in general. Trafton et al. (2005) showed that scientists manipulate mental representations when comparing and aligning mental and external representations. And Trickett and Trafton (2007) showed that scientists spontaneously invent “small-scale” or “local” thought experiments (p. 867) in times of “informational uncertainty” (p. 843).

While it is accepted by all the above authors that imagination plays an important role in science, there are no studies that directly ask when and why scientists use their imaginations. A qualitative study I performed in 2016 begins to address this gap. I recorded more than 10 hours of in-depth interviews with scientists, and collected data over 20 hours of observations from laboratory meetings, colloquia, and informal gatherings, across two collaborating computational systems biology laboratories. The conclusions are relevant for the sociology of science, e.g., concerning who gets to use imagination in science. But they are also relevant for the epistemology of science, as they tell us something about how imagination *should* be used in order to gain new scientific knowledge and understanding.

This article presents two main findings, which are provisional given the small sample size of the study. The first concerns how important each scientist perceived the imagination to be for her or his daily work. The second concerns the central perceived purpose of imagination.

The next section describes the methodology of the study. Section 3 presents quotations from interviews and participant observations concerning the role of imagination. Section 4 provides a robustness check by comparing what the scientists said about imagination to what they said about other elements of their work, including emotion, mathematical reasoning, and humour. Section 5 identifies a tacit norm concerning the use of imagination. Section 6 presents an epistemological analysis of this norm.

2 Methodology: Studying Imagination in the Lab

Participants were selected from two collaborating computational systems biology labs in the USA. Each lab contained 7–10 members and were labelled P1, P2, etc. The observations and interviews were performed between 04 January 2016 and 30 April 2016.

There are many social scientific methodologies that could be used to study scientific imagination. One recommends starting the investigation with a more or less definite understanding of imagination. For example, the *extended case method* attempts to extend and develop an existing theory through "a sequence of experiments that continue until one's theory is in sync with the world one studies" (Burawoy 1998, 17–18, cf. Burawoy 1991, 2000). This method is not feasible for scientific imagination because those working on imagination (in both philosophy and cognitive science) have all but given up on either defining imagination or providing a general theory of it (see, e.g., Kind and Kung 2016, p. 3; McGinn 2004, pp. 1–2; Stevenson 2003; Strawson 1970, p. 31; and Walton 1990, p. 19). There is thus no general theory of imagination to sync up with sociological observations.

Instead of taking up an existing theory of imagination, then, perhaps we could take up an existing theory of an imaginative *subprocess*, like mental imagery, spatial reasoning, simulative model–based reasoning, or (debatably) memory. But again, there remains substantial disagreement concerning the nature of each of these subprocesses. The debate on mental imagery, for example, has been going on for decades and shows no sign of slowing down. And more importantly, the epistemological question of how scientists are able to use imagination to leave the world behind while also learning about the world ideally seeks an answer in terms of the broader faculty of imagination and not one of the more specific subprocesses.

Other social scientific approaches do not require that we possess a theory of imagination in advance. One such approach is *analytic induction* (see, e.g., Znaniecki 1934; Lindesmith 1947). This approach does not require that we possess a theory of imagination, but it does require that we formulate *hypotheses* in advance about the role of scientific imagination. These hypotheses are then tested against observations. The danger here is that too strict a focus on pre-determined hypotheses can cause us to miss interesting details about scientific imagination that are irrelevant to our initial hypotheses.

A more flexible approach is *grounded theory*, which recommends not making theoretical hypotheses in advance, but allowing them to emerge during the study (see, e.g., Glaser and Strauss 1967; Corbin and Strauss 1990; Glaser 1978; Strauss 1987; Strauss and Corbin 1990). Critics of grounded theory have pointed out that no investigation can begin without assuming some theoretical hypotheses. In response, modern grounded theory merely recommends that we avoid making any *explicit* theoretical hypothesis in advance, and avoiding as much exposure as possible to relevant theoretical literature during the data collection phase and early analysis.

I employed a combination of analytic induction and grounded theory in the sense that I formulated some hypotheses in advance, but also allowed new hypotheses to emerge during the study. All hypotheses, whenever formulated, were tested against coded transcripts of semi-structured interviews and field notes from participant observations (of lab meetings, conferences, etc.). The most important hypothesis I formulated in advance was that it would be sensible to talk about imagination as though it was "one thing." I did not assume that the scientists would share this assumption. Perhaps there are many different kinds of imagination with different properties and uses, and that is something which might emerge naturally during the study, but I had to assume that the scientists would at least understand my questions about imagination. I also had to assume something, though perhaps not much, about what imagination is, so that I would "know it when I saw it." To this end, I built on my (2019), where I took imagination to be a cognitive ability, exercises of which are cognitive processes. Those processes must be directed toward some content, at least some aspect of which is not present to the senses. I also follow Arcangeli (2018), insofar as she claims that imaginative cognitive processes do what other processes do, except without the presence of the usual objects. For example, "seeing" an apple in the absence of apples is imagining an apple, likewise for tossing it up and down, judging its weight, tasting it, or hearing the crunch of its flesh. Importantly, we can also imagine that a real apple we see in front of us is made of plastic, or contains poison, or is the entire Earth, and we can reason about the apple as if it were any of these things. This kind of imagination "re-creates" cognitive actions normally associated with the faculty of belief, and again, it requires that some aspect of the object of imagination not be present to the senses (in the case of the poison apple, the poison is not present). Since the faculty of belief need not operate on sensory content, the kind of imagination that re-creates it need not operate on sensory content either. Thus, we can imagine world peace or an infinite number of particles without any corresponding mental image/sound/feel/etc. These considerations point to a very broad characterization of imagination, but it seemed reasonable to start broadly.

