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Gamifying Nature: the aesthetic experience of science as a puzzle-game

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Abstract

The aesthetic judgements scientists make influence which theories, models, and experiments they use and adopt. To better understand the role these judgements play in how science progresses, I examine more closely the role a theorist's aesthetic experience plays in their epistemology. In this thesis, I provide an overview of what has been said thus far regarding the role aesthetic criteria play in theory selection. I conclude with the claim aesthetic judgement is part of the larger aesthetic experience of solving a puzzle-game. I argue the aesthetic experience of solving a puzzle-game shapes how knowledge is produced in the sciences. I give two specific examples to support my claim: the role of symmetry as an aesthetic feature in doing fundamental physics and the role interactivity plays in protein modeling. I argue symmetry functions as a suitable solution to a puzzle in physics, thus playing an important role in the aesthetic experience of doing physics. I also argue the aesthetic experience of creating protein models is defined by the interactive gameplay necessary to complete the task. Epistemic gains are possible within this kind of aesthetic experience because puzzle-games revolve around their own termination.

Dedicated to Carlos and his Rubik-s-cubes

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Introduction

Both Einstein's theory of relativity and Watson and Crick's model for DNA hold a high degree of aesthetic appeal. Not only have they proven groundbreaking and epistemically valuable, they are attractive. However, what makes a scientific theory attractive is not always clear and it is not clear their attractiveness matters to the epistemic goals of scientists. In this thesis, I will argue not only that aesthetic considerations matter to how science proceeds, but that epistemic gains rely upon the aesthetic experiences theorists have while doing their work.

There is a history of theorists preferring some theories, models, or experiments over others because of their 'elegance,' 'neatness,' or 'beauty,' but why this should matter in an empirical investigation aimed at creating epistemic gains is another matter. Early astronomers, tried and failed to capture the workings of the solar system by fitting planetary motion within the elegance of the platonic solids, perfectly circular orbits, and neat Ptolemaic epicycles. Such aesthetic criteria lead theorists astray. On the other hand, Einstein's aesthetic preference for symmetry gave physics the theory of relativity, and Linus Pauling's aesthetic intuitions enabled his discovery of the 'alpha helix' and 'beta sheet,' secondary structures commonly present in proteins. Aesthetic experiences are at play in science in ways which may matter to epistemological gains and setbacks.

That aesthetic considerations play a role in theorizing makes some theorists uncomfortable. Science is, after all, aimed at creating epistemic gains, contributing to our knowledge and understanding of the universe. The aesthetic and the epistemic dimensions of theory are not obviously related. Some will outright deny aesthetic considerations play any role in how science proceeds, suggesting either they are not real or remain irrelevant. Others will try and deny the aesthetic criteria some scientists use, either consciously or unconsciously, are actually ‘aesthetic,’ and insist all functional criteria in good science are merely epistemic considerations. Talk of aesthetic criteria creates an uneasy tension between ideas about what science looks like and how science actually proceeds.

Aesthetic considerations do however play a noticeably active role in how theorists do their work. The testimony of the theorists themselves suggests this. Mathematicians and physicists are known especially for praising the aesthetic merits of the theories and proofs within their respective fields. Theorists across fields have admitted to conscious and unconscious bias toward theories with aesthetic appeal. It remains important to take these scientists at their word and continue to assume the aesthetic experiences of theorists is both relevant to their work and aesthetic in nature. Understanding how theorists experience their work is important to understanding how their work operates. The subjective experience of a theorist is part of the theorist’s larger project and affects how the project proceeds. A flattened or diminished characterization misses elements of what goes on in theory selection and leads to a mischaracterization of the work itself.

What, then, is the relationship between a theorist’s aesthetic experience and the epistemic goals of their work? Philosophers of science have attempted to answer this question over the last 20 years in a slow, careful conversation. They, too, seem cautious with regard to this intersection. This project is a synthesis and small expansion on that conversation.

This thesis comes in three parts: Chapter 1 will review key moves made in the philosophical literature regarding the intersection between aesthetic experience and epistemology in science. The conversation begins with a loose collection of claims which maintain either some form of autonomism or reductionism regarding the aesthetic and epistemic. From there, philosopher James. W. McAllister proposes aesthetic induction, the idea aesthetic features fall in and out of favorability according to their history of being attached to more or less successful theories. Theorists after McAllister go further, suggesting aesthetic features can sometimes play an important role in selecting a theory which is understandable.

In this chapter, I also include the work of aestheticians outside the philosophy of science to enrich the existing conversation and help put forward my own claim. I include Frank Sibley's working definition for what it means for a feature to be aesthetic, an inclusion meant to help clarify and frame the above conversation. I also include C. Thi Nguyen's analysis of games as art. Games represent the same sort of aesthetic experience which shapes how scientific theory selection proceeds. The work of these aestheticians helps to establish the main claim for this project: *the aesthetic experience of working on a problem in science is akin to the aesthetic experience of solving a puzzle-game, and the epistemic gains made in science rely on this experience.*

In Chapters 2 and 3, I take up two examples to illustrate my argument: the role of symmetry in fundamental physics and protein modeling in structural biology. Most discussion regarding the aesthetic dimensions of doing science focuses on symmetry and fundamental physics at large, which is why I include it here. Chapter 2 functions as a familiar illustration as well as an elaboration of my main claim. Chapter 3 deals with a less common example from biology and emphasizes the importance of puzzle-game *solutions* in shaping the epistemic usefulness of gameplay experiences. Here, I outline what it is about protein modeling that makes it an aesthetic experience and how the practice functions like a puzzle-game. In both chapters, I illustrate how framing science as a puzzle-game activity makes more clear the connection between aesthetic experience and epistemic gains.

To say scientific problems work like puzzles is nothing new. However, by highlighting the aesthetic experience of doing puzzle-games, I aim to bring into focus the key role aesthetic experiences play in how science generates knowledge about the world. Science is a gamified experience of nature; both frustrating and satisfying by design, and for this reason also epistemically productive.

Chapter One - The Role of the Aesthetic in Theory Selection

Abstract

Scientists and mathematicians pass aesthetic judgement on their theories, models, and experiments. The aesthetic judgements theorists make within their work influences which theories and models theorists adopt, or which experiments they use moving forward. Sometimes theorists will consciously use their aesthetic judgements, among other criteria, to select theories. Aesthetic appreciation is even considered by some theorists to be an essential feature in doing theory selection. These theorists consider aesthetic judgement epistemically useful. However, it is important to talk first about what it means for a theory to have aesthetic features. I will discuss first what it means for a feature to be aesthetic using Sibley's theory of the aesthetic. Second, I will provide an overview of what has been said about the role aesthetic criteria play in theory selection up until this point. I conclude with the claim aesthetic judgement is part of an aesthetic experience akin to solving a puzzle-game.

1. The Aesthetic

Before I discuss the role aesthetic judgement, criteria, and experience play in scientific theorizing, I will first examine what it means for a concept to be 'aesthetic.' The term 'aesthetic,' like the term 'scientific,' has proven elusive and hard to do a proper conceptual analysis on. For the purposes of this project, I will rely on Frank Sibley's conceptual analysis of the aesthetic, which I will provide in this section.

The reason Sibley's analysis is best suited for my purposes is this: it is one of the more carefully worked out and popular analyses for the aesthetic and the analysis itself begins where others do not: outside the arts. Many aestheticians do work concerning the arts; Sibley's analysis however aims to create a notion of the aesthetic which is functional not only within the arts, but elsewhere. His analysis also avoids making strong metaphysical commitments about the aesthetic and remains focused on the nature of aesthetic evaluation. This conceptual analysis has also withstood the test of time, remaining relevant and powerful within the field of aesthetic theory. Given my own project is not concerned with art but with how science is practiced, this is the most appropriate piece of conceptual analysis for my purposes.

Frank Sibley's notion of the aesthetic, given in his landmark 1959 paper "Aesthetic Concepts," can help to illuminate the nature of aesthetic features and makes more sense of why some features possess aesthetic status. According to Sibley, an essential feature of aesthetic concepts is they cannot be condition- or rule-governed. Aesthetic judgements are not "mechanical," not governed by rules or a set of necessary conditions. Rather, a wide variety of conditions can cause an object to possess a particular aesthetic feature. No one set of conditions makes something "graceful" the way a set of necessary and sufficient conditions makes something "square." Aesthetic concepts differ radically from other concepts in this way. What particular conditions there are remains important, of course, but there is no fixed set of necessary conditions which would allow one to label something as "graceful." A select set of conditions, if present, do not necessarily by virtue of being present make something graceful. One may describe an object with as many non-aesthetic conditions normally associated with "graceful" as possible and the object may still come up short of actually being graceful, and instead be better described as 'wan' or 'insipid.'

Situationally abstracted criteria do not govern aesthetic concepts, instead, circumstantial conditions count toward (or against) an aesthetic concept being more (or less) appropriate. Aesthetic terms can be inappropriate or inapplicable to certain objects, but to determine the applicability of an aesthetic term, one has to point to specific features which count toward or against the use of the term. Specific features of a painting, for example, may count toward or against the appropriate use of the concept "graceful," but no features will fix it necessarily as such.

Aesthetic concepts are open, complex, and contextually dependent; thus, it is impossible to give a list of sufficient conditions for them. Reference to particular, situationally placed conditions are necessary to identifying aesthetic features. Aesthetic judgement cannot be made with a set of criteria abstracted from their context. Non-aesthetic judgements, or "mechanical" judgements, such as judgements of character or judgements regarding a material's suitability to creating a table, have conditions fixed within them. An honest man does not lie. Water makes for terrible table-building material. However, for aesthetic concepts, conditions and principles cannot be derived that would guide with the same consistency.

Within the context of scientific theorizing, the openness of aesthetic concepts may strike some as worrisome. To say aesthetic concepts are so open might raise concerns such as anything to do with aesthetics is too contextually subjective to be useful in science, or the realm of the aesthetic is too nebulous to bear on epistemological problems. However, Sibley's concept of the aesthetic does not entail an aesthetic judgement is "subjective" in the sense that it depends upon personal preference. There are better and worse aesthetic judgements, and while there are no fixed, necessary and sufficient conditions that guarantee an object is or is not "graceful," or "elegant," why these concepts are applicable to an object still must be justified by appeal to specific features. Whether an object can be said to be graceful or elegant can be questioned, but there are better and worse answers to that inquiry. That aesthetic judgement plays a role in theorizing should not, on these grounds, worry anyone concerned about the epistemological integrity of science.

