The Aesthetic Value of Scientific Experiments

In Milena Ivanova and Alice Murphy (2023) the Aesthetics of Scientific Experiments

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1. Introduction

There are many parallels between science and art. In both areas, we can create products of great aesthetic value, engage in activities that are deeply aesthetically pleasing, and produce outcomes, whether artworks, theories, models or experiments, using imagination and creativity. While there are clear analogies between art and science, there are also important differences: science is in the business of delivering epistemic goods, where the primary goal is to construct theories, experiments, and models that help us understand and manipulate the world around us. It is not surprising that effort in the last decades in philosophy of science has been paid to understanding what the aims of science are and how they are achieved. This focus has led to the development of different views on the scientific method and the relationship between theory and the evidence, the nature of representation, etc.. However, in these traditional pursuits, understanding the way values affect these activities has been largely ignored. The "value free ideal" in science emerged as a result of uncovering underlying values that were deemed unhelpful or detrimental to scientific goals, urging us to defend the idea that we should aim to have value free science. Feminist philosophers responded to this picture by arguing that science is not, and even stronger, should not, be value free, and that our values need to necessarily influence what kind of science we want[i]. The debate on values in science in the recent decade then was framed very much around the moral and political values in science, pioneered by Heather Douglas (2009), but in that debate, aesthetic values are sadly missing.

In parallel with these discussions on the value free ideal, some philosophers of science have been asking how aesthetic values are involved in science, and whether they should be eliminated from the scientific process or in fact are constitutive of science. An idea that we often find in science, going back to antiquity, is that beauty can be a guide to the truth (Chandrasekhar (1987)). Other philosophers have argued that beauty can not only motivate scientists but also facilitate their understanding of the subject matter (Breitenbach (2017), Elgin (2020), Ivanova (2020)). Others as well have asked whether it is rational of scientists to use aesthetic judgement, given that aesthetic concepts can be seen as subjective and subject to change. In his seminal work *Beauty and Revolution in Science*, James McAllister (1996) argues that beauty can be an unstable concept, and just like the history of art shows us clearly that what is regarded as beautiful in different artistic traditions can change, such shifts commonly occur in science too. And yet, McAllister provides a sophisticated account to show that despite their changing nature, it is rational to use aesthetic judgements in science. For McAllister, scientists form aesthetic canons when working with successful theories and models, their trust in beauty, then, is based on the past success of such theories and models. By linking beauty to empirical success, and offering such a defence on the back of the past successes of beauty, he offers a way to justify the rationality of trusting beauty and aesthetic values more generally. More recently, Derek Turner (2019) and Adrian Currie (2021) have further emphasised the idea that scientists become 'attuned' to certain aesthetic values through their practices and the products they encounter and work with more generally.

In the above discussion we see what we can call 'big picture' questions being addressed, namely, can aesthetic judgements helps us in the pursuit of epistemic goals or do they undermine them? Can beauty indicate truth, empirical success, understanding or does it lead us astray? While very important, in the more recent literature we are seeing a welcomed expansion of the kinds of questions being addressed, with more work focusing now on exposing how aesthetic values shape specific scientific practices, such as: how do aesthetic values influence the reconstruction of fossils (Wylie (2015, 2021), Turner (2019), Currie (2020))? How do aesthetic values affect studies in chemistry and the discovery of new molecules and substances (Ball (2005, 2021), Parsons (2012))? Can experiments be aesthetically appreciated and what makes an experiment beautiful (Parsons and Reuger (2000) and Ivanova (2021, 2022))? These works uncover the aesthetic features of various aspects of scientific practice. In doing so, they give us more food for thought when it comes to addressing big picture questions but also result in further insight into the diverse ways in which aesthetic judgements feature in science.

In this chapter I explore the levels and contexts in which we find aesthetic judgements in experimental practice. My goal is to explore how scientific experiments are appreciated aesthetically throughout different traditions, whether change in scientific experimentation as a practice, or in the tools and techniques that are used, brings with itself a new way of aesthetically appreciating the experiment, or whether we can say some aspect of beauty remains stable throughout such different traditions. As such, this chapter provides a classification of different ways in which experiments are appreciated aesthetically and illustrates this categorisation with a number of experiments from the history of science. While these experiments belong to different traditions, my goal is to defend a unified way of appreciating those experiments aesthetically, by focusing on the intimate beauty uncovered when we appreciate experimental design well suited for purpose. My analysis also illustrates that different aesthetic aspects of the experiment serve different purposes, and leads to a more optimistic take on the stability of beauty in science.

