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A Constraints-Based Approach to Thought Experiments in Physics

1.0 – Introduction

In this paper, I will analyze Rawad El Skaf's (2017 & 2021) account of thought experiments (TEs) in physics. I will argue that El Skaf's account is strengthened by taking on Amy Kind's (2016 & 2018) constraints-based approach to the imagination, which highlights the epistemic significance of imaginative processes. First, I will present El Skaf's step-by-step structure of TEs wherein he discusses their form, content, and epistemic function. Second, I will explain a canonical TE in physics known as the clock-in-the-box. In turn, I will lay out El Skaf's analysis of the clock-in-the-box TE. Then, I will present Amy Kind's constraints-based approach to the imagination. I will then offer three critiques of El Skaf's account and suggest that each critique is resolved by applying a constraints-based approach to his view. Once the hybrid view is laid out, I will discuss incompatible constraints on the imagination, which I call the home and away constraints. I will argue that a thought experimenter (TEer) may overcome this incompatibility by using home constraints as metaphors for understanding and applying the away constraints. Lastly, I will argue that physics TEs are special since it is an essential feature of theirs that they ask the TEer to consider incompatible constraints on the imagination.

2.0 – El Skaf's Account of TEs in Physics

El Skaf's account is specific to TEs in physics, an arena in which TEs have proven particularly fruitful. El Skaf is optimistic that his view can be generalized to TEs in other areas, and he suggests that TEs should be analyzed along three interrelated dimensions: "their *form*, their *content*, and their *epistemic function*" (El Skaf 2021, 6120). Each of these dimensions is evident in El Skaf's step-by-step structuring of TEs. Thus, let's begin by analyzing the structure of TEs on his account.

3.0 – Step One: Target Theoretical Questions

First, the TEer "identifies a target question(s) and [plans to use] a TE to answer it/them" (El Skaf 2021, 6132). In this step, the TEer is preparing to utilize the TE as a tool to answer their target questions.

3.1 – Step Two: The Scenario

Second, the TEer imagines a scenario. The scenario is composed of four elements: (a) theoretical and empirical statements, (b) an experimental arrangement that includes objects and "things that happen to or are performed by them", (c) a "description of the behavior of the theoretically under-described parts of the experimental arrangement", and (d) "idealizations and abstractions" (El Skaf 2021, 6132-6133). The scenario is an *imaginative scene* that "[c]ontains a more-or-less well-described experimental arrangement and is theoretically delimited" (El Skaf 2021, 6132). Thus, the scenario describes the *content* of TEs, including the particulars, which are the objects of the imaginative content. In El Skaf's view, there are two kinds of particulars: fictive and natural (El Skaf 2017, 20). Fictive particulars represent the fictional content of the TE

(such as a demon), whereas natural particulars represent the actual content of the TE (such as a cat) (El Skaf 2017, 20).

3.2 – Step Three: Unfolding of the Scenario

Once the imaginative scenario is established, the TEer applies "the theoretical statements […] and the description of the behavior of the theoretically under-described parts of the experimental arrangements [in order to] describe and trace the execution of the experimental arrangement" (El Skaf 2021, 6133). Essentially, the TEer *imaginatively unfolds* the scenario. In other words, the TEer presses play, so to speak, on their imaginative scene to describe and trace the execution of their imagined experimental arrangement.

The unfolding of the scenario is "intended to capture the idea that tracing the execution of the imagined experiment is mainly but *not entirely*, theoretically driven" (El Skaf 2021, 6133). The imaginative unfolding, then, is not completely dependent on theoretical and empirical statements, prior beliefs, perceptual experiences, etc. (This point is relevant to the epistemic significance of the imagination that I will put forth in later sections.)

El Skaf claims that the application of the theoretical statements to "describe and trace the execution of the imaginary experimental arrangement is (i) *case*, (ii) *subject* and (iii) *context* dependent" (6133). The application of theoretical statements is case-dependent since TEs are diverse and involve a wide range of imaginative scenarios. As El Skaf puts it, TEers are "asked to reason about measuring instruments as well as microscopic, macroscopic, all the way to celestial objects such as black holes" (El Skaf 2021, 6133). Further, since many imagined objects are not directly present in the sensory experience of the TEer, their "tracing *things that happen to or are performed by them* is mainly [but not entirely] guided by previously acquired theoretical

and empirical knowledge" (El Skaf 2021, 6133). The application of theoretical statements is subject-dependent since some TEers are naturally gifted imaginers who are better at tracing the execution of the imaginary experimental arrangement than others. While ordinary imaginers rely explicitly on theoretical statements, so-called extraordinary imaginers may intuit "how to trace the execution of the experimental arrangement *without explicitly activating these theoretical statements*" (my emphasis, El Skaf 2021, 6133). Finally, the application of theoretical statements is context-dependent since the historical methodological approach to evaluating TEs is surely different than the contemporary methodological approach (El Skaf 2021, 6133).

This step of El Skaf's structure of TEs will be crucial in my analysis since it explicitly involves the imagination. More specifically, this step explicitly appeals to both the imaginative content and the imaginative unfolding of the TEer.