Over the course of a semester, I performed 2 semi-structured, hour-long interviews with a selected number of the participants in the two labs, and short follow-up discussions after the end of the study. The interviews with P1 took place in his office. In the case of P5, one interview was conducted in P5's office, and another involved a trip to P5's lab. The rest of the interviews were conducted either in the common area of P1's lab, at a participant's cubicle, in a nearby classroom, or in the lab's meeting room. P1's lab looked somewhat like a modern business office, except with a higher temperature due to the computer simulations. It was a rough rectangle, the central area containing cubicles of chest height. The lab meeting room was called the "fishbowl," and was a room in the middle of the lab whose walls were almost completely composed of glass. It was joked that the room was made this way so that passersby could keep an eye on what was going on inside. In practice, this worked both ways, with participants flagging down people walking by to come in and contribute to a discussion. Participant observations were performed in lab meetings (which took place in the fishbowl), P5's lab, participant cubicles, workshops, and conferences. The participants chosen for interview were as follows:

- P1: Principal investigator of lab A
- P2: Second-year graduate student
- P3: Fifth-year graduate student
- P4: Postdoc
- P5: Principal investigator of lab B

Lab A used computational modelling methods, while lab B used experimental methods. The two labs collaborated on joint projects, with lab A making computational models of phenomena that were observed in lab B, and lab B testing predictions made by lab A's models. P2 and P3 collaborated with lab B by performing experiments, though they primarily ran simulations in lab A. P4 did not run wet-lab experiments. Labs A and B contained other participants who were often observed (e.g., in lab meetings) but who are not reported on here.

In each case, the first interview established an overview of the scientist's methods and problems, while the second and follow-up interviews went into the details of their daily cognitive work, including how they select problems, build computer models, perform experiments, and interpret and communicate their results. I observed all of lab A's meetings for a semester, visited lab B, and attended colloquia that lab members attended. The initial interview with P1 formally began the study, and this took place before any participant observations were conducted. After this, initial and follow-up meetings were held with participants according to their availability, though in some cases interviews were delayed until after a significant observation, e.g., I delayed the second interviews with P2 and P3 until after they gave group presentations, so my questions could reflect what I had observed. All lab meetings and interviews were (audio) recorded and transcribed, and notes were taken by hand throughout.

The transcriptions were coded into 173 individual codes. The codes were arranged into 12 themes (emotion, practice, problems, pedagogy, socialization, methodological considerations, personal details, important events, cognitive processes, modelling, visualization, and imagination). For example, under the theme "cognitive processes," there were codes such as "simplification," "abstraction," "approximation," "empathy," and "narration," whereas under the theme "visualization," there were codes such as "creating visualizations," "diagram conventions," "aesthetic quality of diagrams," and "considerations of the audience."[8] All themes were mutually exclusive, in the sense that no one code appeared in two different themes. However, two codes (from any theme) could (and often would) be applied to the same portion of an interview or observation transcript or field note.

The codes were brought into rough explanatory relationships that helped explain how the lab's cognitive work was performed. These inspired additional hypotheses that were tested on the participants, through prompts and questions (both direct and indirect) in later interviews. For example, one very popular code with P2, P3, and P4 was "P1 as mentor." Following up on this in later interviews, subcodes emerged, such as "P1 and brainstorming," "P1 and criticism," and "P1 and diagram-design." These contributed to the creation of the pedagogy theme, and inspired the inclusion of P5 into the study, to test the hypothesis that his teaching methods, insofar as they were different from P1's, might affect participant attitudes toward imagination.

A hypothesis I had before the study began was that the scientists might not feel comfortable talking about imagination (inspired by Özdemir 2009). For this reason, I only asked what participants thought about the role of imagination at the end the study, when I felt I had established enough rapport. In addition, reserving this topic until the end was helpful so that the participants would not try to include imagination in their answers to questions that were not about imagination (e.g., because they knew that I was interested in it). This is important because I wanted their attitudes toward imagination to emerge unprompted, as much as possible, at least until the final interview. Until then, they used their own concepts to describe what we might think of as imagination. I coded all interviews and field notes for instances of imagination, or imagination-like concepts, including brainstorming and hypothetical reasoning. Once I recorded the explicit attitudes of lab members toward imagination, I went back to the notes to see if what they had said agreed with their previous statements and the behaviour I had observed in lab meetings, and then asked more questions to confirm my hypotheses in follow-up discussions.

Finally, codes related to the roles of mathematical reasoning, humour, and emotion came up quite frequently. This inspired the following hypothesis: perhaps there are important personal differences between participants that explain the different attitudes they expressed toward imagination. For example, perhaps differences in individual temperaments (like valuing mathematics but downplaying emotion and humour, or vice versa)

[8] For more on the diagrams created by laboratory A, see Stuart and Nersessian (2019).

might be correlated with certain attitudes toward imagination. This gave me a comparison class that could be used as a robustness check. I will present the results of this robustness check after the data on imagination.

