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Intuitions in physics

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Abstract This paper is an exploration of the role of intuition in physics. The ways in which intuition is appealed to in physics are not well understood. To the best of my knowledge, there is no analysis of the different contexts in which we might appeal to intuition in physics, nor is there any analysis of the different potential uses to which intuition might be put. In this paper I look to provide data that goes some way to giving a sense of the different contexts in which intuition *is* appealed to in physics. As I note in the conclusion, there is still much work to be done but I hope that the work here provides us with a first step in the journey to properly understand the use to which intuitions are put in physics and science more generally.

Keywords Intuition · Physics · Philosophy of science

1 Introduction

The aim of this paper is to explore the role played by intuitions in physics. This terrain is not entirely new. There are prior discussions of intuition and the role that it plays in science in general and physics in particular. What I hope to do here, however, is offer new perspective on the role(s) played by intuitions in physics. In this introductory section, I will (crudely) sketch two ways in which intuition has been discussed previously in literature on the philosophy and history of science. I don't claim that the sketch is exhaustive. However, what the sketch offers us is a sense both of the background and of why the present study is both interesting and useful.

The first part of the introduction describes a broadly Kantian treatment of intuition in mathematics and science, that focuses upon discussion of the claim that

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intuition (of a very particular sort) is *necessary* in mathematical and physical sciences. The second part of the introduction focuses upon a debate well thumbed in the history of science, concerning the role that was played by the concept of *anschaulichkeit* in the physics of the early 20th century.

1.1 Kant, intuitions and mathematics

Perhaps the first sustained discussion of the role of intuition in science generally, is due to Kant. Leaning on both Friedman and Parsons, we can draw out a distinction from this Kantian project—the distinction between an intuition *that* p and an intuition *of* p.[1] In particular, in the mathematical sciences there is an obvious difference between intuiting *that* something is the case—for instance, intuiting *that* the interior angles of a triangle sum to 180 degrees—and having an intuition *of* something. Intuition *of* is 'a singular representation, that is a representation of a single object'.[2] This intuition *of* is taken to be akin to perception. It is this latter use of intuition—intuition *of*—that plays a substantial role in a Kantian (and Neo-Kantian) philosophy of mathematics and science, for it is intuition *of* physical objects *as* physical objects that is a necessary condition for the physical sciences; it is intuition *of* mathematical objects that is a necessary condition for the mathematical sciences.[3]

This may be somewhat surprising to some philosophers who may be more used to discussions of 'intuition' where the term is taken to mean something more like 'what we take to be true at the outset of inquiry', which seems to be an instance of *intuition that*.[4] Nonetheless, *intuition of* certainly appears to make appearances in subsequent mathematical works and discussions of the role intuition might play in mathematics. For instance, Godel famously claimed:

> …despite their remoteness from sense-experience, we do have something like a perception of the objects of set theory, as is seen from the fact that axioms force themselves upon us as being true. I don't see any reason why we should have less confidence in this kind of perception, i.e. mathematical intuition, than in sense-perception (Godel 1964, p. 271).

Borrowing from Parsons, we can be explicit: 'Godel does…regard mathematical intuition as significantly like perception.'[5] Perhaps, then, we can say that *intuition of* is *necessary* for physical inquiry.

I do not intend to make a stand, here, on whether or not *intuition of* is a necessary condition for physical and mathematical inquiry. The type of intuition with which I am concerned is, I think, *intuition that*. Thus, I do not intend to take up the issue of whether or not we must have *intuitions of* physical or mathematical objects. My concerns are focused upon the ways in which physicsts use their *intuitions that* in their

[1] Freidman (1990), Parsons (1979, esp., pp. 147–148).

[2] Op. cit., p. 147.

[3] See, inter alia, Freidman (1990, p. 213).

[4] Cf. remarks in Parsons (1995, p. 57).

[5] Op. cit., p. 61.

theorizing; I am concerned with, for instance, the *intuition that* a particular theory is true, or the *intuition that* a particular outcome will be generated by a given experiment. This is not to say that the issue of whether or not *intuitions of* are required for inquiry, is uninteresting; it is merely to note that there are two issues here and that I am not concerned (in this paper) with what role (if any) is played by *intuition of*.

Similar concerns apply to another treatment of intuition, one that also seems to describe intuition playing an important role in theory formulation. Einstein offers a report of the role that intuition plays in the development of the mathematical components of physical theories.

> …the supreme task of the physicist is the discovery of the most general elementary laws [axioms] from which the world-picture can be deduced logically. But there is no logical way to the discovery of the elementary laws [themselves]. There is only the way of intuition, which is helped by a feeling for the order lying behind the appearance, and this Einfuehlung is developed by experience.'[6]

Einstein's use of 'intuition' here, *might* be taken to be an instance of intuition *of*—he is speaking here of intuiting the laws, not *intuiting that* any particular thesis is true.[7] If that's right, then though interesting to hear Einstein repeating a thesis that seems Kantian in origin, it does not tell us anything about the variety of ways in which physicists might appeal to *intuitions that*. Since it is these *intuitions that* which are of concern to me here, I shall set aside this interpretation.