3.3 – Step Four: Output of the Unfolding (OU)

Next, if the TEer imaginatively unfolds the scenario correctly, they will "obtain a proposition as an output" (El Skaf 2021, 6133). More specifically, the output of the unfolding (OU) is "propositional and is the piece of *non-empirically obtained* evidence that is conflicting with one or more theoretical statements" (El Skaf 2021, 6135). The OU is "analogous to the empirically obtained observational statements that constitute the result of some real experiment" (El Skaf 2021, 6135). Thus, the OU comes about via the imaginative unfolding of the scenario.

3.4 – Step Five: Inconsistency Revealed

Next, the TEer must interpret the OU. By interpreting the OU "with a piece of argument […] an inconsistency, real or apparent, is revealed" (El Skaf 2021, 6133). This step makes explicit how the OU "conflicts with an accepted theoretical statement" (El Skaf 2021, 6141). On

El Skaf's account, this step is the most epistemically significant since the main epistemic function of TEs is to reveal inconsistencies.

3.5 – Step Six: Inconsistency Resolved

Finally, the TEer "offers a way out of the inconsistency revealed [in step five] in the form of conjectures, a hypothesis to be further explored and tested by future theoretical developments and empirical confirmation" (El Skaf 2021, 6133). The epistemic upshot of this step is that it guides future research projects to resolve the inconsistency revealed by the OU (El Skaf 2021, 6140).

4.0 – Clock-in-the-Box

Consider the following canonical TE in physics. The *clock-in-the-box* TE, which was devised by Einstein, asks the TEer to imagine a box with a "hole in its side, which could be opened or closed by a shutter moved by means of a clock-work within the box" (Bohr, 225). The TEer is to imaginatively "start by weighing the box, then open the door for a short time in which a single photon can escape from the box, and finally re-weigh the box" (El Skaf 2021, 6122). The clock tells us how long it takes for a photon to escape, and the weight of the box tells us the difference in mass before and after the photon escapes (El Skaf 2021, 6122-6123). We can determine the energy of the emitted photon by $E = mc^2$ (El Skaf 2021, 6123). The complication in this TE is that it allows, in principle, that one can "simultaneously determine the time of the escape of a single photon and its energy with an arbitrary degree of precision" (El Skaf 2021, 6123). Of course, this result is a direct violation of the Heisenberg uncertainty principle, which says that a "measurement of two conjugate variables (such as time-energy) for a given particle, results in a limitation of accuracy of each of these measures" (El Skaf 2021, 6123). In other

words, we cannot know both the time and energy of the photon with perfect accuracy, as the TE seems to suggest. However, Bohr found a flaw in the TE, namely, that "a clock moving in a gravitational field should be given by [general relativity], and not a classical space-time theory, as Einstein seemed to be suggesting" (El Skaf 2021, 6123). Finally, Bohr concluded that the TE should be performed using general relativity rather than Newtonian physics, which, in turn, resolved the apparent inconsistency (El Skaf 2021, 6128-6129).

4.1 – El Skaf on Clock-in-the-Box TE

El Skaf provides a brief analysis of the clock-in-the-box TE using his account. In step one, Einstein targeted theoretical question(s) aimed at the validity of Heisenberg's uncertainty principle. In steps two and three "Einstein imagined an experimental arrangement and traced its execution (implicitly or explicitly) using [Newton's gravitational theory]" (El Skaf 2021, 6128). After the imaginative unfolding, Einstein arrived at step four, the OU. Einstein's OU, which came about via his imaginative unfolding, was that it is possible (in principle) to measure the energy and time of a photon accurately (El Skaf 2021, 6128). Then, in step five, Einstein interpreted the OU as pointing out an apparent inconsistency with the uncertainty principle (El Skaf 2021, 6128). Finally, in step six, Bohr proposed a resolution to the inconsistency in the form of conjecture which, in this case, involves applying different theoretical statements (general relativity instead of Newton's gravitational theory) to the experimental arrangement (El Skaf 2021, 6128-6129).

5.0 – Three Critiques of El Skaf's Account

Though El Skaf's account does well at capturing the general structure of TEs, I find that his account faces the following three issues (the first two being interrelated): (i) it does not

acknowledge the epistemic significance of the imagination that it implicitly houses, (ii) it does not explain how or why a TEer is justified in their beliefs about the output(s) generated by the TE, and (iii) it mischaracterizes theoretical and empirical statements as constituents of the imaginative content rather than constraints on the imaginative content. I will explain each of these issues in order.

The first issue with El Skaf's account is that it does not acknowledge the epistemic significance of the imagination that it implicitly houses. Recall that the main epistemic aim of TEs on El Skaf's account is that they reveal and resolve inconsistencies. These inconsistencies are revealed by a TEer's interpretation of the OU. The OU comes about via an imaginative unfolding of an experimental arrangement in which the TEer "describe[s] and trace[s] the execution of the experimental arrangement" (El Skaf 2021, 6133). The imaginative unfolding is not merely a transformation of background knowledge since it is "mainly [but not entirely] guided by previously acquired theoretical and empirical knowledge" (El Skaf 2021, 6133). Thus, El Skaf's account seems to rely on the imaginative unfolding for epistemic purposes since the imaginative unfolding is partly responsible for generating the OU, which, upon interpretation, reveals inconsistencies. However, El Skaf's view does not *explain* the apparent epistemic significance of the imagination that it implicitly houses. One might naturally question the epistemic role that the imaginative unfolding plays in generating OU considering that the imaginative unfolding is not entirely driven by the TEer's background knowledge. We should expect El Skaf's view to tell us more about the epistemic role of the imaginative unfolding.