3 The Perceived Role of Imagination

During the final interview with each participant, I asked: "Does imagination play a role in your work?" P2 replied,

> I guess some people would say that imagination would help you figure out some of these patterns right?... maybe a long time ago I used to think like that, but now I'm much more in favour of being able to prove it, and not imagine it…For the actual science, I think I don't imagine that much anymore. (interview, 25/04/2016)

She went on:

> I think humans have limited ability to extrapolate…like, when you look at a giant signalling network, okay, you might like, stare at it for a while, and think that if I perturb it in this way, maybe this should happen. Or if you see some output trajectory, you see a behaviour like this [draws a diagram] you might try and reason about it in words, but I won't buy it. Yeah, I think you could reason about anything. (interview, 25/04/2016)

For P2, imagination is to be avoided because we can imagine anything we want. It's not a reliable tool for science. When I asked P2 about some of her more novel contributions, she replied that she simply combined pre-existing models with pre-existing data from the literature. If there is something new in a model, she claimed, it is just new behaviour that was first observed in an experiment. To explain the new behaviour, we require a hypothesis, but this is "basically just describing a relationship" (interview, 25/04/2016). These relationships are then coded into rules using the lab's preferred coding language, and these rules capture sets of equations that describe the observed behaviour. "The human just has to write down the rules" (interview, 25/04/2016). Then the model is run and tested against the data. Imagination, for P2, does not figure necessarily into these processes.

P2's attitude echoes what James McAllister (2013) has called "the problem of arbitrariness" for imagination. In the history of science, the use of imagination has been criticized by scientists who pointed out that imagination is underconstrained by reality—we can imagine anything we like, including what is false. And there is no mark to separate false from true imaginings. Therefore, we should not trust imagination to play any epistemic role in science. And indeed, P2 claimed that it would be better to offload our imaginative duties to computer models (in line with Chandrasekharan et al. 2012).

P3 has a more optimistic view of imagination. For him:

> There's probably a lot of room for imagination. You definitely have to be able to think critically. I typically have to come up with a couple of different ideas for what's possible. It's sometimes hard because you read papers…and they're seminal findings, and then they're never repeated, and taken as dogma for 20 years. And sometimes you realize they're actually not correct. And so, there's creativity in filling in the gaps of what's known, [and] there's creativity in understanding what the limitations are of the literature that's already out there. (interview, 21/03/2016)

For P3, imagination is tied to good (i.e., critical) thinking. It helps him to come up with ideas for what's possible (modal exploration). It also assists in understanding the limitations of the literature (exploration of epistemic possibilities).

P3 went on:

> The experiment too, I mean, when experiments fail there's a lot of just, going back and going over step by step and thinking 'why did this fail, and what happened?' I had certain western blots fail over and over and I've gone through with a friend in the experimental lab to redo it; thinking over and over about where else we might be failing…You end up coming up with a bunch of different ways it might've failed. (interview, 21/03/2016)

In sum, for P3 "there's probably a lot of room" for imagination. It is not always to be avoided, because it allows for creativity and new ideas. These are needed to address problems, including incorrect dogma and failed experiments.

P4 was even more enthusiastic about the role of imagination. He replied:

> I mean, we're scientists right? So you gotta be imaginative. There's imagination in how we present things, which I kind of lack. There's imagination in finding a solution to a problem. Yeah, definitely. Imagination is important. Because at some point you're just solving problems all the way to a finish line. You really need to be a little imaginative, in terms of how you solve them. I mean, that's why we do what we do. (interview, 03/01/2016)

P4 sees imagination as necessary for science, and has clearly thought about his own imaginative strengths and weaknesses. As a follow-up, I asked, "Do you have any thoughts on how your own imagination works, helping you to solve problems?" He replied:

> Mm. I don't know. I mean, I rely on luck a lot. Like, you know, I just fade out. Boom! I haven't made a process out of it yet, and I should. Because as a scientist you should have a process for thinking. But I mean I guess I kind of have a process. Like I like sitting in cafes, looking at people. I like that movement and the hustle and bustle. It triggers my creative instinct. Other times, if I'm writing code, I don't need people around. I probably just isolate myself, come into my cubicle. Just me and my computer and that's it. A little music maybe, and nobody else. There's this other phase when you want to present something, when you want to figure out something, and you need to be around people. And I think hashing it out with your lab mates, that's actually a very important part of the creative process. A lot of good stuff has happened with just hanging out with [lab mates] outside, just talking about random crap. (interview, 03/01/2016)

This mention of collaborative imagination was interesting, so I asked if he would agree that imagination is shared among lab members. He replied, "Yeah, definitely. When we're talking about stuff, I think it's very conducive to talk about what ifs and maybes and perhaps, and things like that" (interview, 03/01/2016).

In sum, for P4, imagination is not just occasionally useful, it's *essential* to what a scientist is because it's necessary for solving problems, which is what scientists do. P4 has thought about how his own imagination works, and did not hesitate to conclude that it's shared within the lab.

We now turn to the two principal investigators. In response to the question about the role of imagination, P5 replied:

> [Imagination] is extremely important to me. I think it's very important to be creative, and I think imagination is a large part of creativity. I think some people will put themselves in a box of the tools that are available to them and say 'What can I answer using these tools?' and other people will just kind of go after the question and say, 'I don't care how I figure this out, as long as I can learn about the system.' I think there's a creative approach to a lot of things, and when you take a creative approach, a lot of the time you end up with elegant experiments…By doing something a little bit more, I hesitate to say artistic, but, um, artistic, I think, you know, thinking about alternative ways to approach a problem, you don't just develop new techniques, you also frequently more directly look at whatever it is you're looking at. (interview, 25/04/2016)

P5 filtered his enthusiasm for imagination through the need for creativity. I asked what he thought the relationship between creativity and imagination was. He replied:

> I mean, it's part of it right? To be creative means, there's something that you want to do or there's something that you just can't immediately go and do, so the imagination is finding a way to make it happen (interview, 25/04/2016).