2. Aesthetic criteria in theory selection: four views

Philosophers have wrestled with the epistemic role aesthetic criteria plays in science. Here, I will review positions popular during the 20th century. Three of these general positions include:

(a) Aesthetic criteria have no epistemic role

(b) Aesthetic criteria are disguised empirical criteria

(c) Empirical criteria are themselves aesthetic criteria

(d) theories become aesthetically attractive through "aesthetic induction"

James W. McAllister, in his 1996 book *Beauty and revolution in science*, goes over each of these positions, the fourth being his own final answer to how aesthetic criteria influence theory selection. All four views, however, are insufficient. I will explain why here but will also note how each view brings us progressively closer to a more satisfying account for how and why the aesthetic features of a theory play a part in determining its empirical merit.

Aesthetic criteria have no epistemic role

McAllister refers to this position as "autonomism."[1] Autonomists insist aesthetic and empirical evaluations of a theory are distinct from one another and do not play into each other. Aesthetic and empirical evaluations are thus irreducible to one another and cannot affect each other. While it is true some theorists will make distinctions between the aesthetic and empirical merits of a theory, others do not. Too many theorists hold aesthetic criteria in high estimation for the autonomism view to be taken very far.[2] The theorists which take aesthetic criteria seriously take it into consideration when making choices about how to proceed in their theorizing. The suitability of a theory is not gauged only by empirical considerations, but by aesthetic ones as well, both functioning as selective criteria.

Autonomism claims usually represents a view about how theory selection should proceed with respect to aesthetic considerations, not how it actually proceeds. Whether or not theorists should consider the aesthetic features of their work is not a question I will address here. I will instead remain focused on what relationship between theorists and their aesthetic judgements is most likely to be in practice.

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[1] I do not refer here to the autonomist position within the ethics-in-art debate, though both positions bear certain conceptual similarities.

[2] McAllister 1996

Aesthetic criteria are disguised empirical criteria OR empirical criteria are aesthetic criteria

Both positions (b) and (c) represent a broader view about the relationship between aesthetic and empirical criteria. This broader view, one McAllister calls "reductionism," is characterized by the idea both aesthetic evaluation and empirical evaluation are aspects and manifestations *of* the same thing and *reducible into* one another.

Position (b) expresses a view which is shy about the very notion of aesthetic *qua* aesthetic. To claim aesthetic criteria are disguised empirical criteria is to claim what might appear to be an aesthetic feature is in fact no more than an empirical feature, and perhaps just one a theorist finds attractive on grounds of personal preference. This is only a small step removed from autonomism. Instead of denying theorists have aesthetic experiences doing their work, this position suggests these supposed aesthetic experiences are veiled mental engagements with empirical criteria, seemingly aesthetic but reducible to an experience with the empirical. There is no true aesthetic dimension important to theory selection on this view.

Position (c) is the more radical of the two positions. This form of reductionism holds that the experience with empirical criteria is fundamentally aesthetic, challenging the idea we can engage with empirical criteria independently of aesthetic experience. In this view, all theorizing is an aesthetic activity both fundamentally and essentially. The empirical is both an expression of aesthetic experience and necessarily reducible to aesthetic experience. This renders the work of theorists into another artistic activity, except one where the artists and their audience are not honest with themselves about the nature of the work they are doing.

Both forms of reductionism are problematic in that neither tracks very well on how theorists relate to the aesthetic dimensions of their work in practice. Positions (b) and (c) risk rendering ‘empirical’ and ‘aesthetic’ into essential ontological categories and insist one is a mere subcategory of the other when they are present within a scientific context. Theorists in practice do make distinctions between the aesthetic and empirical criteria they use to evaluate their theories. However, when theorists talk about the aesthetic or empirical dimensions of their work, it is within the context of how to best proceed given their goals. “Aesthetic” and “empirical” are practical terms for theorists. If the aesthetic and empirical are rendered into ontologically hard-nosed categories theorists themselves would likely not recognize, they are no longer helpful to understanding how theorists select their theories. Reductionist views also do not permit the possibility aesthetic and empirical judgements might augment each other in practice, which is why McAllister proposes a more pragmatic view that improves upon the problems autonomism and reductionism face.

Theories become aesthetically attractive through “aesthetic induction”

McAllister’s aesthetic induction is a type of inductive projection. Inductive projection is:

> If a theory has some property P, and property P correlates
> with successful theories, future theories with property P
> are regarded more favorably.

Theorists aim to create empirically successful theories, and so select theories with features shared with other previously successful theories. Not all features of an empirically successful theory, however, are going to be strictly empirical in nature. Theories with empirical success also have aesthetic features. McAllister suggests aesthetic features fall under a category of inductive projection as well.

McAllister calls this inductive projection with regard to aesthetic properties “aesthetic induction.” Aesthetic features which historically have tracked well with empirically successful theories become more appealing *as aesthetic features*; when present in a theory, a theorist is more likely to be attracted to the theory that shares the same aesthetic features possessed by previously successful theories. Useful theories become not only intellectually but aesthetically attractive when they resemble one another.

McAllister’s support for this theory of aesthetic induction comes from two observations. First, the aesthetic features theorists favor vary with time. Second, the degree of favor those aesthetic features receive correlates with the empirical performance of the theories which possess those properties. Aesthetic features come and go in favor according to their continued presence in successful theories.

McAllister goes on to claim the relative success of a theory which possesses certain aesthetic features determines whether the aesthetic feature contributes to the theory’s beauty. The evaluation ‘beautiful’ tracks with the success of the theories it is attached to. Empirical performance, then, lends a favorable light to aesthetic features and contributes to its perceived merit.

For example, the property of *symmetry* in physical theories has had surprising success and staying power as a feature in theories of fundamental physics. It is still currently regarded as a guiding feature. However, whether it will continue to be attached to successful theories remains to be seen. Some physicists worry symmetry might not be the ultimate aesthetic criterion and guide moving forward.[3] Still, symmetry has proven to be and continues to remain a powerful tool in doing physics. Aesthetic induction may also only be part of the reason certain aesthetic features are selected for and may explain why there is such thing as aesthetic criteria found in the sciences at all.

However, certain aesthetic criteria seem to do more than simply track with empirical success. Symmetry, again, is an attractive feature in a theory, but it also confers an incredible amount of explanatory power to a theory, acting as a fundamental feature to a theory's success. The role aesthetic features play in theory selection seems to go well beyond mere aesthetic induction. In the following section, I will show why the aesthetic features of a theory might actually contribute to a better understanding of the theories in which they appear, making them integral to the epistemic success of the theories they appear in.

3. Beauty begets understanding

McAllister's aesthetic induction only captures part of the story. When a theory meets certain aesthetic criteria, they tend to be criteria which also assist a theorist's understanding of what the theory is designed to capture. Since McAllister introduced his

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[3] Sabine Hossenfelder, *Lost in math: how beauty leads physics astray,* Hachette UK, 2018.

theory of aesthetic induction, Peter Kosso, Carlo Cellucci, and Angela Breitenbach have each put forward a similar idea: the epistemic function of aesthetic experiences and aesthetic criteria are to create and assist scientific *understanding*. These authors represent a trend in the philosophical literature which seeks to further understanding about the connection between desirable aesthetic features of a theory with the empirical success of those theories. Here, I will provide an overview of the claims these authors make about the role aesthetic features play in scientific understanding, and in the following section take these claims and McAllister's aesthetic induction a step further to create a more comprehensive claim about what role aesthetic features play in scientific inquiry.

In Kosso's 2002 article "The Omniscienter: Beauty and scientific understanding," he characterizes 'understanding' simply as seeing how ideas connect to one another. To understand something, one has to recognize specific conceptual links between the ideas and patterns which emerge out of a larger array of information. For Kosso, the concept of understanding is similar to other aesthetic features associated with esteem-worthy works of art. The features coherence, harmony, a sense of "inevitable fit," are all hallmarks of understanding in the same way they are features of a well put together piece of art. Thus, according to Kosso, *understanding is an aesthetic feature* as well as epistemically useful. I will move forward with a more modest version of this claim and say *understanding depends upon aesthetic features*.

In light of this characterization of understanding, it is easier to see how aesthetic considerations can play an epistemic role in science. Certain empirical foundations are necessary for knowledge but not sufficient for understanding. A sense of coherence is a necessary feature of understanding. To understand anything, we need to be able to recognize the coherence between and among ideas, follow links between them as well as see the greater pattern(s) they form. This "conceptual coherence" is the mark of understanding as well as an aesthetic quality familiar within the arts. How the elements of a literary narrative or a piece of music relate to one another gives a sense of balance or coherency, a sense individual elements are properly fitted to the rest of the piece. This same phenomenon is what provides a sense of understanding when a model or theory brings a set of ideas together into a coherent explanatory narrative. And, just as a piece of music is not judged by each individual note which constitutes it, neither are individual aspects of a scientific theory judged in isolation. According to Kosso, an aesthetic judgement such as 'beautiful' does not indicate beautiful theory is correct, but rather indicates its ability to contribute to and enhance our understanding of nature.

Cellucci agrees with Kosso that the aesthetic features of a theory assist theorists in their understanding of nature. In his 2015 article "Mathematical Beauty, Understanding, and Discovery," he characterizes understanding as the recognition of how parts of a whole suitably relate to one another. This is similar to Kosso's characterization, except it emphasizes the condition of seeing the fit between parts as "*suitable*." For Cellucci, this experience of suitability is an important feature of understanding. This experience of suitability may explain in part why theories, models, and even experiments might be deemed 'beautiful.' The sense something fits, belongs, is suited to its place or situation, is an aesthetically satisfying one. When parts of a whole work of art, such as a musical or a painting for example, clearly fit together in a way that feels fitting, it is satisfying. We are usually able to “make sense” of such a piece and are more likely to make a positive aesthetic judgement, one such judgement being ‘beautiful.’