The second issue with El Skaf's account is that it does not explain what justifies the TEer in their beliefs about the output(s) of the TE. Since the output(s) of TEs, including the OU, is crucial to the main epistemic aim of TEs on El Skaf's account, we should expect that his view

explains what justifies TEers in their beliefs about those outputs. Further, we should expect that an account of justification be put partially in terms of the imaginative processes (such as the unfolding of the scenario) since they are partially responsible for generating the OU. However, El Skaf offers no such account. Instead, El Skaf seems to dismiss the justificatory role of the imagination in TEs altogether: "when assessing TEs, ideally a *direct calculation or derivation would form the ultimate justification* that the experimental arrangement is correctly described and traced by these theoretical statements" (my emphasis, El Skaf 2021, 6134). Thus, it seems that in El Skaf's account, TEs have merely derivative or secondary epistemic value. If only direct calculation or derivation forms the ultimate justification for a TEer's beliefs about the output(s) of the TE, then the supposed epistemic utility of TEs that El Skaf's view endorses is significantly diminished. Indeed, I do not see the point of performing TEs at all given that calculations and derivations are the ultimate justification for the imaginary arrangement and unfolding. In that case, we could do without TEs and, instead, stick to calculating and deriving. Therefore, El Skaf's account largely dismisses the epistemic significance of the imaginative unfolding in justifying a TEer's beliefs about the output(s) of TEs.

Further, without an account of justification, the entire epistemic enterprise of El Skaf's view is jeopardized. More specifically, without an account of justification for a TEer's beliefs about the OU, there is no basis with which the TEer can justify their interpretation of the OU. Accordingly, the TEer cannot then be justified in their beliefs about an inconsistency being revealed without their being justified in their interpretation of the OU. Thus, El Skaf's view should explain why the TEer is justified in their beliefs about the output(s) of TEs, which includes the OU.

The third issue with El Skaf's account is that it mischaracterizes theoretical and empirical statements as *constituents* of the imaginative content rather than *constraints* on the imaginative content. (More on what I mean by constraints will be evident in the following section.) Recall steps two and three of El Skaf's structure of TEs, which are the scenario and the unfolding of the scenario, respectively. Both steps involve the imagination: the TEer *imagines* an experimental arrangement – the scenario – and then *imaginatively unfolds* the scenario. El Skaf characterizes theoretical and empirical statements as elements of the imagined scenario. In El Skaf's picture, then, the theoretical and empirical statements are internal to the imagination as constituents of the imaginative content. But this cannot be right. My interpretation of El Skaf's account is that the theoretical and empirical statements describe something in the scenario, which means that the statements cannot be in the scenario itself. If the theoretical and empirical statements are internal to the imaginative content of the TE, as El Skaf seems to suggest, then the statements cannot fulfill their designated function of describing elements of the imaginative content. Without the theoretical and empirical statements being external to the imagination in this way, then I find it a mystery as to how the TEer's imaginative scenario and successive imaginative unfolding can be performed correctly on El Skaf's account.

In later sections, I will suggest that a constraints-based approach to imagination will resolve each of the critiques expressed above. Further, I believe that a constraints-based approach fits in nicely with El Skaf's structure of TEs. Most importantly, though, a constraints-based approach to imagination will strengthen El Skaf's account by explaining the justificatory and epistemic role of the imagination in TEs.

6.0 – Amy Kind's Constraints-Based Approach

Amy Kind offers a constraints-based approach to the imagination. There is a common charge that dismisses the imagination as epistemically relevant. Kind, however, holds that the imagination is epistemically relevant since the imagination can be put to epistemic work in several contexts, including the natural sciences. More specifically, she argues that "the imagination can play a role in the *justification of our beliefs*" (my emphasis, Kind 2018, 232). The justificatory role of the imagination, on her account, comes about by applying constraints to the imagination. There are two specific constraints she has in mind, which she calls the *reality constraint* and the *change constraint*, respectively (Kind 2016, 151). The reality constraint aims to guide our imagination in *representing or capturing the world*, or some subset of it, as it is (Kind 2016, 151). The reality constraint need not be infallible to remain relevant to our epistemic purposes. More specifically, the reality constraint need not represent the world "*exactly as it is*" for it to remain epistemically useful (Kind 2016, 152). Rather, the reality constraint aims to represent the world *approximately* as it is. The change constraint, on the other hand, aims to guide our imagination in *tracking changes in the imaginative unfolding*. Much like the reality constraint, the change constraint need not be infallible to be epistemically useful. The change constraint fulfills the epistemic role of guiding the imagination in tracking the "relevant consequences of the change imagined" (Kind 2016, 153). As imaginers, the closer we come to meeting these constraints, the more ideal our imagination will be and, in turn, the more we might learn from such imaginings (Kind 2016, 153).