I start this chapter with three case studies. In section 2 I explore the beauty of Léon Foucault's pendulum, in section 3 I discuss 'the most beautiful experiment in biology': the Messelson-Stahl experiment, and in section 4 the beauty of the Michelson-Morley experiment. In each of these sections I will identify the different ways in which the experiments are aesthetically valuable. Following these cases, in section 5 I will quickly reflect on the different roles beauty is taken to play in science, before I provide my classification of aesthetic values in scientific experimentation in section 6. Section 7 reflects how my account fits the pre-existing debates on the dynamic nature of aesthetic values and what we can learn about this debate by paying attention to the experiment.

2. Léon Foucault's pendulum

Let us start our exploration of how experiments are appreciated for their aesthetic value by recalling Léon Foucault's well-known pendulum experiment. The experiment was performed inside the beautiful Pantheon in Paris in 1851. The goal of this experiment is to demonstrate a long contested fact: that earth rotates around its axis. To achieve this goal, Léon Foucault hung a heavy brass sphere from a long rope fixed to the inside of the dome of the Pantheon. Underneath the pendulum he placed sand, then swung the pendulum into motion. The pendulum moved slowly back and forth tracing lines in the sand beneath it. After a long period of time the experiment revealed that the traces in the sand were not aligned, demonstrating the Earth's rotation beneath the pendulum.

Why does this experiment qualify as an example of a beautiful experiment in science? To start with, there is certainly something rather awe inspiring and beautiful in the visual features of the experiment. Set up in one of the most beautiful buildings in Paris and resembling a kinetic sculpture with a mesmerising back and forth motion, this is a very visually pleasing experiment. This visual beauty strikes the senses with immediateness. Foucault's Pendulum was also displayed to the public, who would visit the Pantheon to admire the experiment. The experiment, like many others before it, was a public spectacle with an immediately accessible to the senses beauty.

But the visual beauty of this experiment is certainly only one of the ways in which we can appreciate the beauty of this experiment. I think what makes Foucault's Pendulum an example of a beautiful experiment in science goes way beyond its visually pleasing features. The experiment accomplished a very significant goal: it showed the effects of Earth's rotation, a phenomenon that had not previously been demonstrated but has been much disputed. In addition to its significant result, the experiment was beautifully designed too. The demonstration of such a significant fact was accomplished with an imaginative, economic and elegant design, using simple and economical materials for the purpose. I think it is this relationship between the design of the experiment and its significance that presents a very different kind of beauty, an intellectual beauty, which becomes unveiled once we engage more systematically with the experiment. While the visually pleasing features function as an invitation, they invite engagement and fascinate us to discover more about the experiment, we uncover a more intimate, intellectual beauty of the experiment once we appreciate what the experiment accomplishes and how the experimenter set up the experiment to achieve the goal, their creativity and ingenuity.

3. DNA Replication

In the famous paper 'Molecular Structure of Nucleic Acids', published in *Nature* in 1953, James Watson and Francis Crick end their contribution with an important insight: "It has not escaped our notice that the specific pairing we have postulated immediately suggests a possible copying mechanism for the genetic material" (1953a, 737). What they had defended in the paper was the double helix structure of DNA, alluding to a possible replication mechanism, which later in the year they fleshed out in their second (1953b) paper and labelled 'semi-conservative'. The idea behind was that during replication, each strand of the parent DNA unwind from each other and act as a template for the synthesis for new complimentary stands of daughter DNA, resulting in two newly synthesised DNA molecules each presenting one original strand. But this was not the only proposal of how DNA might replicate.

Another contender, due to Max Delbrück (1954), became knows as the dispersive replication mechanism. Delbrück hypothesised that the parent DNA chains break at intervals, with the parental segments combining with new segments to form the daughter DNA, resulting in two daughter helices from each parental helix, with each strand in the daughter helices consisting of alternating parental and daughter DNA. An alternative replication mechanism, that did not involve the DNA strands to unwind and separate during replication, was proposed by Gunther Stent (Delbrück and Stent. (1956)). According to this conservative replication, each of the two strands of the parent DNA molecule are completely preserved in the newly synthesised daughter DNA.

Determining which of these mechanisms is correct was the next priority of the scientific community and in 1958 Matthew Meselson and Franklin Stahl published the results from their experiment, now often referred to as 'the most beautiful experiment in biology'. What they had done to determine the correct replication mechanism was to feed bacteria nutrients containing a heavy nitrogen isotope that is incorporated into the bacterial molecules through metabolising. Then they fed bacteria light nitrogen isotope, which allowed them to study the density of the bacterial DNA. They studied the genetic material through the next generations, knowing the rates at which bacteria multiply. Instead of using radioactive labelling of the DNA strands, common at the time, they decided to use density and separate the heavy from light DNA using density-gradient centrifugation. By studying the ratios of light, heavy and hybrid DNA strands they obtained, they were able to eliminate the conservative and dispersive replication hypotheses, confirming that DNA indeed replicates semi-conservatively.[ii]