Aesthetic assessments, such as “beautiful,” are situational. What makes for an engaging musical might not be what makes for an electrifying metal concert. Similarly, as Cellucci points out, understanding is context-dependent. The beauty of a theory is accessible only to those with the training to understand. Physicists best understand and appreciate the theories which come out of their own field. They are able to apprehend why a theory contributes to a better understanding of how the phenomena and observations in question fit within a larger body of knowledge. Their trained sense for what makes an explanation elucidating informs what lines of inquiry they pursue. Noticing beauty, then, has a role in the context of theory creation and selection, or as Cellucci puts it, beauty has a special role in the context of discovery. We can say, then, aesthetic factors play an epistemic role via their aesthetic nature.

What of truth? Cellucci and Kosso’s claims do not entail aesthetic factors play a role in selecting theories that are true, or at the very least, theories which map well onto reality. Many theories no longer considered true still retain the features which made them aesthetically appealing to their original creators. Yet beauty and other aesthetic judgements are still considered important to theorizing in the sciences. Angela Breitenbach, in her 2012 article “Aesthetics in Science: A Kantian Proposal,” claims aesthetic judgement is indirectly related to the object being judged and directly related to the intellectual activities engaged when reflecting on the object. Aesthetic judgement is a “second-order” response, the object’s beauty depends on the viewer’s intellectual engagement with the object. Judgement is neither entirely contingent upon the viewer or the object, but an interplay between the two. Both the object — in this case a theory or model — and the viewer passing aesthetic judgements on the object make up the content of the aesthetic experience and the judgement which follows. She goes on to suggest a theorist’s aesthetic appreciation of a theory comes from their awareness the theory is a suitable means of making sense of the natural world. Beautiful or engaging theories are understandable, therefore potentially usable, which causes theorists to experience a sense of intellectual harmony with the phenomena they study. Theorists’ aesthetic judgements function as reflective tools, guides for theorists as they attempt to get an intellectual foothold on the world they are attempting to understand. Intelligible explanations are part of the goal. An aesthetic assessment of a theory can be taken seriously as a guide toward achieving this goal; while aesthetic judgements are not infallible means of assessing the truth of a theory, they can point theorists toward the more intelligible, useful theories.

Talk of suitability, understanding, and comparisons made to complete items such as musical numbers or plays might imply nature can be fully understood, that it might even be solvable and there are possible theories which can capture it. I do not want to suggest nature itself is so neat, nor do I even want to uncritically suggest theorists could have such a good foothold on nature. Such claims go beyond the scope of this project. What I do want to suggest, given what I have laid out thus far, is these notions of suitability, understanding, and solvability suggest aesthetic experience plays a larger role in theorizing about nature than might be presupposed.

However, questions about nature are created to be solvable. Theorists use theories to better understand how what they observe fits into a broader theoretical framework of commitments and ideas, so theories are made to feel suitable by design. This simple fact is important to understanding the aesthetic experiences had by theorists. As theorists construct for themselves specific problems made to generate specific information, they create for themselves a framework in which they effectively play a kind of puzzle-game. In the following section, I will argue communities of theorists are engaged in a long series of puzzle-games of their own design. In pursuit of knowledge about the world, scientists engage in a form of gameplay. By examining science through an analysis of the aesthetic experience of gameplay, I argue the act of theorizing itself is better understood when looked at as an aesthetic activity.

4. Suitable solutions

Here, I will take a closer look at the role suitability and harmony play within the context of theorizing as well as the interplay between theorist and theory. When faced with a theory which feels well-suited or fitting, theorists tend to also appraise the theory as beautiful. But well-suited or fitting with respect to what? I will argue this assessment of “suitability” suggests a “beautiful” theory is considered beautiful because it is the right sort of solution for the problem theorists created for themselves, and what makes for a beautiful solution depends upon what kind of problem was created in the first place.

This, I will argue, is the same aesthetic experience as solving a puzzle-game. I will then go on to argue why the aesthetic experience of solving a puzzle-game is epistemically valuable to theorists.

Both Cellucci and Breitenbach suggest the role suitability plays in the aesthetic experience of doing science is important to understanding how theorists experience their work. Breitenbach goes further and connects the role of suitability to the intellectual harmony a theorist has when they come across a theory which provides them with intellectual traction on nature. It is the epistemically productive interplay between theorist and theory which produces more or less satisfying aesthetic experiences. The more satisfying aesthetic experiences, where one will find the 'beautiful' theories, are where theorists experience the most intellectual harmony with their work. Theorizing as an activity, then, can possess the aesthetic property of harmony. The source of this harmony however is not like the harmony one can experience when studying a painting, reading a book, or walking through nature. The source of this harmony is the interactive *interplay* between theorist and theory.

Theorists construct specific problems for themselves which facilitates a constrained, streamlined and mediated experience with the phenomena they study. As nature piques the curiosity of theorists, they initially ask questions like 'how,' 'what,' 'where,' 'when,' and 'why' — and from there construct a problem which goes beyond their initial, simple questions. In a theorist's search for explanations, they design problems made to produce specific kinds of answers by bracketing select information into select theoretical parameters. These specially designed problems are made to generate new information upon being solved. Mathematically based problems are a means of posing questions in such a way that they will produce answers. Experimental systems are means of physically materializing questions designed to produce knowledge.[4] Thus, using existing knowledge and background theory, theorists construct problems designed to have specific solutions. When theorists work on such a precise question, a set of constraints, rules, and a specific goal are brought together and make up what I will refer to as a *theoretical puzzle-game*.

From here, I will refer to problems constructed to produce specific kinds of answers as puzzle-games for the sake of being specific. The sense in which I use the term puzzle-game here also refers to a class of game-objects, such as cross-word puzzles, Sudoku, jig-saw puzzles, puzzle-boxes, and the Rubik's Cube. These objects are designed to have a finite number of solutions, and to be solved in a very specific way. Puzzle-games in the strictest sense are necessarily solvable — they are made to have at least one solution — this is what makes them *puzzle*-games. These same necessary conditions apply in theory selection.

The gaming qualities in scientific theorizing are also important to understanding how aesthetic experience functions to assist in a theorist's epistemic goals. C. Thi Nguyen, in his forthcoming 2020 book *Agency as Art*, lays out an aesthetic theory of games. I will use this analysis to further illuminate the aesthetic dimensions of doing science. Nguyen's main thesis: games create an aesthetic experience of acting and doing

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[4] Hans-Jörg Rheinberger, *Toward a history of epistemic things: Synthesizing proteins in the test tube,* Stanford, CA: Stanford University Press, 1997.

by providing a streamlined experience in which there is a clarity of purpose. Games are a form of art, the medium for which is agency. This is achieved by constructing an experience bounded and defined by specific constraints, rules, and a goal.

Nguyen makes a distinction between ‘goal’ and ‘purpose’ important for both his analysis as well as my own. A *goal* is what it aimed at during gameplay, such as making baskets in a basketball game or rendering all six sides of the Rubik’s Cube chromatically uniform. The purpose for gameplay is whatever motivated one to play the game in the first place, such as winning money, winning a gold medal at the Japan 2020 Olympics, or simply having a little fun. Nguyen also points out the goal and purpose can be the same, both the goal and purpose in playing Poker, for example, is to win money. However, in other game experiences, the goal and purpose will be distinct, such as solving a Rubik’s Cube, the purpose for which is generally the experience of striving to solve it. When goal and purpose are the same, Nguyen calls this *achievement play*, and when the purpose of playing is for the sheer experience, he calls this *striving play*. I bring up this distinction because there is an epistemic purpose to doing science. The ultimate purpose for each piece of scientific research is to further human knowledge of the natural world. This would make, by Nguyen’s lights, any play within the sciences achievement play.

I will also however note the distinction between the two in practice can be fuzzy and will from this point forward commit to the claim there is striving play nested within achievement play.[5] For, as Nguyen himself admits, if striving play is possible, this means

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[5] I will also note here I have limited access to the current manuscript for *Art as Agency* as of March 20th, 2020. If Nguyen addresses this himself, I am not presently aware of it.

we are able to temporarily put ourselves into a confined form of agency via gameplay. Theorists, in the midst of their work, must temporarily commit to striving to complete their project as if striving itself were the purpose for the activity. Theorists do better work when they have a little fun with it. To be continually distracted by the higher purpose of creating knowledge for humanity would interfere with the theorist's ability to focus on their project. As they work, they immerse themselves within the aesthetic experience of gameplay.

A sense of harmony is key to the aesthetic experience of gameplay. As Nguyen puts it, there is a satisfying sense of fitness, or suitability, when a challenge is met with just the right solution, creating a sense of harmony. Nguyen notes the play experiences which stand out most in his mind are the ones which act as graceful solutions to a problem, and it is this experience he suggests is the paradigmatic of harmony which defines the experience of gameplay. Here, I will focus in on the concept of *solution* for my purposes. Consider: when someone solves a puzzle-game, the solution generally feels *suitable*. When part of a puzzle-game's mechanism clicks into place, or when its pieces come together or come apart in just the right way, when the puzzle has been solved, there comes with it a sense of suitability and with it a sense of harmony with the puzzle-game. The tension built up and sustained in trying to solve the puzzle is released. How everything fits together makes sense. Why the solution is what it is becomes clear and the solver now understands the puzzle.

When theorists solve puzzles within their respective fields, they have a similar experience for the same reason. The suitability of a solution to a scientific puzzle then renders the features which make the solution suitable aesthetically attractive in the mind of a theorist. In the previous section, I summarize Angela Breitenbach's proposal for what role aesthetic judgement plays in theory selection. She claims positive aesthetic appraisal of a theory indicates the theory is a suitable means of generating understanding. Productive theories cause theorists to experience a kind of intellectual harmony. When a theory proves to be the right *fit*, everything else appears to fall into place. This experience, I argue, is the same sort of aesthetic, intellectual experience one has when they solve a puzzle-game.

It should be noted here that generally, only the theoretically trained will be able to properly recognize the suitability (and therefore the 'beauty') of a theory. Laypersons are less likely and less able to appreciate what makes a theory beautiful *as a theory*. This is because the theorist possesses the background knowledge necessary to appreciate a theory's suitability to the problem(s) its creators intended it to solve. Nguyen notes something similar occurs in gameplay, for while a spectator can in some ways appreciate the aesthetic merit of an elegant chess move, the special experience of harmony between chess player and the chess game is more intimately available to the chess player. Theorists are the puzzle creators and solvers, the ones best acquainted with the larger context in which theoretical puzzles exist. Scientific communities are self-made puzzle-solving communities.