Constraints do not just guide the imagination. Another epistemic function that constraints fulfill in Kind's account is that they serve to justify our beliefs generated by imaginative projects. How do constraints fulfill this epistemic role? In Kind's view, in epistemically significant imaginings such as those in science, we are "aiming to get things right" (Kind 2018, 243). Our

imaginings, supplemented by constraints, "can have truth as a non-constitutive aim" (Kind 2018, 241). Granted, the imaginer carries prior beliefs, perceptual experiences, etc., that "infuse [their] imaginings" (Kind 2018, 243). These beliefs about the world "act as constraints on [the] imagination, just as pre-programmed variables set constraints on computer simulations" (Kind 2018, 243). Since we consider ourselves justified in believing the output of computer simulations, particularly in science, we should afford a similar justification to our beliefs in imaginative outputs based on imaginative simulations. Further, Kind says that "though the imagination is not *by its nature* constrained, the introduction of constraints – even substantive constraints – in our mental processes should not be seen to suggest that these mental processes no longer count as imaginings" (Kind 2018, 243). Thus, by way of analogy between computer simulations and imaginative simulations, Kind argues that our constraints on the imagination justify the beliefs generated by the imagination since the constraints inform and guide our imagination in *getting things right*.

6.1 – Temple Grandin

Kind offers an example of Temple Grandin, an animal scientist with extraordinary imaginative ability. (Note that Kind's account applies to ordinary imaginers, too.) Grandin's work "has significantly improved the welfare of animals throughout the world by revolutionizing the design of livestock-handling facilities" (Kind 2018, 234). One of Grandin's successful designs is an innovative dip vat, which is a "pool-like structure" found on farms that are "filled with pesticide to rid animals of parasites" (Kind 2018, 234). Her design process for the dip vat was completely imaginative; she did not rely on a computer simulation or real experiment to design the dip vat (Kind 2018, 235). Grandin, "[h]aving imagined her new dip vat design, […] believed that it would work […] before she saw the new dip vat in action; in fact, she believed it

[would work] before the dip vat was even built" (Kind 2018, 235). Further, it is clear from Grandin's account of her imaginative process that she took herself to be justified in believing that her design would work (Kind 2018, 235).

According to Kind, Grandin is indeed justified in her belief that her design would work due to Grandin's constrained imagination. Further, it is not Grandin's prior beliefs, perceptual experiences, etc. that are doing the epistemic work in her imaginative process (Kind 2018, 238). More specifically, Grandin's prior beliefs alone are "insufficient to generate the [new] belief" (Kind 2018, 238). Rather, it is Grandin's imagination doing the epistemic work since it "bring[s] those prior beliefs to bear in the current situation" (Kind 2018, 238). In this case, Grandin is justified in her beliefs about the efficacy of her design *because* of her imaginative process.

For Kind, this justification comes about via the constraints on Grandin's imagination. The reality constraint plays a role in Grandin's imaginative simulation since she presumably aimed at capturing the world as it is; she imagined the structural design, dimensions, materials, etc. of the dip vat. The change constraint is evident in Grandin's imaginative simulation since she imaginatively unfolded the scenario by imagining animals going through the dip vat, and describing what reactions they may have. More specifically, Grandin assumed a "cow's eye view" of the situation in which she was able to describe and trace the reaction that cows would have as they traverse her dip vat design (Kind 2018, 235). Grandin's imaginative simulation was informed and guided by both reality and change constraints in the same way that a computer simulation is informed and guided by its inputs. Therefore, in Kind's view, Grandin's imaginative process justifies her beliefs about the efficacy of her new dip vat design.

7.0 – Applying Constraints to El Skaf's View

I will now apply Kind's constraints-based approach to El Skaf's account of TEs. In doing so, each of the three critiques discussed earlier will be resolved. Ultimately, a constraints-based approach to El Skaf's account will significantly strengthen his view.

7.1 – Resolving First Critique

Recall my first critique of El Skaf's view, which is that it does not acknowledge the epistemic significance of the imagination that it implicitly houses. The imagination seemingly plays an important epistemic role in El Skaf's account, though it does not seem to be acknowledged by El Skaf himself. An important sequence of steps in El Skaf's structure of TEs is steps three to four, which is the unfolding of the scenario and the OU, respectively. The imaginative unfolding, *if done correctly*, lends itself to the non-empirically obtained OU. El Skaf focuses on the OU rather than the imaginative unfolding since, in his picture, the OU directly informs the main epistemic function of TEs. But this picture dismisses the epistemic significance of the imaginative unfolding. The OU does not come about entirely by the TEer's appeal to background knowledge. Rather, it is through imaginative unfolding that the TEer arrives at the OU. Since the OU is an output of the imaginative unfolding, we should expect that El Skaf's account has some metric that explains the epistemic significance of the imaginative unfolding. Unfortunately, there is no such metric in El Skaf's account. By applying a constraints-based approach to El Skaf's view, however, one can explain the epistemic significance of the imagination, namely, that it is partially responsible for bringing about the OU. Further, by taking on a constraints-based approach, El Skaf can explain why the imaginative unfolding is reliable, namely, because it is informed and guided by external constraints. Thus, applying a constraints-based approach to imagination, El Skaf's account need not leave the epistemic significance of the imagination unexplained. Rather, El Skaf's account can use a constraints-based approach to

explain why the TEer's imaginative processes are epistemically significant in generating the output(s) of the TE.

It is unclear from El Skaf's view how, without constraints on the imagination, the TEer imaginatively unfolds the scenario *correctly*. Consider El Skaf's notion of gifted imaginers who can "trace the execution of the experimental arrangement *without explicitly activating these theoretical statements*" (my emphasis, El Skaf 2021, 6133). In gifted imaginings, the imaginer need not rely explicitly on background knowledge. Gifted imaginers may reliably arrive at the same OU as ordinary imaginers. However, El Skaf's view does not explain the epistemic work being done by the gifted imaginer's imagination. By applying a constraints-based approach, El Skaf's view can explain how gifted imaginers arrive at an OU without relying on background knowledge. It is because their imaginings are informed and guided by constraints. The reality constraint and change constraint act as guides for the imagination such that the TEer can arrive at the OU without relying explicitly on background knowledge. Thus, El Skaf's account can be strengthened by a constraints-based approach since it allows his view to explain the epistemic significance of the imagination that it implicitly houses.