This experiment is often regarded as the most beautiful experiment in biology and one of the reasons for which it is so celebrated is because it is an example of a crucial experiment in science (Ivanova (2022a)). The experiment is regarded to have conclusively settled the question of DNA replication by giving clear confirmation of the semi-conservative mechanism whilst eliminating the two other competitor mechanisms of replication. For many, it is this ability to deliver a decisive answer to the question how DNA replicates that makes the Meselson-Stahl experiment beautiful. James Watson himself argues that the experiment gave a simple answer to a question (Holmes, 411). Historian of science Ernst Peter Fischer also supports this view, claiming that "the Meselson-Stahl experiments speak for themselves and made all further commentary superfluous" (1999, 21). Fredric Holmes further argues that the simplicity and clarity of the result makes this experiment easily presentable to students, serving as an exemplar experiment for science education (2001, ix).

But the significance and clarity of the experimental results is only one side to the experiment's beauty. Of importance to determining the ultimate source of aesthetic value of the experiment is not only *what* the experiment did but *how* it did it. The experiment has an elegant, original and apt design, optimally suited for the purpose it was set out to achieve. The very idea behind the experiment is considered beautiful and ingenious. The use of density as a way of labelling the genetic material was an original feature of the experiment, allowing Meselson and Stahl to study how the genetic material changed through the next generations of bacteria they studied. Ernst

Peter Fischer argues that "There is something beautiful in this idea alone" (1999, 21). The idea behind the experimental set up is original, elegant, and optimal, showing innovative and creative thinking as well as aptness by delivering on the job it was designed to do. Just like our first example, the pendulum experiment, the ultimate beauty of the Messelson-Stahl experiment is to be found in appreciating the relationship between the design of the experiment and the lessons it delivers, decisive results that answered a really important question.

We have examined two notable examples of beautiful experiments in science that did something different: while the former demonstrated an important concept, the latter confirmed a hypothesis among three proposed contenders. While serving different goals, these experiments have something in common: they are both cases of experiments producing results aligning with theoretical expectation, they confirm or demonstrate hypotheses or theories we have already entertained. But not every significant result in science is one of theoretical alignment. In many cases the significance of a result is to be found in its unexpected or surprising nature. In the next section, I want to discuss the beauty of the famous experiment designed by Albert Michelson and Edward Morley to detect the velocity of the earth relative to the ether to illustrate why it is a beautiful experiment despite its controversial results.

4. Detecting the ether

By the end of the 19th century, the scientific community largely committed to the wave theory of light, according to which light is transmitted in a medium that became known as the luminiferous ether. The question that puzzled the scientific community was the nature and properties of this substance though which waves propagate. At the time it had been suggested that if one assumes that the velocity with which light propagates in the ether is the same in all directions, then the first order effects that could be measured to determine the relative velocity of the earth through the ether would cancel out, but very small second order effects could be measurable. To make such a measurement possible, a highly precise instrument was needed and a well set up experiment, which was what Albert Michelson set out to do. The beautiful idea behind the experiment was the realization that they could send two light beams of similar length across two different perpendicular to each other paths, thus ensuring the two beams could be differently effected by their journey through the ether. What was surprising and unexpected for Michelson and Morley who implemented the experiments was that they did not detect significant relative effects. The experiment was systematically revised to account for potential sources of interference, from the temperature variations of the two revolving arms of the interferometer, which Michelson dressed in paper boxes to control for temperature fluctuations, to elevating the interferometer to a mountain top or placing it under water. Despite the progressively more precise nature of the experiment, the results did not change significantly. As Gerard Holton (1969) reflects:

> Its fascination, which has been felt equally by textbook writers and research physicists, derives from its beauty and mystery.
>
> Despite the central position of the question of ether drift in late-nineteenth century physics, nobody before Michelson was able to imagine and construct an apparatus to measure the second-order effect

> of the presumed ether drift. The interferometer was a lovely thing. Invented by the twenty-eight-year-old Michelson in response to a challenge by Maxwell, it was capable of revealing an effect of the order of one part in ten billion. It is to this day one of the most precise instruments in science, and the experiment is one that carried precision to the extreme limits. Einstein himself later paid warm and sincere tribute to Michelson's experimental genius and artistic sense. (1969, 136)

The experiment has often been praised for its beautiful design and careful execution; with Einstein himself arguing that Michelson was like an artist in science, paying attention not only to devise a good but also a highly beautiful experiment. Holton (ibid., 136) notes that the experiment is beautiful both because of its design and execution, showing the meticulous way in which Michelson continued to refine the method of testing to reduce sources of error. But when it comes to its results, how can we understand them in light of what experiences they afford? As Holton explains, beyond the beauty of the design, the results were ‘enourmously puzzling’ (ibid., 137). The results violated the expectations of the community, and Michelson himself struggled to accept the implications of his experiment. While Hendrik Antoon Lorentz and George Fitzgerald took the results very seriously, proposing independently a contraction hypothesis to accommodate the experimental results, many in the community were unsure what to make of the results. What the null results generated was a prolonged problematisation in the community, since they were putting into question an assumption that has been accepted as a fundamental truth: that the ether exists.