In sum, for P5, imagination is part of being creative, which is important for finding novel solutions to problems.

Finally, P1 answered in the following way:

> There's a certain amount of [imagination] in trying to generate new hypotheses, trying to understand how different systems work together. Being able to think creatively about that, to come up with new ideas, is definitely important. I think to me, the biggest, I don't know if I would call it imagination, but putting things in the proper context, you know, 'How could this be used to do things in biology that haven't been done before?' I do feel like imagination is a component of that…And it's really important to think about what impact a project is going to have, before deciding to invest a lot of time and effort into it…Or, you see a talk…you know, good papers, or good talks, they're fun because you see the creativity that somebody had. They figured out that they could use this to do something completely different. And that's really exciting. (interview, 03/03/2016)

He added:

> I think imagination is really important for computer programmers. What could be going wrong? And filtering down the set of possibilities requires some creativity. And I've noticed some people are really good at it, and other people are really crappy at it...And partly that's experience, but then, you know, when it gets to be something, more and more subtle things... I know I'm good at that. (interview, 03/03/2016)

For P1, imagination is important and makes science exciting. It allows us to generate hypotheses and evaluate the promise of new projects. It is also important for dealing with problems. P1 can evaluate how imaginative someone is, including himself, and compare levels of imaginativeness.

To summarize this section, participants exhibited varying attitudes toward imagination: the more senior participants granted larger roles and saw imagination as a positive, even essential component of their work. Less senior participants attributed a diminished role to imagination and saw it as less essential, even as a danger. For those participants who appreciated imagination, its primary role concerns (creative[9]) problem-solving. The next section will compare this with the results of similar questions concerning mathematical reasoning, emotion, and humour.

4 The Perceived Roles of Mathematics, Emotion, and Humour

When I asked participants about imagination, I also asked about mathematical reasoning, emotion, and humour. This was to see if there were any correlations between attitudes toward these elements and attitudes toward imagination, and to see if the participants' answers to these questions exhibited the same general patterns as their answers about imagination did.

Thus, I asked: "What is the role of mathematical reasoning in your work, and how important is it?" To this question, I received more or less the same answer from every participant: they all agreed that mathematical ability is generally neglected in the teaching of biology, but knowing how to reason abstractly and formally is vital for computational systems

[9] P1, P3, and P5 all mentioned creativity in their comments on imagination. I will not try to summarize the large and growing literature on creativity in this paper, but a common assumption in that literature is that creativity requires novelty, and one way to be novel is by using the imagination. This sentiment is also found in the writings of scientists; e.g., Max Plank wrote that creative scientists require imagination, "for new ideas are not generated by deduction, but by an artistically creative imagination" (1949, p. 109). This sentiment is consistent with what I found. Still, the connection to creativity deserves further discussion, and I thank an anonymous reviewer for suggesting that I emphasize it. For more on the relation between imagination and creativity outside the scientific context, see Gaut (2003) and Stokes (2014, 2016).

biologists. They agreed that a lack of mathematical fluency is one of the main obstacles to fruitful interaction between computer modellers (who are comfortable with math) and experimentalists (who typically are not). They agreed that it was difficult or impossible to explain the content of computer models to experimentalist collaborators without going into the details of the models (which typically involve algorithms based on non-linear dynamical equations, bi-stability, and graph theory).[10] Interestingly, all participants answered this question by correlating mathematical reasoning with formal reasoning, as in the ability to translate molecular pathways into computer code.

In sum, mathematical ability was uniformly perceived as crucial for the future of (computational) biology, currently neglected in biological pedagogy, and important for building and managing computer models. Lack of mathematical fluency was seen as one of the biggest obstacles to effective interdisciplinary collaboration. There was no behaviour observed in the lab meetings that contradicted this attitude, but much that supported it.

When asked the same question about humour, again I received very uniform answers. Humour was perceived by all lab members as an important way to make other lab members feel comfortable, and generally promote social cohesion. Social cohesion is good for facilitating collaboration, which is a basic good for these labs. None of the participants claimed that humour played any epistemological function.[11]

Finally, I asked participants the same question concerning the role of emotion in their work. Here there was slight variability: The more senior a participant was, the more roles they could identify for emotion in their work. Nevertheless, even comparing the most to least senior lab members, none of them attributed any positive epistemic role to emotion. Rather, they treated it as a danger to be avoided. For example, P1's response to the question was: "I think it's very important for motivation that something is exciting. You know, the feeling that you're contributing to something important or big… [Nevertheless] we try to be objective and neutral and not bring emotion into our interpretation of data or our evaluation of what mechanisms are important" (interview, 03/03/2016). P5 replied even more negatively. "I definitely hope there is not an influence of my emotion on what I do! (Laughs). …there shouldn't be a lot of place for emotion and as far as your results are concerned, because you should basically be reporting the facts, I mean that's what science is right?" (interview, 25/04/2016). Again, none of the behaviour in lab meetings contradicted these statements.