7.2 – Resolving Second Critique

Recall my second critique of El Skaf's account, which is that it does not explain why a TEer is justified in their beliefs about the output(s) generated by the TE. I have already discussed that the imaginative unfolding is epistemically significant, as it is partially responsible for bringing about the OU. But what justifies a TEer in their beliefs about the output(s) of the TE? El Skaf does not provide an answer to this question, aside from his related claim that "a *direct calculation or derivation would form the ultimate justification* that the experimental arrangement

is correctly described and traced by these theoretical statements" (my emphasis, El Skaf 2021, 6134). Once again, this shifts the epistemic significance away from the imaginative unfolding.

A constraints-based approach to El Skaf's account allows his view to explain the TEer's justification in their beliefs about the output(s) of a TE. More specifically, per Kind, the imagination justifies us in our beliefs insofar as the imagination is constrained. On a constraints-based approach, the TEer is justified in believing the output of a TE insofar as their imaginative process was constrained. The upshot of El Skaf's view of taking on such a constraints-based approach is that the epistemic significance of TEs can be put in terms of the TEer's imaginative processes rather than in terms of calculations and derivations. Good imagination, i.e., constrained imagination, is no longer epistemically second-rate on El Skaf's account if he adopts a constraints-based approach to the imagination since the TEer can be justified in their beliefs about the output(s) of the TE if their imaginative processes are constrained. This, in turn, reflects the epistemic utility of TEs in science, particularly in cases in which computer simulations, analog experiments, or real experiments cannot be performed.

If the justification of the imaginative unfolding comes about only by direct calculations or derivations, and not the imaginative processes of the TEer, then an epistemic account of TEs (such as El Skaf's) would turn out to be uninteresting. (Of course, I do not mean to say that El Skaf's account is uninteresting. Rather, I think that the epistemic significance of the imaginative process is left unexplored and unappreciated in El Skaf's account.) As it stands, it seems that El Skaf's view implies that one should focus on the epistemic role that calculations and derivations play in the natural sciences rather than the imaginative processes involved in TEs. But, of course, this is not El Skaf's project. To advance an epistemic account of TEs in the natural sciences El Skaf's account should highlight the epistemic function of the imagination within those TEs. The

position I have advanced is that El Skaf can highlight the epistemic function of the imagination in TEs by adopting a constraints-based approach to the imagination, which justifies the TEer's beliefs in the output(s) of TEs.

7.3 – Resolving Third Critique

Recall my third critique of El Skaf's view, which is that it mischaracterizes theoretical and empirical statements as constituents of the imaginative content rather than constraints on the imaginative content. El Skaf has mischaracterized the role that the theoretical and empirical statements play in TEs by suggesting that they are constituents of the imaginative content. Instead, I suggest that the theoretical and empirical statements are constraints on the imagination since they inform the imaginative content. More specifically, the theoretical and empirical statements describe the theoretical and empirical details of the imaginative content and its particulars. For example, imagine trying to fit a couch through a door. Empirical statements might include that the couch is ten feet long, and the door is ten feet tall, etc. These statements are *external* to the imaginative project and, in turn, inform the imaginative content: you imagine the couch as ten feet long, the door as ten feet tall, etc. In general, the theoretical and empirical statements figure into the imagining by way of being on a constraint; the statements describe elements of the imaginative content. Without constraining the imagination with the theoretical and empirical statements, though, one might imagine the couch to be three feet shorter than it is, in which case the imaginative project is not reliable. Thus, the theoretical and empirical statements must be external constraints on the imaginative process that inform the details of the imaginative content. This move should be uncontroversial. For a TEer to imagine a scenario and imaginatively unfold the scenario correctly, we should expect that the imaginative content is informed by their background knowledge, which includes theoretical and empirical statements.

In this way, the TEer is aimed at getting things right. Should the TEer not constrain their imagination using theoretical and empirical statements, the imagined scenario and imaginative unfolding are not aimed at getting things right. An imagined scenario that is not informed by background beliefs would fail to deliver justified beliefs about the output of the TE.

Let's reconsider El Skaf's analysis of the clock-in-the-box TE. In steps two and three, Einstein is said to have "imagined an experimental arrangement and traced its execution (implicitly or explicitly) using [Newton's gravitational theory]" (El Skaf 2021, 6128). Einstein's imagination was constrained by Newton's gravitational theory; it is Newton's gravitational theory that describes the behavior of the objects in the imaginative unfolding. Further, Newton's gravitational theory is external to the imaginative project, i.e., it is not contingent on Einstein's imaginative project. In other words, the theoretical and empirical statements made in the context of Newton's gravitational theory are external to Einstein's imaginative processes, and they guide his imaginative unfolding of the scenario. The behavior of the objects of Einstein's imaginative unfolding was governed by the underlying physics of Newton's gravitational theory. Thus, the theoretical and empirical statements act as constraints on the imagination because they inform and guide the imaginative content and its unfolding. El Skaf characterizes theoretical and empirical statements as constituents of imaginative content. But, if that is the case, then they cannot fulfill the essential role I have suggested for them, which I take to be the same role El Skaf has in mind. Thus, recharacterizing the theoretical and empirical statements as external constraints that inform and guide imaginative content better characterizes their respective epistemic role in TEs.