Despite not delivering on expectation, I take this to be a beautifully designed experiment that delivered highly significant results, but the aesthetic response we have to those is not analogous to the one we have then results align with theoretical expectation. Discovery in science is often associated with an awe inspiring beautiful moment, when our expectations meet experimental outcome. But in cases where an experiment delivers a productive disruption, we can also experience aesthetic responses, but those would be more analogous to the responses we have to very disruptive revolutionary works of art that challenge our fundamental assumptions. I think there is scope for us to accommodate both the results aligning with expectation and the productively disruptive results that do not align with our theoretical frameworks as aesthetically valuable, while recognising the aesthetic responses they give rise to are different[iii]. As such, the Michelson-Morley experiment is an example of a highly elegant, innovative design that delivers a significant outcome. The innovative nature of the experiment are sticking; the interferometer itself, as an invention, is one of the most elegant and simple instruments ever invented in science and used today for many discoveries in physics. The experiment was well set up to achieve its goal, were there an ether, this experiment was going to detect it. Instead, its profound results[iv] fuelled productive problimatisation in the community, and later aided physicists to accept Einstein's special theory of relativity.

5. Levels of Aesthetic Appreciation in Science

With the above cases in mind, we should ask the very general question first: where do we find aesthetic value in scientific practice? In Ivanova (2017a) I distinguish between three levels of aesthetic judgements made in science: *objects*, *products* and *process*. That the objects of scientific enquiry can exhibit aesthetic properties and evoke in us aesthetic experiences is easily motivated: nature, after all, allows us to engage with plenty of pleasing phenomena, entities and processes[v]. From the stunning rosy vernicap mushrooms (*Rhodotus palmatus*) we can encounter in our forest hikes, the colourful rainbow lorikeet (*Trichoglossus moluccanus*) we can see flying in the sky, to the perfectly hexagonal honeycombs in a beehive, nature is a source of much aesthetic appreciation. But such aesthetic responses are also a product of engaging with nature under carefully crafted experimental settings, such as the observation of the process of crystallisation under a powerful microscope or the decomposition of light through a prism.

The products scientists create are also subject to aesthetic appreciation. Scientific theories, models and mathematical proofs are very often praised for their beauty and elegance. In theoretical physics, much discussion is given to the beauty of Einstein's theories of special and general relativity. His principle theories are regarded by many to be the culmination of beauty in science, since the theories achieve great unifying explanatory power under a small set of scientific principles (Ivanova (2020)). Galileo Galilei is often praised to have devised a highly elegant thought experiment, which utilises economic concepts and materials to showcase an important novel concept: that of acceleration (Murphy (2020)). Similarly, scientific images are also subject to aesthetic judgement and appreciation. The recent images produced by NASA's James Webb Space Telescope (JWST) are an excellent example. Images such as Cosmic Cliffs inspired awe and wonder in the public with their beauty. To produce such beautiful images, scientists had to make a number of judgments of aesthetic nature when translating the data collected by the telescope, to use colours not detected by the telescope, to produce such beautiful images[vi].

In addition to the objects of study and products of scientific activity, the very process of developing a theory, mathematical proof, designing an experiment or preparing an image, involves creativity, imagination and aesthetic sensibility. Such practices are often paralleled with artistic production, and the involvement of the aesthetic sensibility is as much a feature of contemporary science as its early predecessors. Scientists as far back as Leonardo da Vinci and Robert Hooke would enhance the aesthetic features of their subject matter in their depictions, generating in the viewer awe and wonder when engaging with the depicted specimen. Similarly today, as we discussed above, astronomers at NASA use colours to create the beautiful images obtained with the JWST. Aesthetic judgements are integral to many scientific fields, from astronomy to biology, and medicine to chemistry and palaeontology. But also the very process of scientific discovery is often compared to artistic production. Pierre Duhem, for instance, argues that it is impossible to follow the process of constructing a physical theory "without feeling keenly that such a creation of the human mind is truly a work of art" (1954, 24). Similarly, Ernest Rutherford argues that "the process of scientific discovery may be regarded as a form of art", continuing that "a well constructed theory is in some respects undoubtedly an artistic production." (quoted in McAllister 1996, 14). In addition to seeing the creative process in science as parallel to artistic creativity, Henri Poincaré (2001) explicitly devises an account of scientific creativity at the heart of which is the aesthetic sensibility of the scientist, which acts as 'the delicate sieve' that scans and evaluates which ideas that the mid produces are useful by judging first their aesthetic appeal. At the heat of this account is the idea that "care for the beautiful is care for the useful" (Ivanova 2017b).