But not all solutions are attractive. In the world of puzzle-games, some puzzles are better designed than others. Declarations of 'clever!' or 'beautiful!' are sometimes uttered by puzzle hobbyists when they solve a well-designed puzzle. A grunt of irritation or disappointed silence usually follows after a puzzle proves uninteresting or overly-complicated. Not every solution will prove aesthetically satisfying. An aesthetically satisfying puzzle depends upon the puzzle's design, from which the solution follows. Similarly, some scientific puzzles prove more aesthetically satisfying than others. What solutions prove satisfying to theorists will depend upon the theoretical commitments they and their colleagues make when creating theoretical puzzles in the first place. Sometimes a theory works but it is not always clear why. Other times, a theory may address a problem that is itself hard to grasp, intellectually black-boxing elements of the problem and rendering the solution aesthetically unsatisfying. It makes sense, then, not all solutions will receive positive aesthetic evaluation. Some theories will prove to be more aesthetically satisfying in much the same way some puzzles are simply more interesting than others.

There are also epistemically better and worse solutions. The purpose in creating these theoretical puzzles is to produce explanations about how the natural world operates, but not every solution represents a good explanation. Before Einstein, Newton's laws of gravity could not explain the "wobble" in Mercury's orbit. Urban Le Verrier proposed there was a planet between Mercury and the Sun causing this wobble, saving the Newtonian theory of gravity. This planet, it turns out, does not exist. Later, Einstein's theory of relativity revised 20th century understanding of how gravity works. Thereafter, a nonexistent planet was not needed to explain the wobble.

Both Le Verrier's Vulcan and Einstein's relativity help to explain the problem of Mercury's wobble. And both are perfectly acceptable solutions to the puzzles out of which they originate, but only the latter proved to have empirical traction. These different solutions to the same problem both come out of two different puzzles, one constructed to generate an explanation for Mercury's wobble, the other constructed to expand and move beyond Newton's physical laws of nature. The puzzle Le Verrier made and solved assumed a Newtonian universe and was addressed to the specific problem of Mercury's orbit within the boundaries of Newton's theory. The scope of the theoretical puzzle which produced Einstein's relativity went beyond Mercury and did not, by design, assume a Newtonian universe. The boundaries which constructed each puzzle were different, resulting in different solutions with different epistemic implications.

Thomas Kuhn addresses the above example in his 1962 book *The Structure of Scientific Revolutions*. Here, Kuhn proposed his famous (or infamous) theory of scientific paradigm shifts. This theory aims to explain why there seems to be this historically regular series of jumps made from one paradigm of theoretical knowledge to another. Part of Kuhn's explanation is this: science generally proceeds as "normal science," science which does not challenge the fundamental theoretical paradigm in which it is situated, but when enough anomalies pop up the prevailing assumptions within a field have to be bent or broken to explain the anomalies. The field undergoes a "paradigm shift." Mercury's wobble, in the above example, is one such anomaly, something which cannot be properly explained within the existing theoretical paradigm. Within the confines of the prevailing physical paradigm, Verrier's solution was a good one. A theory does not have to give theorists empirical traction with the real world to be a suitable solution to the puzzle it solves. Rather, there are epistemically better and worse puzzles, themselves constructed out of epistemically better and worse theoretical assumptions and theories.

It is important I address how it is talk of science as a puzzle-game makes sense when we consider the radical breaks and shifts fields of science seem to experience regularly. As anomalies pop up within a field, practitioners notice, and as they continue to wrestle with these anomalies, the *way* they construct their problems and the *types* of problems they construct come into question. To meet new needs within the field, new puzzles are assembled when the old do not seem to be giving theorists the epistemic gains they are after. In entertaining new (and sometimes radically different) puzzles, theorists court paradigm shifts. Once a new approach to doing physics presents itself, for example, physicists then have to evaluate the new approach to doing physics. In one of Kuhn's many follow up essays to his 1962 book, "Objectivity, Value Judgement, and Theory Choice," he claims the criteria operative in theory choice do not function as rules, but as values. These values, however, are not a matter of personal preference, they are a matter of better or worse judgement. When theorists are asked by their peers to justify their radical choices as they break away from a prevailing paradigm, they have to provide an explanation which can be judged and evaluated according to a shared set of values and goals. The new puzzle and its startling solution have to be assessed as being suitable to the broader purposes the community shares.

The goal in doing science is epistemic: the generation of knowledge and understanding. Nguyen claims games concentrate our experience toward producing certain ends, they are designed to sculpt and shape activity which makes certain moves and outcomes more likely. The overall purpose to theoretical puzzle-games is epistemic, to be sure, but the puzzle-game also renders the practice of science into an aesthetic experience which the epistemic gains rely upon. Theory selection is an aesthetic activity. In pursuit of well-formed problems and suitable solutions, theorists employ both aesthetic and epistemic means to epistemic ends, but the nature of the activity itself is aesthetic first and foremost; a game with practical implications. Some theorists are more enamored with their work than others, and some pursue more obviously aesthetically aware fields of study. ‘Beauty,’ as a positive appraisal of a theory, is merely a surface level expression of the deeper aesthetic experience theorists have when doing their work. However, all theorists, mathematicians, physicists, chemists, biologists, etc., are engaged in a larger puzzle-solving game of their own design. Science is the gamification of nature.

Chapter 2 - Symmetry in Physics: an aesthetic criterion

Abstract

There is doubt as to whether the aesthetic experiences of theorists are relevant to understanding theory selection. However, in order to best understand the epistemology of theory selection, one has to consider the subjective and intersubjective experiences of the theorists involved. In the previous chapter, I suggest the aesthetic experience of solving a puzzle-game is the same kind of aesthetic experience which shapes how theorists do their work. In this chapter, I will lay out a specific example: the role of symmetry as an aesthetic feature in doing fundamental physics. Here, I briefly explain what symmetry is in the context of physics, how it fits the within Sibley’s theory of the aesthetic, and why symmetry frequently functions like a suitable solution to a puzzle in physics, playing an important role in the aesthetic experience of doing physics and the epistemic goals of physicists.

1. Challenging Aesthetic Considerations in Science

Some theorists and philosophers are reluctant to admit aesthetic considerations as being important to theory selection qua aesthetic. Some uncritically assume anything “aesthetic” is subjective to variable personal preferences — such as the preference for blue hats over red ones — and thus cannot assist a theorist’s work in a meaningful way. Others assume the realm of the “aesthetic” is too nebulous to rely upon for indication a theory has merit as a scientific theory, meant to be grounded in empirical observations and clear, careful reasoning. They deny aesthetic features can play any epistemic role.

True, not every theory considered beautiful has withstood empirical scrutiny. If the planets did track along the frames of Platonic solids, this would possess an appealing geometric-symmetric beauty. Planetary motion, however, cannot be captured by this kind of beauty, no matter how beautiful the theory might be. However, this sort of protest highlights what aesthetic features *do not* do within theory selection, hence, distracts from questions about what role aesthetic considerations *actually do* play. Successful theorists have been guided in part by certain aesthetic criteria. Some rely upon them heavily. Aesthetic considerations as criteria do not have a perfect track record but neither have they proven irrelevant. To discount the role of aesthetic considerations based on any hasty generalizations would be a mistake.

Out of all challenges to the relevance of aesthetic considerations to theory selection, the one most often addressed is in Cain S. Todd's 2008 article, "Unmasking the Truth Beneath the Beauty: Why the Supposed Aesthetic Judgements Made in Science May Not Be Aesthetic at All." Here, he challenges the idea any of the features mentioned thus far, such as simplicity, unity, and symmetry, are actually aesthetic features. He critiques philosophers for assuming aesthetic features are epistemically relevant simply because they are pointed to by theorists and spoken of in aesthetic terms. Such "aesthetic" properties, he suggests, might simply be epistemic properties which serve epistemic purposes; claims about aesthetic experience being expressions of mere enjoyment at the exercise of doing science.

Todd claims we should be more skeptical of claims about the role aesthetic judgements play in scientific theorizing. These properties serve epistemic ends; thus, they are likely to be epistemic. Aesthetic factors, he claims, are unlikely to have any epistemic role as aesthetic factors. Todd does not go so far as to claim the supposed aesthetic properties and features relevant to a theory's selection are not aesthetic, but he claims their status as aesthetic remains to be proven, and the burden of proof falls on the philosophers who assume they are such. Todd does not make a positive claim which would fit him into any of McAllister's aesthetic theory camps, reductionist or autonomist. Rather, he argues it remains *undemonstrated* the helpful features in question ought to be considered aesthetic. His argument entails either a form of reductionism or autonomism are the default, a form which does not consider aesthetic considerations relevant or real.

Setting aside the possibility Todd's view might relies upon a fallacy of division, assuming what is true of the whole of theorizing is true of its parts, it is at least too restrictive. Carlos Cellucci, in his 2015 article titled "Mathematical Beauty, Understanding, and Discovery," dismisses Todd's skepticism as too strong. Epistemology is not confined to the context of justification, but includes the context of discovery, and within that context are guides to selecting theories, and some of these guides are aesthetic in nature. That the ends of theorizing are epistemic does not entail the means to those ends are solely epistemic. Aesthetic factors may, then, have epistemic roles as aesthetic factors. When theorists have an aesthetic experience when they do their work and it informs how they proceed, it is worth paying attention to for that reason alone if we are to understand how science operates.

It is important to maintain the aesthetic considerations in theory selection are aesthetic in nature. The burden of proof is on Todd, not on the philosophers of science who take theorists at their word when they report having aesthetic experiences relevant to their work. Understanding how theorists experience their work is important to understanding how their work operates. The subjective and intersubjective experiences of the theorists themselves is part of the larger project of science and affects how the project proceeds. Flattening or reducing the notion of aesthetic criteria as disguised epistemic or empirical criteria thereby flattens our characterization of theory selection. A flattened characterization misses elements of what goes on in theory selection and leads to a mischaracterization of the work itself. Theorists and their experience of their own work cannot be excluded in this discussion. If we are to understand theory selection, we must take the theorists' claims about the role of their aesthetic experience seriously.