7.4 – Background Knowledge as a Constraint

As I have just suggested, theoretical and empirical statements (among other background knowledge) act as constraints on the imagination in that they inform and guide the imaginative content. We can think of the theoretical and empirical statements as constraints applied *through time*. It was implicit in my earlier discussion that the theoretical and empirical statements are applied *before* the scenario is imagined. This is to ensure that the imaginary experimental arrangement is aimed at getting things right. For example, Bohr's imaginary experimental arrangement was informed by a previous consideration of theoretical and empirical statements in the context of both general relativity and quantum mechanics. If the order of operations were reversed, and Bohr imagined an experimental arrangement *before* considering the theoretical and empirical statements in the context of general relativity and quantum mechanics, then the imaginative content would certainly be misinformed. Without considering, say, *that gravity is acting* on the clock-in-the-box, Bohr's imagination has free reign; the clock in the box might magically start floating, or fly away completely before he begins his imaginative unfolding. It is not until the theoretical and empirical statements (in the context of general relativity and quantum mechanics) constrain the TEer's imagination that the imagined experimental arrangement is aimed at getting it right. It is appropriate, then, to apply the theoretical and empirical statements *before step two* on El Skaf's structure, that is, before the scenario is imagined. This ensures that the imagined scenario is consistent with the underlying physical theory.

However, the theoretical and empirical statements continue to constrain the imaginative process after the scenario is imagined. The imaginative unfolding is also constrained by the theoretical and empirical statements. What keeps the clock from magically flying away in Bohr's imaginative unfolding is that it is subject to general relativity, in which things do not magically

float. Bohr, of course, does not need to constantly remind himself during the imaginative unfolding that gravity (as described by general relativity) is acting on the clock. That job is left to the constraints, which guide the imaginative unfolding. As Kind might put it, the theoretical and empirical statements are analogous to the inputs of a computer simulation. The theoretical and empirical statements inform and guide the content of the imagination in the same way that the inputs of a computer simulation guide and inform the contents of the computer simulation.

Thus, I suggest, contra El Skaf, that the theoretical and empirical statements are not constituents of the imaginative content. Rather, the theoretical and empirical statements are external constraints on the imagination that *inform and guide* the imaginative content and the imaginative unfolding.

7.5 – More Constraints Through Time

The reality constraint and change constraint are also constraints applied through time. The reality constraint aims to represent the world as it is, while the change constraint aims to track changes in the imaginative unfolding. One might naturally suppose that the reality constraint is applied before the change constraint. After all, the TEer first imagines a scenario *and then* imaginatively unfolds the scenario. But the reality constraint and change constraint need not be separated in this way. Instead, we should think of these constraints as working "closely in tandem with one another as the imagining unfolds" (Kind 2016, 152). Thus, both reality and change constraints act on the imagination together, and "should not be seen as operating one before the other" (Kind 2016, 152).

The reality and change constraints can strengthen El Skaf's account since they explain how steps two and three of his structure are correctly performed by the TEer. More specifically,

the reality constraint explains how a TEer correctly imagines an experimental setup. On the other hand, the change constraint explains how a TEer correctly applies "the theoretical statements […] and the description of the behavior of the theoretically under-described parts of the experimental arrangements [in order to] describe and trace the execution of the experimental arrangement" (El Skaf 2021, 6133). Without the reality and change constraints, El Skaf's picture cannot explain how a TEer can perform steps two and three correctly. El Skaf cannot claim that it is by appealing to background knowledge that a TEer completes steps two and three since, on his account, the imaginative unfolding is not entirely theoretically driven. Further, in El Skaf's account, the background knowledge is internal to the imagined scenario and therefore cannot inform or guide the imaginative content or its unfolding. By taking a constraints-based approach, however, El Skaf's account can explain how a TEer correctly performs steps two and three, since the constrained imagination is aimed at getting things right.

8.0 – Incompatibility of Constraints

In this section, I will explain why TEs in physics are special. I will suggest that an essential feature of physics TEs is that they ask TEers to consider incompatible constraints on the imagination, which I call *home constraints* and *away constraints*. Home constraints are constraints that involve the TEer's background beliefs, perceptual experiences, etc. Away constraints are constraints that appeal to things beyond our everyday beliefs and perceptual experiences, such as unobservables and the underlying physics that governs the behavior of the objects in the imaginative unfolding. Then, I will argue that the incompatibility can be avoided by using home constraints as metaphors for understanding and applying away constraints.