In sum, for all members of the lab, mathematical ability and humour were considered goods that achieve certain aims, while emotion was generally considered a pitfall to be avoided for specific and agreed-upon reasons. The valance of these cognitive features, as well as their uses and effects, appears to be settled. One possible explanation for this agreement is indoctrination: the students merely repeat what their mentors teach them. However, P2 had only recently begun her time in the lab, P2 and P4 were educated on a different continent, and whereas P1 had been in this university for a decade, P5 had only been there for 2 years, which makes it unlikely that P5 would have indoctrinated students in the same way as P1 unless there was something like worldwide agreement on the valance and uses of mathematical reasoning, humour, and emotion for computational systems biology. In any case, the hypothesis that participants give similar answers to the same question because they are uniformly

[10] For a discussion of one way the participants overcome this problem, see Stuart and Nersessian (2019).

[11] Comparing this attitude to the behaviour observed in lab meetings, however, I believe that humour does play a much more important, even epistemological role in the lab. For instance, it is often through humour that serious new ideas arrive. But this must be the topic of another paper.

indoctrinated appears not to be supported by the data collected on imagination. Here, as we have seen, attitudes vary widely. If the lab environment influences participants toward uniformity of opinion, it fails to do so for imagination.

In sum, given the same questions, participants replied with one voice on the importance and purpose of mathematical reasoning, humour, and emotion, regardless of whether the valence of the item in question was positive (math and humour) or negative (emotion). Imagination is therefore a special case.

5 When and Why Imagination Is Thought Appropriate for Use

If the preceding sections are correct, to find instances of scientific imagination, we should look at what scientists do when problems arise, since this is the one unifying idea in all their discussions of imagination. But which kinds of problems? To find out, I went back through the field notes and interview transcripts and coded any statement containing the word "problem," and any discussion of a problem, even if the word "problem" wasn't used. Here is a list of problems that P1 identified explicitly: managing the time of the lab, finding and training the right people, getting the work of the lab to catch on in the general discipline, getting the right sort of data from collaborators, and long term: producing a model of the cell that is descriptively and predictively accurate and understandable. The problems that P5 listed explicitly using the word "problem" included the following: finding and training the right people, making the lab more interdisciplinary, understanding how cells use molecules or receptors to make sense of their environment, getting the right sort of data from experiments (cell microscopy imaging), and long term: understanding heterogeneous cell responses in a way that can be made practical (e.g., in medical contexts).

At no point did I see any evidence that any of the above-mentioned problems were directly addressed using imagination, and this was confirmed in interviews. Instead, when problems like these arose in practice, they were usually followed by a series of standard questions, a practice that I call "problem-whittling." For example, if the problem was that existing models of a certain signalling pathway do not predict empirical data, the lab members would ask questions like: What models are there, and who made them? What data do those models accommodate, what data do they miss? Who could we talk to about this? and so on, until the problem was transformed (whittled-down) into a maximally specific version of the original problem.

Let us therefore distinguish between genus- and species-level problems. A species-level problem has been maximally specified. It is whittled-down completely into its component parts, and all the relevant background knowledge has been brought to bear. The process of problem-whittling reveals exactly what is and is not working in our attempts to make progress. A genus-level problem is not completely broken down. For example, "How do we make a better model of this signalling pathway?" is a genus-level problem because there are a number of ways we might understand "better model" (i.e., better for what purpose, and how much better?). It is not yet clear what is desired and why, and what resources we have at our disposal. A species-level version of this same problem will look something like this: "How do we make *this* kind of model, of *these* features of *this* signalling pathway, for *this* epistemic purpose, better in *this* sense, given all that we know?

Once we turn to species-level problems, we find many instances of imagination being used. And these episodes are always found after a genus-level problem has been whittled-down into a species-level problem. Sometimes the whittling process itself points to a solution. To make a better model of type T of features F of pathway P in sense S given background information I, you need to know all that is relevant about T, F, P, S, and I. It may turn out that any of these problem components is not yet maximally specified, in which case, more work needs to be done to narrow it down (e.g., there might be two types of model type T: Ta and Tb, and we have not considered Tb yet). Often, the exercise of problem-whittling is enough to end the conversation until further research is carried out. Other times what is required is to reach out to a certain expert for advice. Other times still, a brute force trial and error method might be the easiest way forward. But when these options are not available, the lab begins imagining. Here are some examples.

P3 learned about a feature of a target system that he was modelling. He added this new feature to his model, which should have made it more accurate. But instead, the model "exploded," producing infinitely long chains of a certain molecule. To address this, he self-reports imagining many possibilities of what might be interacting with what, and how. When he could not decide what to do on his own, he shared his problem with the group, and then with an external expert, to offload some imaginative work (more on this case below).

P4 wondered how to create a visualization for the output of a particular model. To do this, he imaginatively considered user experience. What would a biologist want to see if they were not an expert on this pathway, or on mathematical modelling? This exercise was an important source of input that guided his choices.

P5 was growing cells on plates to observe under the microscope. But he noticed that using two-dimensional plates "flattened" observations. He wanted to know if there was any other way to grow cells that could be observed through a microscope. He self-reported using his imagination to design a small plastic device that allowed him to grow and image cells in three dimensions—this proved to be a huge leap forward.

P3 noted that it's difficult to keep track of what goes wrong in a western blot experiment despite taking careful notes, because he sometimes records his notes incorrectly as well. For example, he might prepare the wrong media for an experiment, but think he has prepared the correct one, so he enters "prepared media" in his notes, as though he did it correctly. Then, when the experiment fails, he returns to his notes and cannot find the error. To address this, P3 imagined the pros and cons of other ways of performing experiments, including perhaps video-recording everything he did.