Todd however brings up an important question: is the role of aesthetic experience within the context of scientific theorizing that important? There is a tendency to dismiss or not dwell on the aesthetic experiences of theorists. The literature on the role aesthetic experience plays in theory selection is relatively small possibly for this reason. In the previous chapter, I summarized key moves within the literature that propose ideas which come close to answering this question. I then go on to suggest theory selection proceeds much like a puzzle-game, making theory selection itself an aesthetic experience, not merely informed occasionally by aesthetic considerations. My claims suggest the aesthetic experience of doing theory is critically important making epistemic gains.

Thus far, I have not provided any specific examples for how the aesthetic experience of doing a puzzle game forms scientific theory selection. In the following sections, I will make my main claim clearer within the context of fundamental physics and the aesthetic criterion of symmetry. The role of symmetry as an aesthetic feature is the most discussed within the relevant aesthetic, philosophical literature. This is due in part to the public appreciation of symmetry's aesthetic merits by physicists themselves. Using symmetry, I will further demonstrate why conceptualizing theory selection as being part of a puzzle-game helps us better understand the role aesthetic experience plays in constructing scientific explanations.

2. Symmetry in Physics

Throughout the 20th century, fundamental physics has been largely driven by aesthetic considerations in the form of symmetry. In a popular book titled *Fearful Symmetry*, physicist A. Zee begins with a sentiment popular among his peers: "Nature, at the fundamental level, is beautifully designed" (3). Zee, in agreement with other theorists, agrees there is an aesthetic dimension to theorizing, and admits symmetry is an aesthetic criterion important to doing physics. The goal in doing fundamental physics, he claims, is to have as few laws as possible and to come up with a single, unified description for nature. Symmetry, he and many of his colleagues are sure, will guide physicists toward realizing this goal.

I will set aside for now Zee's commitment to symmetry as an aesthetic feature and his mention of other important aesthetic considerations, such as unity and simplicity. I will return to symmetry as aesthetic in the following section. For now, I will briefly elaborate on the role symmetry plays within fundamental physics.

The following information in the following two paragraphs is taken from David J. Gross' still-popular 1996 article, "The role of symmetry in fundamental physics." Symmetry principles summarize the regularities of physical law and provide theorists with the structure and coherence they hope to find in nature. It has also permitted theorists to proceed confidently when repeating experiments sensitive to time and place. Symmetry principles provide the theoretical underpinning which makes this regularity possible. Without this regularity, physical laws (as we know them) would not be discoverable. It is believed, then, given this success, symmetry as a feature dictates the form laws in nature take.

Symmetry has important implications for the existence of conservation laws, principles in classical mechanics, and the classification of elementary particles in quantum mechanics. As physicists explore higher energy, shorter distance phenomena, more symmetry of various kinds are discovered. Gross and some of his colleagues suspected that by the end of the 20th century (then only four years away) all fundamental symmetries would be local gauge symmetries. Toward the end of his essay, Gross states "when searching for new and more fundamental laws of nature we should search for new symmetries." The way forward in physics is to continue to be guided by the search for symmetry. This conviction remains popular among theorists today. What makes something symmetrical, be it physical objects, phenomena, or the underlying laws of nature, is the property of *invariance*. The property of invariance is to remain unchanged after having undergone a transformation around some axis. Geometrical figures possess familiar forms of invariance. A square turned on its plane by 90 degrees in either direction remains unchanged, the 90° turn here being the transformation. A circle turned any number of degrees on its plane also remains unchanged, possessing more instances of invariance, therefore more symmetry, as it remains unchanged under a greater number of transformations. A perfect sphere possesses even more symmetry; no matter how many degrees and along what plane it is rotated, it does not change.

Invariance in physics is when physical reality appears the same from different viewpoints of possible reference. One old example of invariance in physics is symmetry along a Galilean transformation. Galilean relativity asserts there is no distinction between being at rest and being in motion at constant velocity. To test whether a theory is consistent with the principle of Galilean relativity, the theory is transformed by translating corresponding variables from the theory's original equations in their initial reference frame into a second reference frame. If the variables in this second frame still adhere to the original reference frame equations, the theory is said to be invariant with respect to Galilean relativity. The discovery of different possible kinds of transformations gives rise to different possible kinds of symmetry. Currently, fundamental physics, as a field, is in part a search for more possible symmetries. As of now, supersymmetry, postulated as possible but not yet confirmed, is the next big symmetry to be discovered.

Symmetry has proven to be a useful criterion. Theorists have actively sought out symmetry in their work and have met with great success. Einstein considered symmetry a primary feature of nature. This assumption then led to great theoretical and empirical success. Putting symmetry first continued to prove spectacularly successful for the next century. It is now considered a dominant and fundamental concept in physics and a natural guiding principle. If given the choice between two theories, all else being equal, the more symmetrical is chosen. It is also the case the theory possessing symmetry is considered more beautiful.

Symmetry is also widely considered to be an *aesthetic* feature of nature (or at the very least a feature of the theories used to describe nature.) Many physicists also consider symmetry to be a beautifying aesthetic feature, a sentiment Zee explicitly states. Symmetry makes a theory beautiful, and in seeking out symmetry in nature, physicists also seek beautiful theories. The idea that nature has a beautiful underlying design is a faith as old as the ancient Greeks, a faith continued by theorists such as Einstein, Dirac, Poincaré, Heisenberg, and many physicists which have come after them.

Symmetry is, in fact, an aesthetic feature, as I will demonstrate in the next section, but it should be emphasized here theorists take aesthetic features seriously as reliable guides in their work. This reflects certain assumptions about nature: that it is unified, coherent, and symmetry is the feature that makes it so. As Gross puts it, “at the fundamental level nature, for whatever reason, prefers beauty and is marvelously inventive in inventing new forms of beauty.”

3. Symmetry as an Aesthetic Criterion

McAllister places symmetry as one of four classes of aesthetic properties to be found in scientific theories. He justifies this classification by pointing to the fact symmetry is considered a beautifying feature.[6] It is also perhaps one of the oldest lasting aesthetic criteria in selecting theories about nature, the Greeks considered it a beautifying feature, as well as indicative of truth. What kind of symmetry is prioritized has changed over the last 2500 years; however, the category of symmetry remains as important to theorizing about nature as ever. But this does not tell us what it means for symmetry, as a feature, to be aesthetic.

According to Sibley's theory of the aesthetic, laid out in more detail in the previous chapter, aesthetic features come in a variety of forms which depend upon the particular object in possession of those features. A graceful drawing must have line, whether actual or implied. This does not make line itself a necessary condition for the concept 'graceful.' 'Line' is necessary to the concept of 'drawing.' Whether or not 'graceful' is an applicable term will depend on specific features of a particular drawing. A person assessing the drawing must be able to point to what lines and what about how those lines fit into the whole and make the drawing a graceful one. Similarly, dance requires motion, but what makes for a graceful dance will depend upon how the motion within a particular dance renders the dance itself graceful. There is grace of line in drawings, and grace of motion in dance. Wherever there is a graceful item, what makes this item graceful is dependent on the particulars of the specific object in question. There are

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[6] McAllister, 1996.

numerous ways to be graceful, a way for dance and a way for drawing achieve grace. This is also true for symmetry.

For something to be symmetrical it must possess the property of invariance along some axis of transformation. This seems at first to be a strict and necessary criterion that makes symmetry’s status as aesthetic dubious. However, a closer examination of the role invariance plays in symmetry makes symmetry’s status as aesthetic clearer. There are a number of ways to be symmetrical, some of them have already been referred to here and in the previous section. Each kind of symmetry is defined by the axis of invariance applicable to the case in which the symmetry is found. Some ways of being symmetrical include: geometrical, dynamical, continuous, discrete, local, global, passive, and active. Squares, circles, and spheres have geometric symmetry. Galilean relativity is a principle of global symmetry. Each symmetrical object, system, or law turns on a different axis of invariance. Symmetry, like grace, is contextually subjective.

I admit, there is something “mechanical” about how we determine whether or not something is symmetrical. If there is an axis of invariance, the object pivoted on that axis can be said to possess some form of symmetry. However, the aesthetic feature “balance” works similarly to symmetry. An example: for a painting to have balance, there has to be a certain degree of symmetry within the painting’s composition, meaning there will be at least one identifiable axis of “invariance” with regard to at least one particular element within the composition. However, what specific elements give a painting balance remains subject to the particular painting as well as the medium painting itself. Similarly, what makes for a balanced musical composition will have nothing to do with visual presentation, rather its balance will depend on some other kind axis, where and how that axis is placed differs from any axis found in a painting. Similarly, there are various axes by which a theory can be symmetrical, hence the above-mentioned list of forms of symmetry. What makes something symmetrical remains contextually subjective.

Sibley's insistence there is no "mechanical" means of determining whether a feature is aesthetic is perhaps too strong or at the very least somewhat unclear. He seems to equate his term "mechanical" with the abstract criterion of: a set of necessary and sufficient conditions *independent of context or medium*. The type of symmetry a theory can possess will depend on what sort of axis of invariance is possible, which in turn will depend on what theoretical medium in which the theory is situated. By drawing a parallel between the features 'balance' and 'symmetry' above, I aim to demonstrate symmetry still possesses the contextual subjectivity of a Sibleyian aesthetic feature.

The contextual subjectivity of symmetry requires one to know what they are looking at if they are to appreciate symmetry as a feature. In his account for the notion of the aesthetic, Sibley claims a certain kind of sensitivity is required to notice or discern aesthetic features. He calls this sensitivity "taste," a term I will not use here due to its status as a technical term in other realms of aesthetic theory, but instead I will refer to this sensitivity as "expertise." Physicists possess the expertise required to seek out, find, and select for theories with the appropriate kind of symmetry. They also are the only ones who possess the expertise to properly appreciate the symmetry physical theories are designed to exhibit.

This expertise does not, however, entail the symmetry found in physical law is only accessible to the trained. It must be brought out and pointed out to other theorists as well as laypersons, and while the latter may struggle to see and appreciate physical symmetry, they can nonetheless be guided to seeing and appreciating it. This, too, according to Sibley, is a feature of aesthetic concepts. One may not initially see what makes a dance graceful, but another with the right sort of expertise can bring the uninitiated’s attention to what elements make the term ‘graceful’ appropriate. So, too, with symmetry.