To take stock, there are three general contexts in which aesthetic judgement enters in science: object, product, and process. But when thinking about the scientific experiment specifically, we can further delineate more specific categories in which we find aesthetic value in the experiment. In what follows, I propose a categorisation of the levels at which we can appreciate an experiment aesthetically and then draw some conclusions about their function.

6. A classification of aesthetic aspects of experiments

Earlier in this chapter we followed three celebrated experiments and explored their aesthetic dimensions. These examples help us illustrate the different ways in which we can appreciate an experiment aesthetically. Specifically, here I introduce six different categories at which we make aesthetic judgements and aesthetically appreciate the scientific experiment. After introducing these categories, I argue for the special relationship between design, significance and ingenuity displayed in a well-designed experiment for purpose.

a. Subject of study

The phenomena that are investigated under experimental conditions can be highly aesthetically pleasing. From cells, light and electricity, to the beautiful structures that can be generated in the process of electrodeposition, scientists report finding a lot of visual beauty in their subject, be it in intricate shapes, colours or patterns. Such features seem to be particularly prominent in some fields, such as chemistry (Ball 2005, 2021; Parsons 2014), as well as biology and astronomy (Ivanova 2022c). Scientists report that the beauty in the subject they study is a great source of beauty, awe and wonder. Ball's beautiful study of the aesthetic dimension of chemical experimentation is a great illustration of how chemists value the sensual aspects of their work, being motivated not only by visual beauty, but also by other sensory experiences in the lab. The aesthetic dimension of scientific studies acts not only a motivator for their work but also contributes to scientists' work satisfaction and overall well-being. As a very recent study on scientists' aesthetic attitudes and well-being reported (Jacobi et. al. 2022), regularly encountering beauty in the lab contributed to scientists' well being and sense of flourishing.

b. Instruments

The tools used by the experimenter can have their own aesthetic value. From beautifully crafted microscopes and particle chambers, to complex structures like the large hadron collider or an algorithm, the instruments and technologies utilised in the experiment can display craftsmanship and pleasing aesthetic features that can be appreciated in their own right.

[here insert image 1 and image 2]

Image (c) Whipple Museum, Cambridge (Wh.0196)

Image (c) Whipple Museum, Cambridge (Wh.1782)

The technology used in the lab can be both visually pleasing and appreciated for how it was created, giving rise to experiencing a more intellectual form of beauty. As we noted earlier, the interferometer, originally invented to detect the ether and now used for many precise measurement experiments, is a highly beautiful instrument, comprising minimal elements while enabling the study of complex phenomena. In his contribution to this volume, Mike Stuart discusses the case of Melvin, the 'robot scientist', and the aesthetic regard scientists have for creating such a successful experimental tool. Similarly, the recent James Webb Space Telescope was also regarded as highly beautiful. The beauty of this powerful telescope was found both in its visual features, with its intricate hexagonal gold plates, as well as in the more intimate beauty that is revealed when we appreciate the highly complex and timely effort behind building such a precise and innovative technology.

c. Experimental design

As we saw in the opening first sections of this chapter, experiments have been consistently praised for their elegant, economical and simple set up, but also their aptness. The idea of aptness is especially important when it comes to experiments in the context of big science. Experiments in modern settings can be incredibly complex. Take, for example, the experiments at the Large Hadron Collider at CERN. The experiments are running on four large detectors (ATLAS, CMS, ALICE and LHCb), the data is generated and analysed using machine learning algorithms, and the scientists working on the experiment (over 2500 of them) are located across many countries. This collaborative experiment could not be further from the experimental set ups we discussed in the early days of experimental practice, where the experiment was performed by one individual, the equipment was simpler, and the experimental results were immediately accessible. In the complex set up of today's experiments, scientists work in large teams, the data the experiment produces is not perceivable immediately, rather it involves complex and timely analysis and selection techniques, and the very set up can seem complex by comparison. But I want to emphasise that even in the case of big experiments, beyond the complex set up and technology, we can appreciate the optimality of the design fit for purpose. In this sense, the design remains beautiful, being appreciated for how it is set for the goal of the experimenters.

d. Creative process

As already detailed in the previous section, constructing and running the experiment can be paralleled with artistic production. Experimenters, like artists, utilise their creativity, imagination and aesthetic sensibility in diverse stages of experimental process. The scientists that come up with the design and those who carefully carry the experiment out can be praised for their skill and capacity in conceiving of the praiseworthy design or delivering important results. What is particularly fascinating about science today is that the creative process is shared not only among many individuals, who collectively explore possibilities to conceive of the most optimal experimental designs and tools, but they are also assisted by machines not only for running the experiment, analysing and interpreting its data, but also in their very design, which opens a number of underexplored questions about the nature of creativity and coproduction with machines.