8.1 – Zoom Out

I recognize that my discussion about the incompatibility of constraints might seem like a pivot away from my earlier project. But I will zoom out a bit in this section to connect the dots, so to speak. Thus far, I have set out a hybrid account of TEs in physics (and the sciences in general) that applies a constraints-based approach to the imagination onto El Skaf's account. In the following sections, I will discuss a feature of some TEs in the sciences and special sciences, which is that they ask the TEer to consider incompatible constraints – the home constraints and away constraints. Note, however, that the incompatibility of constraints is not only an issue for my hybrid account. El Skaf's account faces the same issue but in a different way. On El Skaf's account, TEers must appeal to everyday beliefs and perceptual experiences as well as things that "go beyond" theoretical and empirical statements (El Skaf 2021, 6134). El Skaf packs all these elements into the imagined experimental arrangement. (Recall my third critique of his account.) These elements, though, are at odds with one another. On one hand, the TEer is to consider their everyday beliefs and perceptual experiences. On the other hand, the TEer is to consider that, say, quantum mechanics is at play, which goes beyond our everyday beliefs and perceptual experiences. I consider these elements as constraints on the imagination, i.e., they are external to the imagination, and they inform the imaginative content and its unfolding. El Skaf, however, considers these elements as constituents of the imagining itself. The burden is on me to explain how a TEer overcomes the incompatibility of constraints. In the same way, the burden is on El Skaf to explain how a TEer overcomes the incompatibility of the elements packed into the imagined scenario and its unfolding. We should expect El Skaf's account, as well as mine, to explain how a TEer is to overcome this incompatibility – whether it be by explaining away the incompatibility of the elements packed into the imagined scenario (in El Skaf's case), or by

explaining how the incompatibility of constraints can be avoided (in my case). In the following sections, I will explain my side of the story.

8.2 – Home Constraints

Recall that the constraint's role in the imaginative process is to both inform and guide the imaginative content and its unfolding. Home constraints are constraints that involve the TEer's background beliefs, perceptual experiences, etc. For example, the home constraints that act on Bohr's imagination in the clock-in-the-box TE include but are not limited to (i) his familiarity with spatial extension (length, width, height), (ii) his previous perceptual experiences involving boxes, clocks, scales, etc. and (iii) his beliefs about how the contraption is supposed to work. The home constraints inform Bohr's imaginative content by giving the content its imaginative character. More specifically, the home constraints fill in the particulars of the imaginative content: Bohr imagines a box of a particular dimension, a particular color, a particular material, etc. for all objects in the imaginative scenario. Thus, the home constraints act as constraints on the particulars of the imaginative content based on the TEer's everyday beliefs and perceptual experiences.

8.3 – Away Constraints

Physics TEs also ask us to consider things far from our everyday beliefs and perceptual experiences. TEers, especially those in physics, are "asked to reason about measuring instruments as well as microscopic, macroscopic, all the way to massive celestial objects such as black holes [which] are not actual objects present (and sometimes non-existent objects that could not even be present) to sensory experience" (El Skaf 2021, 6133). I call these constraints – the ones beyond everyday beliefs, perceptual experiences, etc. – the *away constraints*. For example,

an away constraint in the clock-in-the-box TE is Bohr's consideration that both quantum mechanics and general relativity govern the behavior of the objects in the imaginary experimental arrangement. Bohr is asked to imagine a single *photon* shooting out of a clock-in-the-box contraption as it moves through a *gravitational field* given by general relativity. This is far from his everyday beliefs and perceptual experiences. Away constraints, then, are constraints that are beyond everyday beliefs and perceptual experiences.

8.4 – Physics TEs Ask for Incompatible Constraints

What is distinctive about TEs in the sciences or special sciences that appeal to unobservables is that they incorporate both home constraints and away constraints. But I take it that not *all* TEs in *all* the sciences or special sciences have this feature. TEs in physics are particularly special since, to my understanding, they *all* ask the TEer to consider both home constraints and away constraints. The trouble is that these constraints are incompatible with one another. The home constraints fill out particulars based on TEer's everyday beliefs and perceptual experiences. The away constraints appeal to objects, unobservables, and/or underlying physics beyond our everyday beliefs and perceptual experiences. How, then, does a TEer apply these incompatible constraints to their imaginative projects?

I suggest that the TEer uses home constraints as a metaphor for understanding and applying away constraints. To do so, the TEer appeals to their everyday beliefs and perceptual experience to simplify what is asked of them by the away constraints. I will explain what I mean by referring to the clock-in-the-box TE. As mentioned before, an away constraint on Bohr's imagination is that he considers both general relativity and quantum mechanics, which is far from the everyday experience of the world. After all, one would not conclude *based on experience* that things are made up of quantum particles and that massive objects bend

spacetime. Thus, it is not entirely clear how Bohr would go about applying the away constraint to his imaginative project. However, one way to understand the away constraint is to relate it to home constraints by way of metaphor, i.e., Bohr can use the home constraints as a metaphor for understanding and applying the away constraints. In his consideration of general relativity, Bohr presumably used the following metaphor: spacetime is *like a fabric* that bends in the presence of a massive object. Further, in his consideration of quantum mechanics, Bohr may have used the following metaphor: the photon is *like a small, bright, orb-like object* that moves extremely fast. Note that these metaphors are indeed home constraints since they are in terms of everyday beliefs and perceptual experiences. Further, note that these metaphorical home constraints constrain the imaginative content in just the way we should expect them to, i.e., they inform the imaginative content. Bohr likely imagined a small, bright, orb-like object rather than a "true" photon, and this is sufficient for his conducting the TE in a way he can understand. Thus, home constraints can be used as metaphors for understanding and applying away constraints to the imagination.