We can succeed in getting others to see something as graceful or symmetric when they might not have otherwise, whereas the same does not apply to other features. You either do or do not see a square as a square. Some mental reflection and a certain degree of intellectual sensitivity is required to see the square as symmetrical or as well-suited to its place within a drawing. That a physicist can get other physicists or laypersons to notice physical symmetry, that a certain degree of selective notice and reflection is required, is further suggestive of symmetry’s status as an aesthetic feature.

Here, I have given an account for what it means for symmetry to be an aesthetic feature. In the following section, I will suggest what larger role symmetry as an aesthetic feature plays in the aesthetic experience of doing physics. I argue symmetry has appeal as an aesthetic feature because it has proven to be the most suitable solution to simplifying the laws of nature.

4. Puzzles Within Physics: the aesthetic experience of science as a game

In this chapter, I have argued symmetry can be appropriately understood as an aesthetic feature as well as an empirically functional one. This however does not explain what *role* its aesthetic status plays in theory selection. Here, I will argue conceptualizing physical theory selection as a puzzle-game offers a conceptual framework which can be used to make more sense of what role aesthetic judgement plays in doing science. In the previous chapter, I argued a theory possesses aesthetic merit because it suits whatever theoretical problem, or puzzle, it acts as a solution for. What makes for a beautiful solution will depend on what kind of problem was created in the first place, in the case of fundamental physics, the goal is theoretical unity and simplicity. Symmetry is the most aesthetically suitable solution to the theoretical puzzles in fundamental physics, and the aesthetic experience of solving a puzzle-game is what points physicists to symmetry.

In section 2 of this chapter, I mention the goal for the field of fundamental physics is to end up with as few laws as possible and to come up with a unified description for nature. Theorists aim to have explanations for phenomena come out of a unified description with only a few set of laws. Symmetry is proving to be a promising means of achieving this goal. As also mentioned in section 2, symmetry principles are able to summarize regularities within physical law, provide theorists with coherent structure for their theories, and makes explanations for the regularity of nature possible, which in turn allows for the discovery of new laws and phenomena. Right now, a kind of symmetry called ‘supersymmetry’ is the next proposed solution to a number of specific problems (‘puzzles,’ for my purposes here) within the field.

A note: seeking to find simplicity and unity in the fundamental laws of the universe is itself an aesthetic preference for how nature should be rendered by theorists, but this discussion goes just beyond the scope of what I am trying to achieve here. This chapter remains focused on providing an explanation for what aesthetic experience does within the context of specific theory selection projects. While closely related to what I discuss here, going more into depth as to why physicists as a community pursue explanations which contribute to unified and simplified descriptions of nature goes beyond the scope of this thesis.

In his previously mentioned 2002 article, Kosso suggests one form of symmetry, gauge symmetry, is not beautiful, but it is the recurring themes within its variations which warrant it positive aesthetic appraisal. He suggests this positive appraisal is due in part to a theorist’s commitment to finding simplicity and unity in nature, not the symmetry itself. Kosso also points out another common feature of beautiful theories is they give more than what was put into them. Meaning, when theorists get more explanatory information out of a theory than what they put into creating it, the theory is more likely to be deemed beautiful. Such a feature may confer to theorists a sense that nature is unfolding before them, or that things have fallen into place and everything ‘clicks’ together into a coherent whole. As mentioned in the previous chapter, Breitenbach claims this experience contributes to a theorist’s understanding by giving them a sense of intellectual harmony with the natural word, a sense they have tuned into the underpinnings of the universe.

Symmetry has proven to be both an elegant and recurring solution to the theoretical puzzles within fundamental physics. It possesses a certain kind of simplicity as well contributes to the desired goal of unifying the fundamental theories of nature. Each theory puzzle within physics, as part of a larger project, is aimed at rendering nature simpler and seamless. Symmetry as a solution is an effective means to simplifying the laws of nature, rendering symmetry itself elegant in the eyes of theorists. The goes beyond McAllister's theory of aesthetic induction, where a theory is attractive because it appears in historically successful theories. Theorists are engaged in a puzzle-game activity of their own design, their aesthetic experience of their work a game-like experience. Upon coming up with a solution which solves their theoretical puzzle, theorists will experience a similar attraction for the solution a puzzle-game enthusiast feels upon examining the solution to one of their favorite toys. A sense of suitability, a feeling of success and release, an appreciation for the aesthetic appeal of symmetry as a feature; this all constitutes the aesthetic experience of doing fundamental physics.

Fundamental physics cannot be done outside this experience. The epistemic gains of the field depend upon the aesthetic experience of doing a puzzle-game. To do physics, a very specific problem has to be made. Functionally, it is a puzzle, and with it necessarily comes a solution. By seeking to solve this puzzle, theorists entangle themselves in the puzzle-game experience. In doing so, theorists create for themselves an aesthetic experience informed by aesthetic criteria. Symmetry feels like a suitable solution because these theoretical puzzles are designed to render nature more simple and unified. This is how symmetry as an aesthetic feature contributes to the creation of scientific explanations. Symmetry’s aesthetic appeal comes out of its place within the larger game of physics.

Chapter 3 - Protein Puzzles

Abstract

Protein modeling is another example of how the puzzle-game experience shapes scientific practice. In this chapter, I examine protein modeling as an interactive practice, paying special attention to how interactivity defines the practice. The aesthetic experience of creating protein models is constituted by the interactive gameplay necessary to complete the task, and it is the solvability of protein structures which makes the activity a puzzle-game activity. Epistemic gains are possible within this kind of aesthetic experience because puzzle-games revolve around their own termination.

1. Representing Proteins in (Digital) Space

Proteins are complex, biological macromolecules[7] which make up the majority of an organism's mass. Proteins vary widely in size, shape, and function. Structural biology is the study of bio-macromolecule structure and the majority of structural biology is concerned with the structure of proteins. Many structural biologists focus on what is called protein modeling, the practice of creating a 3D model to represent the 3D structure of a protein. The first proteins to be modeled were myoglobin and hemoglobin, blood proteins responsible for the movement of oxygen through the circulatory system, in 1957 and 1960[8], respectively. With the creation of these models,

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[7] A molecule is a group of atoms bound together. 'Macromolecule' generally refers to a very large collection of atoms bound together into single unit, such as a protein or piece of DNA.

[8] John Cowdery Kendrew, R. G. Parrish. "The crystal structure of myoglobin III. Sperm-whale myoglobin," *Proc. R. Soc. Lond. (1957) A***238:** 305–324.; Max F. Perutz, Michael G. Rossmann, Ann F. Cullis, Hilary

the field of structural biology was born. Since then, 151,363[9] (and counting) protein models have been published in the worldwide Protein Data Base.

The oldest and (until very recently) most common way of modeling proteins is through a process called *x-ray protein crystallography.* Creating models is an interactive process, requiring modelers to coax batches of their select protein into forming crystals, which they then blast with radiation to obtain the data needed to create an 3D model. The process in short: modelers first must find a way to crystallize their protein of choice, assuming the protein *can* be crystallized. Modelers achieve this by experimenting with various chemical solutions; come up with the right chemical concoction, and a batch full of many copies of the protein forms into a solid with a rigid, predictable, crystal-like pattern.

Once the protein crystal is made, it is blasted with x-rays which diffract off the crystal's structure. The diffraction patterns are then used to determine the protein's structure. With the assistance of computer programs, learned knowledge about physics and chemistry, and years of intimate training with other protein models, modelers use this diffraction data to construct a digital 3D model of the protein. Once this model is made, the protein's structure is said to have been *solved*. Because a protein's form and function correlate, knowledge of the protein's structure can then go on to be used to

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Muirhead, Georg Will, and A. C. T. North. "Structure of haemoglobin: a three-dimensional Fourier synthesis at 5.5-Å. resolution, obtained by X-ray analysis." Nature 185, no. 4711 (1960): 416.

[9] According to the RCSB Protein Data Bank at https://www.rcsb.org/ as of April 29th, 2019. H.M. Berman, J. Westbrook, Z. Feng, G. Gilliland, T.N. Bhat, H. Weissig, I.N. Shindyalov, P.E. Bourne. *The Protein Data Bank Nucleic Acids Research*, 28 (2000): 235-242.

determine how the protein functions and be used to develop effective pharmaceutical drugs.

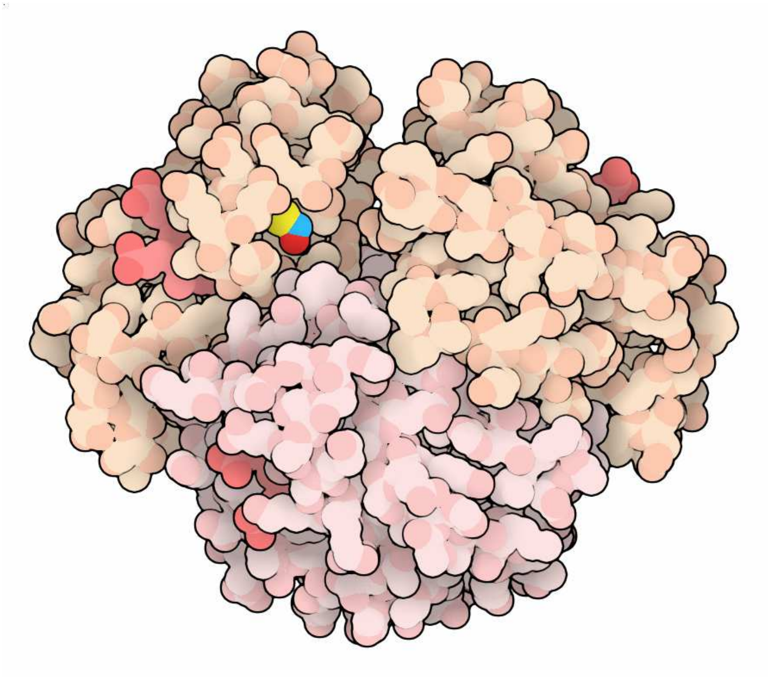

Image: 3D model of the protein S-Nitrosylated Hemoglobin[10]

During this whole process, modelers come to know their subjects in a deep, affective way. To create a crystal and obtain usable, replicable diffraction data, modelers must construct for themselves a puzzle and then solve it. This puzzle-activity requires the modeler to interact with the protein as a physical object, a digital object, and as a game. The modeler's interactions are guided by their knowledge of physics and chemistry but just as importantly are also guided by their personal embodied knowledge of the protein's "moods," gained through years of acquaintance with both proteins and their models.