One final example: in a discussion about the sources of P1's data and how he builds models, P1 said,

> There's a lot of [empirical] information we get, and it can provide a lot of insights. And yet, it leaves a lot to the imagination. We're trying to fill in the details in some way, trying to make sure that we have all the things that are important. If there are other things that we know are important that aren't being measured, which is often the case, then we have to put those in our model. An example would be, in the t-cells that we study, they're stimulated in a particular way. How they're stimulated is very important for what the outcome is. And yet we don't know very much about how they're stimulated. The experiments stimulate the cells, but we don't know much about what, at a molecular level, is going on in those conditions. So we're forced to just, make up some plausible scenario, by which the cells are activated. (interview, 03/03/2016)

I asked P1 how he "makes up a plausible scenario." He replied,

> Signalling begins with the receptors that are activated. The simplest model is, you have a receptor that triggers some series of events downstream. And then you just say, okay, at some point, the receptors became activated, or some fraction of the receptors became activated. And we'll take as our input parameter variable that fraction of receptors that's activated, and we'll see what happens if we activate a certain fraction of our receptors at a certain period of time, for a certain period of time, and see how that

> propagates through the system…But exactly how that works, we're sort of again, abstracting. We don't know how the receptors become activated. (interview, 03/03/2016)

In this extract, P1 explains a common species-level problem for computational systems biologists: without knowing the underlying molecular processes, the modellers have to add in certain details themselves into their models, essentially by making educated guesses. As P3 indicated to me with his "exploding" model, there are typically only a few ways that seem "natural" when it comes to filling in the details. The point is that this guesswork only takes place after everything else that can be done, has been done.

The use of imagination to address species-level problems could be found for even the most mundane issues. For example, P2 gave a presentation, and P1 wanted to help her improve her presentation skills. As a group, they told stories of people with very good presentation skills and then imagined P2 using the techniques of these star presenters, dismissing some they did not think would fit her personality and style. There were dozens more cases like these.

In conclusion, uses of imagination were easily identifiable in relation to species-level problems, and never in relation to genus-level problems. This was true for all problem-types, from theoretical to experimental to mundane. The participants were therefore correct when they said (in interviews) that imagination was important for solving problems, but it was only for species-level problems, and only when other methods had already failed, or when those other methods required too much effort or were unfeasible for some other reason.

There are a number of possible explanations for this finding. For one, this study was constrained to lab meetings and interviews, and lab meetings are often trouble-shooting sessions. So, it should be expected that I would observe very specific problems being addressed there. But in interviews as well, the problems that they mentioned in connection with imaginative solutions were invariably quite specific, even though the challenges they labelled as "problems" tended to be genus-level ones.

Below, I argue that there are some good epistemological reasons for scientists to apply imagination primarily to species-level problems. To anticipate, it would make sense not to resort to imaginative speculation until after you had whittled-down a genus-level problem into a species-level problem because the better we grasp a problem, the likelier we are to solve it. And we can usually grasp species-level problems better than genus-level problems precisely because they are broken down as far as possible. The different aspects of the problem are grasped independently, and focus can be placed on the recalcitrant aspects. This method of analysis is typical, and indeed characteristic, of mature science.

If this is right, perhaps the following norm is implicitly governing the use of imagination in labs A and B:

> Norm: Don't use imagination to address genus-level problems; only use it when necessary for addressing recalcitrant species-level problems.

In the next section, I consider the epistemological reasons for and against such a norm.

6 Discussion: Epistemological Considerations Concerning an Implicit Norm Governing Scientific Imagination

First, genus-level problems typically have a larger solution space than species-level problems. For example, in a chess game, "How do I win?" is a genus-level problem. There are an infinite number of solutions. “Where should I move my knight given the current set up and everything I know about my opponent?” is a species-level problem, and there are a much smaller number of possible solutions. Of course, in a sense, there are always an infinite number of possible solutions to species-level problems as well (you could smash the chessboard at t_0, or t_1, or…). But there are only a finite number of solutions actually considered by scientists as live options for any given species-level problem. For example, when faced with the exploding model problem, P3 only seriously considered two solutions, one that was ad hoc and easy to implement (but might have negative future consequences), and another that was computationally more difficult but could provide a more realistic model of the system. If neither worked, another could be found, but scientists do not (and cannot) consider an infinite number of solutions to species-level problems. Genus-level problems, on the other hand, have so many options for resolution that imagining how these might play out would typically be a waste of time, for example, because many of them would cease to be live options if the question was made more specific. A first-year physics student imagining how to solve the inconsistency between general relativity and quantum mechanics would serve themselves (and science) better by learning the relevant details first.

A second consideration is that human imagination is not very powerful. There is probably a continuum of strengths of imagination, but even at its most powerful, we cannot track the variations of many variables at once as they play out on the mental stage (Cowan 2001). Because of this, our imaginations will be better equipped to deal with problems whose solution space is smaller.

This relates to considerations about constraints on the imagination. Species-level problems have more constraints because more background knowledge is brought to bear. And many philosophers have argued that imagination will be more epistemically reliable when it is constrained (Wilkes 1988; Kind and Kung 2016, p. 13). Imagine what it would feel like to be inside an elevator accelerated upward at 9.8 m/s^2 in the absence of a gravitational field. If the imagination is completely unconstrained, the answer might be that in this situation, everything turns into strawberries. When the imagination is constrained, however, the answer might lead us to Einstein’s principle of equivalence. That is not to say that the more the imagination is constrained, the better it is. At some point, further constraints will only hinder the generation of novel ideas.