One might naturally question how this metaphor between home constraints and away constraints is justified. The metaphor is justified insofar as the metaphorical home constraint, much like other constraints on the imagination, is aimed at getting things right. That is, the metaphorical home constraints aim to approximate the element that is beyond our everyday beliefs and perceptual experiences. Home constraints, to be used as metaphors for understanding and applying away constraints, must be sufficiently close to the away constraint to which it is metaphorically related. We saw this relation in the clock-in-the-box TE as described above, in which Bohr approximated the behavior of spacetime by imagining it as a fabric that warps in the presence of a massive object. Further, he approximated what a "true" photon looks and behaves

like by imagining it as a small, bright, orb-like object. These metaphors are sufficient to get the TE off the ground, so to speak. Bohr need not imagine the fabric of spacetime or a photon *exactly as they are* to perform the TE in a reliable way conducive to executing its epistemic function. Ideally, the result of the TE would be the same whether Bohr uses metaphorical home constraints, or he imagines a "true" photon, "actual" spacetime, etc. What I mean is that if the metaphorical home constraints are approximately what they aim to represent, then the TE can be reliably and justifiably performed, *as if* the TEer is imagining the "true" thing. This is reminiscent of Kind's reality and change constraints, which need not be infallible to remain epistemically relevant. In the same way, home constraints and away constraints need not be infallible to maintain their epistemic relevance; the TEer must be aimed at getting things right for the metaphor to be justified. Consider Bohr once more. Had he imagined, say, that spacetime was like a solid sheet of metal and, say, that photons are classical particles that move slowly, then he is not aimed at getting things right; his imagination is not constrained in the right way. Further, if Bohr were to use a home constraint as a metaphor for an away constraint in this scenario, the metaphor would not be justified since the metaphorical home constraint does not approximate the away constraint. (Spacetime does not behave like a solid sheet of metal and photons are not classical particles that move slowly.) Ultimately, one can be justified in using home constraints as metaphors for understanding and applying away constraints insofar as they are aimed at getting things right; the home constraints must approximate the away constraint in a way that is sufficient to get the TE off the ground.

8.5 – Is this Special?

I have set out to show that TEs in physics are special since they ask the TEer to consider incompatible constraints. Is this phenomenon specific to physics TEs? I do not have the space to

conduct a field survey of TEs in other areas of the natural sciences, but I take it that the answer is no. However, it is certainly not the case that *all* TEs in the natural sciences have this feature. As I understand it, the natural sciences, in general, contain a diverse set of TEs, some of which ask the TEer to consider incompatible constraints and others that do not. For what is worth, all the physics TEs with which I am familiar require that the TEer consider home constraints and away constraints. Thus, while it might be the case that there are examples of TEs in other natural sciences that ask the TEer to consider incompatible constraints, it is not an essential feature of the TEs since (to my knowledge) there are examples of TEs in those areas that *do not* ask the TEer to consider incompatible constraints.

Take Temple Grandin's TE for example, which can be classified as an engineering TE. Grandin's imaginative process was constrained by home constraints; she imagined the dip vat having specific dimensions, the support rods being made of a particular material, etc. But there are no obvious away constraints on her imagination. She need not, for example, consider the fluid dynamics of cows wading through the liquid of the dip vat; that is not a necessary part of her imaginative project. Thus, asking the TEer to consider incompatible constraints is, at least, not an essential feature of TEs in engineering. Indeed, I take it that there are examples of TEs in each of the natural sciences (besides physics) that do not have this feature.

While all TEs are constrained by the home constraints, not all TEs are constrained by the away constraints, as we saw in Temple Grandin's TE. However, all TEs in physics that I have considered and encountered are constrained by both home and away constraints. This should be uncontroversial considering that, for TEs in physics to be imaginatively depicted and unfolded correctly, the TEer must appeal to underlying physics that goes beyond everyday beliefs and perceptual experiences. The imaginative unfolding, in which the TEer traces and describes the

execution of the imagined experimental arrangement, cannot be done correctly without an appeal to the physical theory which describes the unfolding of the imaginative experimental arrangement. The combination of home and away constraints is made apparent in the clock-in-the-box TE, in which Bohr stated that, in considering the TE, "it was essential to take into account the relationship between the *rate of a clock* and its position *in a gravitational field* well known from the *red-shift* of the lines in the sun's spectrum following from Einstein's *principle of equivalence* between gravity effects and the phenomena observed in accelerated reference frames" (my emphasis, Bohr, 226). The rate of a clock is a home constraint since it is familiar in everyday experience. Considering the clock's position in a gravitational field based on Einstein's principle of equivalence, however, is an away constraint since it is beyond our everyday beliefs and perceptual experiences. We have already discussed how Bohr might overcome the incompatibility of the imaginative constraints, namely, by using a home constraint as a metaphor for understanding and applying the away constraint.

Thus, as far as I can tell, physics TEs are special in that they are the only kind of TEs in the natural sciences which has an essential feature that asks the TEer to consider incompatible constraints on their imaginative projects. Of course, my suggestion is that this incompatibility can be overcome by using home constraints as a metaphor for understanding and applying away constraints.

9.0 – Conclusion

In this paper, I have developed a hybrid view of TEs that applies Kind's constraints-based approach to the imagination to El Skaf's account of TEs. I pointed out three critiques of El Skaf's account and explained how taking on a constraints-based approach resolves each of the critiques, thus strengthening El Skaf's account. Then, I discussed what explanatory and

epistemic work that constraints on the imagination do for El Skaf's account. I then argued that TEs in physics are special since they ask the TEer to consider incompatible constraints. I suggested that a way out of this incompatibility is for the TEer to use home constraints as a metaphor for understanding and applying away constraints.

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