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[10] David Goodsell. S-Nitrosylated Hemoglobin. *RCSB Protein Data Bank*. 2019. 10.2210/rcsb_pdb/mom_2019_5.

Thus, a modeler’s experience of their subject cannot be considered merely an empirical one, nor one strictly determined by laws and formulas and memorized rules. Information cannot be plugged into an algorithm which will reliably put out the protein’s structure. Modelers must personally get to know, fiddle with, and solve protein structures using their own intellect, training, and personal sensitivities. Creating a protein model is best understood as an aesthetic activity in service of epistemic goals.

The core of this aesthetic activity is *interactivity*. In the following section, I will discuss an aesthetic theory of interactivity and explain why interactivity as a concept is important to understanding aesthetic activities such as gameplay and protein modeling. Interactivity is especially important to talk regarding puzzle-games, as rigidly conceptualized throughout this thesis. I will then go on and address some reservations protein modelers have expressed regarding this particular aspect of their work. Protein modelers can be somewhat uncomfortable about the aesthetic features of their work. Finally, I will end by discussing further the epistemic value of the puzzle-game experience. One can better understand how science proceeds when one acknowledges the aesthetic dimensions inherent in the process. To conceptualize science as a series of entangled puzzle-games helps make sense of the aesthetic dimensions of science and can help philosophers better understand how we construct scientific knowledge.

2. Interactivity as Aesthetic Activity

Protein modeling is an interactive activity, but what it means for something to be interactive is not always clear. The concept ‘interplay’ was brought up and explored some in section 4 of chapter 1 as being important to the aesthetic experience of gameplay. Understanding the nature of interplay, or interactive play, with a non-sentient subject is important to understanding how protein modeling functions like a puzzle-game. Here, I will lay out a theory of what it means for an activity to be interactive as given by aesthetician Aaron Smuts. In the following sections, I then go on to explain why the interactive nature of protein modeling makes it a gameplay experience with important epistemic consequences.

Aestheticians frequently use the concept "interactive," but do so without giving a precise or helpful definition for the concept. Aaron Smuts, in his 2009 article, "What is Interactivity?," notes this hole in the literature and puts forward what he claims is the beginnings of a more helpful and precise definition of interactivity. The definition he gives is general, meaning the definition of interactivity should be applicable to art, nature, and wherever else the phenomenon may be found. By taking this approach, and not restricting the definition of interactive to the realm of art, Smuts creates a definition helpful to examining other aesthetic activities, phenomena, and experiences outside the realm of art. In this section, I give and use Smuts definition of interactive to draw attention to the sort of engagement necessary to do protein modeling, and in doing so draw attention to the aesthetic nature of puzzle-solving.

Smuts begins his analysis by reviewing past theories of interactivity from other aestheticians. Previously, theorists have simply stated interactivity is about use or control over some object or media, but this concept is too broad. Others, the most notable being Dominic M. Lopes, have suggested interactivity boils down to an inputoutput system, structured participation, or participation in certain procedures, which does not capture well the notion of interactivity as a phenomenon outside of computer art. All these theories are both (a) too broad because they admit cases of non-interactivity and (b) too narrow because they only deal with the arts and not other instances of the activity. Smuts chooses to analyze the concept more generally, rather than try and draw a definition of the concept from the arts. This move is similar to Frank Sibley's approach to defining the aesthetic, in that it can be useful to understanding aesthetic experiences outside an art museum and representative of every possible instance of real world interactivity. Thus, Smuts' approach is most appropriate for my discussion here.

In constructing his own definition of "interactivity," Smuts begins with the observation that interactivity is only present between two or more agents. These agents can be any combination of human or non-human. For interactivity to be possible, both agents must provide some kind of response to the actions of the other agent. He points out one cannot be said to be interacting with anything if the other agent responded with complete randomness or complete predictability. Neither behavior is a feature of interactivity. The kind of response one would expect from interaction with another agent is something between controllable and random. This leads him to define something as interactive if it (1) responds to being acted upon, (2) does not completely control the situation, (3) is not completely controlled in the situation, and (4) does not respond with complete randomness. That is to say, a thing can be considered interactive if: it responds to who or whatever is trying to interact with it, does not exert complete control over the action, is not controlled completely by the action, and does not respond to the attempt at interaction with complete randomness.

Smuts notes things in of themselves are not interactive, but it is in relation to our own capacity to participate with another actor we find the phenomenon. “Interactive” is a contingent property, an agent’s interactive capabilities dependent in part on the agent it interacts with. Similar to Sibley’s notion of the aesthetic, Smuts notion of interactive includes the condition of contextual dependence — the possibility and nature of interactivity depends on the context in which an agent is situated. This contextual dependence is why Smuts puts emphasis on the word “with” when examining how we use the word “interact.” Inter-action requires at least two actors. Previous conceptions of ‘interactivity’ in the aesthetics literature do not capture much more than the element of control involved in interaction. The nebulous and imprecise appeal to control is too broad and does not capture what it is we mean by the use of the word *inter*active. By drawing attention to the interdependency inherent in interaction, Smuts provides a concept that can be used to better understand interactive activities with more precision.

In the context of protein modeling, one can ask at least two questions regarding interactivity. First, what agent(s) does a protein modeler interact with? Second, if it can truly be considered an interaction in Smuts’ sense of the word, what form does this interaction take? There are at least two stages of interaction involved in the process of creating a protein model, and the nature of these interactions differ. In the early stages of the process, when modelers are trying to create a protein crystal, samples of the physical protein itself are being interacted with. Once a crystal is made, x-ray diffraction done, and the diffraction data collected, interaction is mediated through this data within a framework of physical, chemical, and biological laws and principles. The nature of the interaction with the protein samples is more straightforward than the interaction modelers have with the protein through its diffraction data, and I will elaborate on the nature of each interaction in turn below.

3. Interacting with Proteins

This section reviews and examines the interactive process of protein modeling in light of Smuts' theory of interactivity. For insight into how protein modeling is done, I rely on an anthropological ethnography of the practice. There are at least two different forms of interaction at work in protein modeling, the first is an interactive creation experience and the second an experience in puzzle-gameplay.

In her 2015 book *Rendering Life Molecular*, Natasha Myers gives an ethnographic account of the contemporary protein modeling community. I chose to use Myers' ethnography for the purposes of this chapter because her work captures the aesthetic dimensions of protein modeling not readily apparent in the polished publications produced by structural biologists themselves. Modelers are not as prone to waxing poetic or fretting over the aesthetic dimensions of their work as publicly as physicists. For this reason, I rely on Myers' work for most of the information on the practice of protein modeling in the following section.[11] This ethnography focuses specifically on

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[11] Myers' ethnography is rich and detailed. She spent several years observing and collecting information on the protein modeling community via: interviews; observations in laboratories, meetings, classrooms,

rendering a picture of what values are at play in the protein modeling process. She states: "my rendering amplifies and animates modelers' practices. In so doing, I render up a range of practices that are otherwise hard to see… and I animate a host of subjectivities, sentiments, and values that are not otherwise readily visible in twenty-first century laboratories."[12] The following paragraphs are an examination of protein modeling derived from Myers' anthropological study of modelers as theorists. The focus will remain not on the mechanics of protein modeling, but on how modelers relate to their work.

Creating Protein Crystals. Proteins are large, complex chemical molecules. On the molecular scale, they are unwieldy, bulky, often asymmetrical items. Should they crystallize in vivo (in their native environment), this would spell disaster for the organism. They are not generally prone to crystalizing. For this reason, creating protein crystals proves a challenge. Modelers understand the basic chemical composition of the protein and will often have a general idea of its native function. Modelers also have an understanding of the relevant physical and chemical laws and regularities which constitute the boundaries of what is possible for a protein to do and what can possibly be done to a protein. The protein's chemical composition, its chemical and physical properties, and the rules of nature are all used to inform how the protein modeler approaches getting a sample of their protein to form a crystal.

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conferences; analysis of their literature, editorials, news headlines blogs, and other educational media used to train modelers, as well as the interaction between modelers on social media forums.

[12] Natasha Myers. *Rendering Life Molecular: Models, Modelers, and Excitable Matter* (Kindle Locations 788-793). Kindle Edition.

However, since the modelers do not know what form the protein takes (getting this information is the modeler’s task, after all), getting the protein to crystallize involves a great deal of informed guesswork and luck. How proteins respond to a given solution is only somewhat predictable. Again, there are rules; how proteins respond will not be totally random, the same set of chemical and physical conditions will have the same effect each time a protein sample is subject to them, and there are chemical conditions known to be inhospitable to nearly all proteins. Even so, it is not always clear how a protein will respond to a modeler toggling the chemical conditions they are placed in. Informed guesses are made with varying success.

Getting a protein to crystallize and finding a set of conditions that will cause it to do so reliably is an interactive back-and-forth between the modeler and the protein sample, according to Smuts’ definition. The protein (1) responds to the efforts of the modeler, (2) the proteins do not control the interaction, (3) the protein is not completely controlled by the interaction in a predictable way, and (4) the response the protein gives is not random. This part of the modeling process, getting the protein to form a crystal, can take years, and does not always succeed. But if a modeler successfully creates a crystal, the modeler moves into another form of interactive engagement. Up until diffraction data is obtained from blasting a protein crystal with radiation, modelers interact more directly with the object at the center of their modeling experience. However, once the diffraction data has been obtained, the experience changes. They go from directly interacting with the protein itself to engaging with the protein crystal’s diffraction data. The nature of their interaction with the protein then becomes quite different.

Using Diffraction Data. Once modelers obtain quality diffraction data, half the job is done. The next step is to make a model of the protein out of this data. How the data translates into a model is not obvious. More often than not, the data does not give the modeler an obvious basis for determining where and how the protein's different elements are placed and oriented. The data cannot be plugged into a formula or algorithm to get the protein's structure. Data in hand, modelers have a new and altogether different problem. They must find a way to render the data into a representational model of the protein.