In sum, the more specific we get about a problem, the more background knowledge we mobilize, and this background knowledge can help focus the imagination and shrink the solution space, which can be useful for solving problems. Nevertheless, there will be exceptions to this norm. For example, recalcitrant species-level problems that have eluded solution for a long time, despite great effort, can sometimes only be solved by questioning elements of the background theory. For example, physicists in the Newtonian tradition tried to tweak their mechanics to account for the anomalous perihelion of Mercury. But in the end, this species-level problem (of how best to tweak the mechanics) was not one that we needed to answer. Einstein’s work led to a new set of species-level problems that were only conceivable after we re-thought genus-level problems about the nature of time, space and gravity.

In addition, it probably will not hurt if someone with a lot of scientific experience and intuition occasionally brings their imagination to bear on a genus-level problem. In fact, it might be helpful. Thus, P1 noted that mature fields of science “tend to solve the same problems over and over again, at higher and higher levels of resolution, rather than taking on new challenges.” And it is important that expert scientists occasionally question the scientific status quo, e.g., to find those new challenges. Therefore, the norm governing scientific imagination should weaken over the course of a scientist's career, so that the imagination is brought to bear (occasionally) on genus-level problems as expertise increases.

To explain how this norm weakens, we can look to scientific pedagogy. Here is a plausible story about how imagination is pushed away during undergraduate education, only to be later embraced during graduate training. At the undergraduate level, students learn to solve species-level problems. There is no advice offered about how to solve more general (genus-level) problems. Rather, students learn the tricks of the trade by solving simplified problems, often represented formally or mathematically. These problems can seem unconnected to the cutting edge. Students also reproduce historical experiments in the lab, but again, they do this not to answer cutting edge questions but rather to learn certain problem-solving methods. It might be unclear to the student of science how these standardized problem sets and historical experiments are relevant. And certainly, throughout this period, students need not mobilize a great deal of imagination. Indeed, it is possible that they are actively discouraged from doing so (Özdemir 2009). When the student enters graduate school, however, their mentors introduce genus-level problems and begin teaching them how to whittle these down into species-level problems: check for this, read that, talk to this person, etc.. Students might still be discouraged from using their imaginations while they learn to apply standard methods of solving species-level problems. Especially since the problems assigned to beginning graduate students by their mentors will have been selected to cement and develop existing skills. It is only when the student reaches the cutting edge *and* the best available methods fail that s/he is required to imagine truly alternate pathways.

And indeed, imagination *should* be avoided to some extent during undergraduate education in favour of learning foundational methods, just as improvisation and composition are not taught to piano students until the basic techniques of playing the instrument are in place. High-level improvisation and composition become possible only when a student's fingers move automatically and the rules of music theory are comprehended. Eventually, even the most fundamental tenants of music theory can be questioned and explored imaginatively. It seems natural that the same would hold for science, which is a pursuit that also mixes theory and craft.

When I asked the participants if this narrative captured their experience, they agreed that it did, and gave personal anecdotes to confirm it. I suspect that echoes of this story will ring true for others with science training. Many famous scientists have criticized this "numbing" of imagination during science education. Here is a selection from physicists David Peat and David Bohm:

David Peat:

> As far back as I can remember, I was always interested in the universe. I can still remember standing under a street lamp one evening—I must have been eight or nine—and looking up into the sky and wondering if the light went on forever and ever, and what it meant for something to go on forever and ever, and if the universe ever came to an end…These sorts of ideas continued right through school, along with a feeling of the interconnectedness of everything. It was almost as if the entire universe were a living entity. But of course, when I got down to the serious business of studying science at university, all this changed. I felt that the deepest questions…were never properly answered…Instead, we were all encouraged to focus on getting concrete results that could be used in published papers and to work on problems that were "scientifically acceptable." So fairly early on, I found myself getting into hot water because I was always more excited by questions that I didn't know how to answer than by more routine research. And of course, that's not the way to build up an impressive list of scientific publications. (Bohm and Peat 1987, pp. ix-x)

David Bohm:

> I, too, felt that kind of wonderment and awe in my early days, along with an intense wish to understand everything, not only in detail but also in its wholeness.
>
> However, in graduate school at the California Institute of Technology...I found that there was a tremendous emphasis on competition and that this interfered with such free discussions. There was a great deal of pressure to concentrate on learning formal techniques for getting results. It seemed that there was little room for the desire to understand in the broad sense that I had in mind. Neither was there a free exchange and the friendship that is essential for such understanding.
>
> Although I was quite capable of mastering these mathematical techniques, I did not feel that it was worth going on with, not without a deeper philosophical ground and the spirit of common inquiry. You see, it is these very things that provide the interest and motivation for using mathematical techniques to study the nature of reality. (Bohm and Peat 1987, pp. xi-xii).