e. Significance

As we saw in our discussion of the Meselson-Stahl experiment, the experimental results can also be regarded as aesthetically pleasing. Here we can find a diversity of responses depending on the nature of the result. Experiments can produce results that align with theoretical expectation, confirming a theoretical prediction or discover something new. They can lead us to enriching our understand but also to identify the limitations of our understanding. Surprising, unexplained, anomalous result can lead to productive problimatisation which then leads us to ask new questions, generate new ideas and potentially further our understanding of the subject matter. As noted earlier, a pleasing design without a significant result does not have the same aesthetic value, a particular deeper aesthetic value is found in the intricate connection between design and significance. And significance in experimental results can be found in those results that are expected, aligning with theoretical expectation as well as those that violate theoretical expectation. Surprising and anomalous results can be deeply profound, prompting us to productive investigations.

f. Performance

The experience of running the experiment can be seen as a process of deep aesthetic engagement. Whether it is because the experiment reveals beautiful phenomena or aptness of design, or the very feeling of being involved in the process of exploring and discovering, the experimenter as well as the audience engaging with the experiment, report having aesthetic experiences. Experiments in past traditions were often performed with audiences, becoming a public spectacle that fascinates and evokes diverse aesthetic experiences. In this volume, Adrian Holme explores the famous artworks by Joseph Wright of Darby that depict beautifully the public nature of the experiments performed in the early days of the Royal Society and the diverse nature of the aesthetic responses the audience had when witnessing the experiment. While scientific practice is now very different, and labs are rarely open for the public to observe the daily running of an experiment, we nevertheless still encounter the spectacle of science with different settings. For instance, NASA's recent initiatives to share the beautiful James Webb Space Telescope images are analogous to the early experimenter opening the door to the public. While the setting is different, the aim remains the same, to evoke an aesthetic response in the public and fascinate them about science and its discoveries.

My argument so far has focused on identifying the diverse aspects in which we can find beauty and aesthetic value in the lab, be it in the very phenomena we study, the experimental instruments, the design of the experiment, its results, in its performance or it encapsulating human ingenuity and creativity. In our earlier exploration of the three scientific experiments, we identified at least one of the above six categories of aesthetic value in them, but we also saw that beautiful experiments often present several of these aesthetic dimensions. Next, I want to argue for something much stronger than the idea that to value an experiment aesthetically is to appreciate one of the above six categories in which the experiment can be pleasing. Beyond defending the classification here, I want to emphasise the distinction between immediately accessible via the senses beauty and the intellectual beauty we experience upon appreciating the design of the experiment and its significance. This distinction is important not only because it directs our attention to the different ways of appreciating, but also because it motivates the idea that the immediately accessible to the senses beauty and the more intellectual beauty play different functions in science. Visual features can be great motivations for pursuit in science; they can also help in science communication and serve as didactical tools. But a deeper, more intimate beauty is found when one appreciates the creativity in designing a well-suited experiment that delivers significant results.

I have already emphasised in previous work (2022) that by significance of results I do not only mean experimental results that align with expectation, by detecting a theoretically predicted particle or phenomenon, or by confirming a theory or a hypothesis, but also those that violate expectation. Whether it is an anomalous result, a null result, or a surprising result, such results can be the most productive experimental results since they can point the finger at reconsidering particular assumptions, techniques or experimental set ups. As we discussed in the case of the ether, the null results invited a fruitful problimatisation in the community. While eventually these results were seen as confirming evidence for special relativity, originally they were the anomalous result that questioned the ether hypothesis. As Hossenfelder (2018) argues, similar productive reassessment is happening now in high-energy physics with the non-detection of supper symmetric particles. The null results are not only challenging the theory that has entailed their existence, but also the aesthetic principles that have been constituting the development of physical theories in the last century, from the special and general theories of relativity, quantum mechanics and the standard model. These very aesthetic principles of naturalness, symmetry and simplicity, Hossenfelder argues, are at stake as well as physicists look for a way forward from the null results and failure to detect these theoretical particles. Thus, for me it is not only that these two ways of appreciating focus on different features and serve different function, the beauty that we encounter though the appreciation of the well designed experiment that delivers a significant results seems to be a particularly special source of aesthetic value.

While my focus in this section has been to offer a classification of the ways in which we can come about to appreciate an experiment aesthetically, I have also defended the idea that different categories of aesthetic appreciation can play different role, and that the relationship between design and significance is a particularly important source of aesthetic value. With this argument in mind, next I want to return to the question that has occupied philosophers for many decades: are the ways in which we appreciate aesthetically the objects of science stable or subject to change? Whether focusing on the scientific experiment can deliver new insight into this question is the subject of the next section.