Creating a protein model out of diffraction data is a learned craft. Modelers must first familiarize themselves with all available knowledge about the chemical and physical properties of proteins. They have to learn what a properly modeled protein fold looks like and get a feel for how proteins behave in their native environments. In approaching their data, modelers must also learn to sense and feel when and where a model is off and a learned feel for what makes a protein model a good one. Both acquired knowledge about the rules of nature as well as first-hand knowledge of other protein models is necessary to making sense of the data. To get this latter kind of knowledge, which is both personal and not easily communicated to others, modelers must interact with other protein models.

In getting to know models, modelers must play with them. With time, interacting with previously created models as 3D computer objects and the data used to produce them familiarizes modelers with better and worse molecular configurations. Years of guided, trained interaction with complete as well as in-progress protein models renders the modelers themselves into skilled knowers of what makes a good protein model. By giving themselves over to this interactive project, modelers are both in control as well as controlled, never completely the controlled or the controller. Given all this, Myers claim modelers are thus “tangled up” with their models. This “tangled up” feature of protein modeling is also a characteristic of interactive relationships, according to Smuts.

The tangled-up interplay between modeler and model defines the aesthetic experience of protein modeling. However, protein modelers are aware of this aesthetic feature of their work and many have reservations and mixed feelings about it. Before I make the argument that this aesthetic experience is analogous to the experience of doing a puzzle-game, I will examine some of these reservations Myers herself observed in her subjects. I will then conclude this chapter with a final discussion of how protein modeling is another example of the puzzle-game experience in science as well as how this experience contributes to the epistemic goals of its practitioners.

4. Discomfort and Reservations

Protein modelers express unease about the relationship between their bodies and knowledge of their proteins. It is through the movement of their own physical bodies protein modelers feel through their work and come to know their proteins, but they do not trust their bodies entirely, wary of the interactive dimensions of their work. The worry is their embodiment practices will lead them astray, causing them to anthropomorphize their proteins and thus warp or pollute the epistemic integrity of their models. Yet at the same time, this community also insists upon embodied knowledge, refusing to allow their to trainees automate the process. This is similar to the tension physics as a community experiences over beauty assessments. The rhetoric of "anthropomorphic" proteins and "beautiful" theories do not sound very "scientific," making it tricky for some scientists to navigate what is and is not appropriate behavior when they work.

Protein modelers are consciously neo-Darwinist in their thinking. They are wary of inadvertently prescribing intention or personality to molecules which, of course, have none. Protein modelers claim to prefer using "mechanistic" rhetoric in an effort to maintain a non-anthropomorphic conceptualization of their proteins. However, in practice, protein modelers go on to embody these machine metaphors, acting out the motion of their proteins. In Myers' ethnography, she would point out to her subjects they physically embodied their work, expressing ideas with enthusiastic gestures and whole-body demonstrations, which in turn made these subjects uncomfortable. They would resort to holding their bodies still, but this made it difficult for them to think about and explain their work. There is a tension between how modelers feel they should think through problems and how they actually do.

At the same time, modelers openly distrust mechanizing the *process* of creating models. Experienced modelers insist their trainees get to know their models, data, and tools inside and out. It is preferred practice for a modeler to have a "feel" for the protein being modeled, the machines used to collect data, the data itself, and the code behind their modeling programs. To not fully understand and appreciate any of these is to "black box" knowledge, a vice in modeling communities. Automation is not good practice. Thus, there is also the insistence modelers know the ins and outs of their practice with their bodies as well as their minds.

The commitment to a "mechanistic" view of proteins thus seems half-hearted. Modelers end up performing and embodying the machine metaphor, rendering proteins into *lively* machines. Discomfort and reservation remains over this lively dimension of the practice, a dimension which acts in part as an expression of the more aesthetic nature of their work. In using their bodies, modelers assess their models-in-progress as either "pained," "strained," "relaxed," or "happy" — anthropomorphic evaluations meant to express models as well or poorly suited to the data used to make them. These sorts of evaluations are key to feeling through the puzzle-game of protein modeling. This interactive experience, while informed by data and guided by empirical considerations, is an aesthetic one.

The tensions felt by communities of scientists when aesthetic concerns come up makes assessing the role aesthetic experience plays in science tricky. Throughout this project, I have embraced the role of aesthetic experience as being important and interesting to the epistemology of science. However, this tension among scientists is valuable all well and worth noting here. In chapter 1, I briefly discussed Kuhn's theory of paradigm shifts, which highlights the value of tension in scientific communities in moving the sciences into new, interesting, and productive directions. Tension, I will note, is part of the aesthetic experience of solving a puzzle-game. Again, as I mentioned in chapter 1, where there is tension among scientists about how their science is being done, the *way* science is done and the *type* of problems the community pursues comes into question. Questions concerning methodology matter to the progression of science. Sometimes, the puzzles scientists need to solve are ones concerning methodology, which includes, among other things, how they engage in their work aesthetically.

5. The Protein Puzzle-Game

The key stage of protein modeling is rendering a model out of diffraction data. Obtaining diffraction data is its own sort of challenge, but the experience of interacting with and solving a protein structure is the experience I will focus on here. In this section, I will examine more closely the nature of puzzle-games and the puzzle-solving experience in the context of protein modeling. In doing so, I will highlight what it is about the puzzle-solving experience that makes it epistemically valuable to the larger project protein modelers are engaged in: the production of scientific knowledge.

Modelers are “tangled up” with their models in an interactive relationship. To say this may at first seem like a stretch. Aaron Smuts’ own example of the paradigm example of interactivity is the interaction between two persons, both autonomous agents. In interacting with a person, say, in conversation, neither agent is completely in control or controlled, but always somewhere in between while the interaction persists. Both agents are tangled up in the interaction: the boundaries between the controller and the controlled nonexistent, hence the controller and controlled are functionally nonexistent. However, more interestingly and more appropriate for my claims here, the other key example he gives involves only one genuinely autonomous agent: playing the game PAC-MAN. A reasonably good player can also be said to be tangled up in the interaction involved in gameplay, a hard boundary between controller and controlled also nonexistent. The player and game both respond to the actions of the other, and the player is submersed in the activity, bound up as both a responder and the responded to.

This however raises a question: what if a modeler, a PAC-MAN player, or a Rubik's Cube solver have already mastered their respective (puzzle) games? Mastery entails the "interaction" is no longer interactive in the Smuts sense of the word, since one agent has total control over the action. Smuts himself addresses this in his PAC-MAN example. He claims in cases like these, once a player masters the game of PAC-MAN, playing the game is no longer an interaction, but a different kind of play. Similarly, working through a puzzle one has already solved and can solve again without effort is a qualitatively different kind of play experience, one more like fiddling with a child-proof cap — the puzzling part of the puzzle is gone.[13]

Smuts himself does not explore too deeply the difference between human interaction and the interaction of gameplay, but the difference plays an important role here in better understanding the interactive dimensions of protein modeling. Games, as the previously mentioned C. Thi Nguyen points out, are constituted by a set of constraints, rules, and a specific goal. These conditions are necessary to have an interactive relationship with a non-autonomous object in the first place. Such strict

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[13] Unless you are the sort who is still regularly defeated by child-proof caps. If so, these remain puzzling to you.

conditions do not exist in casual person-to-person interactions. Similarly, these strict conditions make possible the epistemically valuable interactions modelers have with their models. In this way, protein modeling is game-like. Puzzle-solving is its own subset of gameplay, and I claim here protein modeling is a form of puzzle-gameplay because the experience includes *solutions*.

Puzzle-games are entities created to be solvable according to a set of constraints and rules for engagement. What sets them apart from other games is the puzzle-game experience is designed to be *terminated*. Once a puzzle has been solved the activity is terminated and the possibility for true Smutsian interaction gone. There is nothing left to puzzle out. The unknown solution drove the whole puzzle-game interaction, but once the solution is known, the puzzle experience ends. Protein modeling is determined throughout by its interaction with an unknown object, the interaction itself constructed by the goal of rendering the unknown into a known. It is a goal-oriented activity made to eliminate itself in revealing the object whose invisibility makes the activity possible. Knowledge of the protein's physical structure terminates the protein model puzzle-game. The aesthetic experience of the puzzle-game experience hinges upon this condition.

It is this eliminative solvability which makes the puzzle-game approach to obtaining scientific knowledge both fruitful and enticing. It is an intellectually manageable approach, one which has the promise of a result by the end. For this reason, scientific puzzle-games are epistemically valuable. They produce results in the form of solutions. The aesthetic experience of interacting with a puzzle-game gives a scientist traction on the material world they are trying to model. This is perhaps more immediately obvious in the sciences that use mathematical models and theories. It is easy to see a mathematical approach to explaining how the natural world works like a puzzle-game. The puzzle-game approach is not however restricted to predominantly mathematical approaches in science. We see the aesthetic experience of puzzle-gaming exists in protein modeling as well. The often curiously emotional and personally embodied practices in structural biology also utilize the experience of the puzzle-game. In these cases, without the experience of the puzzle-game, there would be no epistemic gains. Aesthetic judgement and experience make these activities possible. The epistemic gains are the product. Without the aesthetic experience, we would not have the epistemic gains.

Concluding Thoughts

This thesis does not focus on the “beauty” of “beautiful theories” as does most of the philosophy of science concerned with the aesthetic dimension of doing science. ‘Beautiful’ as an aesthetic evaluation is made by theorists, previous work summarized in Chapter 1 examines this and I refer to it occasionally here. However, I chose to focus on the role of other aesthetic experiences such as striving, satisfaction, and fun. Beauty seems to play a role in these experiences, but a deeper examination of this relationship remains just outside the scope of this project. In making other aesthetic experiences the focus, I turn the conversation afield into potentially new and interesting territory. I owe inspiration for this move to C. Thi Nguyen’s decision to do the same within art aesthetics. This thesis is as much an expansion on the philosophy of science as it is on the philosophy of games.

Science is often fun, and that fun is important to better understanding nature. Aesthetic experience and epistemic gains in science are intertwined. Scientific problems have a puzzle-game structure which shapes the aesthetic experiences theorists have when they work. This puzzle-game structure provides theorists a framework in which they can produce the epistemic gains they are after. Not all theoretical puzzle-games are created equal; some lead theorists astray and some are not very satisfying. However, puzzle-game activity continues to define the aesthetic experience of doing science. If theorists are to know nature, they must make a game of it.

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