Frustration at the stunting of imagination is understandable, though perhaps this stunting serves a purpose. We must learn to hit the piano keys before we can write a song. With this made explicit, we can now consider how to improve the relationship between scientific pedagogy and imagination. Again, by analogy to music, consider a novice pianist who is frustrated by their teacher's emphasis on technique and theory. One solution to keep the student motivated is by exposure to examples of great music played by master pianists. The student is reminded that once the techniques and theory are mastered, they will also be able to express their musical imagination as much as they like. They know imaginativeness is valued, only not yet. Can we say the same for a young hopeful scientist? There are historical examples of great scientific breakthroughs, but these are not required reading, and if they were, they would not be enough to convince would-be scientists that their imagination will be important in *their* future scientific career. It can seem to undergraduates that science only involves solving abstract puzzles, balancing equations, or performing routine experimental manipulations, and this is not true. Students must be made aware that *every* professional scientist uses imagination in their daily work, and that imaginative strength will eventually prove an important advantage. It is debatable whether the realities of how professional scientists engage their imagination in their daily work is sufficiently well-known to students of science; at least, this was the impression of the scientists in this lab. This could be changed by giving undergraduate students access to the daily work of professional scientists, including the importance of imagination in that work. One way to do this might be to have novice students spend some time with professionals specifically to inform them that and how imagination is used at the cutting edge.[12]

This story about pedagogy is only a hypothesis, which I am now testing in a larger study. If correct, it raises many new questions. For instance, if the norm considered in this article is to be enforced, how are species-level problems practically distinguished from genus-level problems? Any answer will be complicated by the fact that what counts as a species-level problem can change over time for a scientist, or a scientific community. Also, a species-level problem is one that can be broken down no further. In practice, scientists will not (need to) go *all* the way down to, e.g., quantum field theory (supposing this was possible). Each subdiscipline's domain will have its own implicit understanding of the maximum required level of detail. Thus, a species-level problem is one that is located toward the "bottom" of its discipline's implicit boundary, where that boundary is ontological, epistemological, and methodological. Another way to put the point is that a species-level problem is one for which background knowledge is

[12] This might take the form of an exemplar-based education; see Croce (2019).

at a maximum, where "maximum" must be interpreted contextually. Still, more research is required to find out how experienced researchers know which problems count as species-level problems and why, so that students of science can learn to identify them as well.

7 Conclusion

Scientists in labs A and B agreed about the role of several different elements of scientific practice, including mathematical reasoning, emotion, and humour, but they disagreed about imagination. The more senior a participant was, the more they valued the role of imagination in their work. When imagination was valued, this was primarily because of its ability to help in solving problems. And only what I have called "species-level" problems were observed being addressed with imagination. This could be explained by an implicit norm: Do not use imagination to address genus-level problems; only use it when necessary for addressing recalcitrant species-level problems. This norm has some epistemological considerations in its favour, and could realistically be enforced thanks to the contextual distinction professional scientists are able to draw between species- and genus-level problems. The strength of such a norm should also vary inversely with background knowledge and scientific experience (both of which usually co-vary with seniority). This weakening of the norm was also observed. Finally, a story about scientific pedagogy can be told that explains the trend away from and back to imagination over the course of a career.

Before I finish, I want to address two other possible explanations for my findings, and two objections.

P2 is the participant who expressed the least trust in imagination, and who claimed not to use it. P2 was also the youngest, and the only female lab member. (I exclude considerations of race here, as there was no majority race in the two labs). An alternative explanation about her answers in terms of gendered power dynamics might therefore be tempting. It is certainly possible that P2's undergraduate education had an institutional bias against women that exacerbated the numbing of imagination, or simply acted to reduce confidence. But all the other lab members independently agreed that they had felt the same way during undergraduate education. So, while it might be that the experience is worse for female researchers, being male does not eliminate the phenomenon. I think explanations in terms of gender dynamics add to, but do not compete with, the explanations given above for this study's findings.

A second and related explanation for the fact that the more senior participants valued imagination more highly in these laboratories is that as scientists increase in seniority, they also increase in confidence. After all, principal investigators have made it through graduate education and have started labs of their own. To explain their success (if only to themselves), they need factors that differentiate them from others who did not succeed. Imagination is often praised by scientists as such a feature. I would hypothesize that it is a relatively "safe" feature to praise, because praising one's own imagination comes across more modestly than simply claiming to be more intelligent than others. It is also sufficiently substantial: attributing one's success to organizational abilities or luck might be taken as expressions of false modesty. Again, however, I think this alternative hypothesis about increased confidence adds to (without taking away from) the other explanations discussed in this article.

Now I will turn to two quick objections. The first concerns the constraints on scientific imagination. Surely it is important to exercise constrained imagination when trying to solve certain species-level problems. However, scientists sometimes make progress by purposely breaking the constraints of a scientific theory. The kind of imagination used to do this might require a different philosophical and sociological account. I accept this: not all exercises of imagination need to be constrained by background theory. I have merely been pointing out that this is one use of imagination valued by scientists.

A final objection might just be an expression of disappointment. The literature on imagination is rapidly expanding, yet no clear definition of imagination exists. Perhaps the reader was expecting such a definition, or at least a taxonomy of kinds of scientific imagination in the labs observed. Given the limited sample size of this study, I have avoided attempting such an analysis, and instead merely presented the attitudes that were expressed, and compared these against the behaviour of scientists in lab meetings to locate a norm that appears to be governing imagination use in these labs. Much more research is needed to identify and define the kinds of imagination used in science. In sum, I sigh with the impatient reader, because I also want more. But while progress comes slowly, it comes.

To conclude, in this article, I identified a norm that implicitly guides imagination use in these two labs: Do not use imagination to address genus-level problems; only use it when necessary for addressing recalcitrant species-level problems. The scientists confirmed that this norm is in place, and provided anecdotal evidence for a pedagogy-based explanation for how the norm arises and is enforced. The epistemological justification I have given for the norm explains why we should have it, and why it should weaken over time. I have also argued that while the norm is at least partially justifiable, it should be combined with different pedagogical strategies to prevent it from having negative consequences on imaginative would-be scientists.

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