7. Implications

When thinking about the role of beauty in science, many scientists and philosophers have expressed two very opposing views. On the one hand, some believe the concept of beauty in science is objective, stable and agreed upon independently of the tradition, school of thought or time period a scientist belongs to. Contrary to art, where it is believed aesthetic judgements can vary, in science, it is claimed, aesthetic judgements are stable. This Platonic view, often expressed by scientists such as Paul Dirac, gives assurances that using aesthetic judgements in science is not threatening to its objectivity, since these values are shared among scientists, and beauty can indeed guide the rational endorsement of scientific theories. This view, however, has been challenged. Is it plausible to assume aesthetic judgments enjoy stability across different time periods or even different schools or labs and aesthetic judgements in science are different to those we make with regard to artworks?

Looking at the history of art makes it clear that our aesthetic judgements can vary. Who would forget the history of the Eiffel tower in Paris, when first erected in 1887 a very large group of contemporary artists in France wrote to complain against the decision to build the tower and demand its immediate demolition. The reason was that the tower did not fit the existing aesthetic sense of the French, calling it a 'black factory chimney', 'an insult to the French fine taste' and a 'monstrosity' over the beautiful Parisian skyline. But it did not take that long for the eye sore to become an icon and symbol of the beauty of modern architecture. The building now symbolises the beauty that can be achieved when architects use cast iron, a material that allowed for taller, more intricate and original shapes to be constructed than ever before. How did this aesthetic transformation become possible?

One way to see the acceptance of a previously unacceptable artefact as beautiful is to argue that people's aesthetic attitude changed, and appreciation grew for the beauty of the new building. In *Beauty and Revolution in Science* (1996) James McAllister argues that just as in art, in science too aesthetic attitudes can change. And in fact, such attitudes are learned, they are a response to appreciating the success of an artefact through a tradition. Just like in art, where appreciating the possibilities that using cast iron enabled eventually resulted in aesthetic attitudes towards buildings like the Eiffel Tower to change, in science, McAllister argues, it is through our appreciation for successful theories that we shape our aesthetic attitudes and canons. So while we might initially think theories such as quantum mechanics or the standard model do not fit our aesthetic ideals, working with these theories and appreciating their success can change our idea of beauty, slowing shifting our expectation as to what is a beautiful theory.

Two crucial questions emerge from this dispute on the nature of aesthetic appreciation in science. First, are experiments appreciated differently throughout different traditions or is there stability in aesthetic judgements when it comes to the experiment? Second, if we accept beauty is a dynamic notion, as McAllister suggests, do revolutions in aesthetic attitudes regarding scientific theories coincides with such attitudes changing in how experiments are appreciated or are these independent? To address these questions we can get insight from Parsons and Rueger (2000), who argue that the way we appreciate aesthetically can be tied to a particular methodology. In their paper, they study experiments in the 17th century, arguing that at the forefront of aesthetic appreciation at the time is not the ingenuity of the experimenters or the design but rather displaying nature's beauty through the experiment. But they see a shift in aesthetic appreciation in the 19th century, where at the forefront of appreciation comes the design of the experiment, its economy, simplicity, optimality and aptness. As they argue:

> [N]ow it is only with the assistance of the confirmed or illustrated theory that an experiment is thought to give us insight into nature. Whatever beauty is displayed in an experiment, it cannot be the beauty of nature itself; the economy

> of an experiment reflects the economy of our own cognitive households, not the economy of nature. This is clearly different from the view of the eighteen century natural philosopher who appreciates nature itself through the frame of the experiment. (ibid., 411)

Parsons and Rueger argue that the way experiments are appreciated aesthetically is correlated with scientific methodology – when science was more inductively driven, what mattered was the beauty of the natural phenomenon, while when science became more hypothetico-deductive, this appreciation becomes more focused on what the design does to confirm or disconfirm hypotheses. What is aesthetically appreciated in the later methodological tradition is not nature's beauty as much as the display of "'aptness' in the relation of result and tools, of plan and success" (ibid., 411). The experiment becomes beautiful due to its "optimally suited to achieve its purpose" (ibid., 411-412). This account leaves it open that appreciation of future experiments might change as well due to change in scientific methodology, thus aligning with McAllister's thesis that sees aesthetic judgements as revisional and the concept of beauty as dynamic, subject to reevaluation. However, Parsons and Reuger help us see that the revolutions in aesthetic appreciation of experiments are not aligning with the aesthetic revolutions at the level of how theories are appreciated. For instance, whereas McAllister sees an aesthetic revolution in the shift from circular to elliptical planetary motion in the 16^{th} century and another one with the development of quantum mechanics in the 20^{th} century, Parsons and Reuger see a transition in aesthetic appreciation of experiments during the mid 19^{th} century when the focus is on the comparison of precision measurements with theoretical quantitative predictions.

A last point I would like to reflect on regards the idea that methodology can reshape how we aesthetically appreciate the experiment. It is undeniable that scientific methodology has changed dramatically. We now live in period of big data science where scientific experiments produce enormous amount of information where special selection procedures are needed before analysis takes place. Also, the relationship between theory and data has changed, in the sense that in many areas data is now leading the formation of hypotheses and identification of correlations. We also live in the age of assisted science, where machine-learning algorithms are not only running experiments and analysing the data they produce, but are even designing them. The philosophical tradition that searched to answer the question 'what is the scientific method?' has been replaced by methodological pluralism. Philosophers now recognise that science adopts a plurality of methods depending on the subject, the availability of data and possibility of testing. Analogously, experimental practice has changed dramatically over the centuries and perhaps at no other time has it been more different than contemporary experimental practice. But while we observe many changes in experimental practice, it is unclear whether we should be concluding from this that the way we appreciate aesthetically the experiment has changed. Perhaps in addition to looking at the historical evolution of experimental practice, we also need to see its diverse nature from today's perspective in order to appreciate the different contexts in which we make aesthetic judgements in the lab. Above I identified six categories of aesthetic appreciation of experiments and I think these categories can be taken to be rather stable. We appreciate aesthetically the highly complex AI generated images or images produced with highly complex microscopy just like we appreciate da Vinci's depictions of the human body. We appreciate the complex hadron collider as well as the interferometer, both visually and intellectually upon discovering how and why they are constructed. Most importantly, we continue to appreciate the deep beauty that is uncovered when we appreciate the design of an experiment, the relationship between design and experimental result, and the creative aspect of imagining and producing an ultimate experimental set up for purpose. The experiments I discussed in the first sections of this chapter help us illustrate this point, while very different they all exemplified a beautifully designed, apt experimental set up, showing the creative thinking of their designer, and provoked prolong admiration with their significance. While working in big groups rather than alone with a relatively small equipment, scientists today as their counterparts in the past find beauty in the very performance in the experiment and the sense of involvement and achievement this experience gives rise to. Just like one could walk into the Pantheon in Paris to admire the beauty of Foucault's pendulum, today CERN occasionally opens the doors to the public so that they can appreciate the beauty of the experiment and its magnitude (I was lucky to recently visit the ATLAS experiment and ask a lot of naïve questions the scientists who run it). In this sense, even though the very performance of experiments has changed, that this daily practice can involve aesthetic appreciation from the practitioners as well as viewers continues to be an important aspect of experimental practice. In this sense, I hope to have given a convincing argument for the stability of the aesthetic categories I identified in this chapter, while also identifying the different functions beauty judgements can play when we think about the experiment.

8. Conclusion

In this chapter I have argued that experiments are appreciated aesthetically on many different levels, from the visually pleasing phenomena they unveil, to the instruments and tools they employ, to the ingenuity and creativity they are a product of, to the experimental design, the significance of the result, to their performance. While in each of these six contexts we can appreciate a certain aesthetic dimension of the experiment, I also drew a delineation between immediately accessible to the senses beauty, like visual beauty, and the beauty that is revealed when we appreciate the design of the experiment and what this experiment achieves. These different kinds of beauty play a different function in science. While the visual beauty of an experiment may invite us to engage with it and find out more about it, acting as a motivator and aiding science communication, we find a deeper, more intellectual, beauty once we find how the experiment is set up, the instruments that are used, how the experimenters constructed the design and what the experiment achieves. The categorisation I have proposed allows us to identify continuity between different experimental traditions despite their changing set ups.

[i] For a recent overview on the value free ideal see John (2021).

[ii] This is a very brief description of the experiment, for a more detailed analysis see Franklin and Laymon (2020), Holmes (2008) and Weber (2019).

[iii] A number of recent articles have explored the role of surprise in science (Currie (2018), French and Murphy (2021) as well as the more disruptive dimension of experimental results (Ritson (2020)).

[iv] See Murphy (this volume) for a systematic analysis of the nature of profundity in scientific results.

[v] The literature on environmental aesthetics is very rich to make justice here, influential accounts have been developed in Brady (2013), Carlson (2000), Saito (2017) and Parsons (2008).

[vi] In my (Ivanova 2022b) I argue that the visual beauty of these images are simply an invitation to engage with the more intimate, intellectual beauty we encounter upon appreciating how the images were produced, the significance of this new instrument

and the enormous effort into constructing it, and the fact in makes the audience become part of the beauty of scientific discovery.

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