However, if I am wrong to interpret Einstein's report as an instance of *intuitions of*, then how does that bear on what follows? Well, this remains a report only of Einstein's introspections of his intuitions and, powerful as these intuitions surely were, to map the uses to which *Einstein* introspected that he put intuition is not necessarily to map the full range of uses that intuitions are put to in physics. Since it is the latter in which I have an interest, this self-report, though interesting, is not terribly enlightening. So, although the act of introspection may yield useful data upon some cases, it is hard to see how this will help us to develop a *full* understanding of the uses of intuition in physics. What we need, if we are to more fully understand scientific practice and the methodology deployed by practicing scientists, is some sense of the range of different uses to which practicing physicists put their intuitions.

1.2 Anschaulichkeit

There is a concept that has been subjected both to some wider study in the philosophical literature and that seems close to that of intuition: *anschaulichkeit*. The *intuitions of* that we described above, are, we said, considered *necessary* for physical theory. We cannot scientifically engage with the physical world unless we have intuitions *of it*; we

6 Einstein (1981, p. 12).

7 So far as I can tell, Poincare takes a similar position to Kant (though the details are distinctive). As Folina (1994, p. 222) puts it, for Poincare: '[t]he intuition of an n-dimensional continuum is that which makes brute sensations into conceptualizable experiences. This seems to capture explicitly the spirit of Katn's notion of the form of sensibility.'

cannot engage in mathematical theorizing unless we have intuitions *of* mathematical axioms, and so on. In contrast, as we shall see, *anschaulichkeit* at least *seems* to be deployed in the matter of judging when a theory is correct.

The German word *anschaulichkeit* has a rich history in the history of science—particularly in issues surrounding the development of quantum mechanics at the start of the 20th century. The term is most frequently translated as meaning ‘visualizable’, though is (notoriously) hard to translate precisely and is sometimes translated as meaning something very similar to ‘intuition’[8]; other times it is translated as meaning something akin to ‘intelligible’ and has a close connection to the English terms ‘clarity’ and ‘insight’.[9] Regardless of the *proper* translation of the term, it plays a rich role in the history of scientific practice and has a close connection to intuition. Let us consider some details of the case.

The evolution of quantum theory in the 1920s called into question whether or not a theory’s being *anschaulichkeit* (in the sense of *being visualizable* in space and time) was desirable, or not. On the one hand, we find the attempts of Schrodinger to articulate the core of quantum theory and atomic structure in such a way that the resulting theory and models would be *anschaulichkeit*: visualizable in space and time. For instance,

> we cannot really alter our manner of thinking in space and time, and what we cannot comprehend within it we cannot understand at all. There *are* such things—but I do not believe that atomic structure is one of them.[10]

Taking a different path, we find the likes of Pauli. For instance,

> I consider this certain—despite our love of our good friend Kramers and his colourful picture books—‘and they children, they love to listen.’ Even though the demand of these children for *Anschaulichkeit* is partly a legitimate and healthy one, still this demand should never count in physics as an argument for the retention of fixed conceptual systems.[11]

Heisenberg is less subtle. In a letter to Pauli he writes:

> What Schrodinger writes about *Anschaulichkeit* makes scarcely any sense, in other words I think it is bullshit [*Mist*].[12]

I don’t want to pursue the vexed question of how to (re-)interpret *anschaulchikeit*. Such a project is substantial in itself.[13] For a number of reasons, such work is orthogonal to the aims of the current project: the work is important; it is also important to set it to one side, here.

As we have seen, the debate between Schrodinger, Pauli, Heisenberg (et al.) is a debate concerning constraints on a *good* theory; it is a debate about what properties

[8] See, for discussion, Gieser (2005, p. 68 fn 228).

[9] See, e.g. de Regt (1997, p. 462).

[10] Schrodinger (1928, p. 27).

[11] Pauli (1979, p. 188).

[12] Heisenberg (1926, p. 221).

[13] de Regt (2001) offers an excellent study.

a theory *should* have. According to Schrodinger, a good theory is one whose models *should* be *anschaulichkeit* and hence visualizable in spacetime. According to his opponents, this is not the case. This disagreement is therefore a debate about what kinds of properties physical theories *should* have. Such a debate doesn't tell us how, as a matter of fact, practicing physicists deploy their intuitions. Since the target of the current paper is an account of the *actual* ways in which physicists deploy their intuitions, the debate as to whether or not a theory *should* only be accepted if it is *anschaulichkeit*, is of only tangential relevance to the current project *even if* it turns out that there is an intimate connection between a theory's being *anschaulich* and it's being intuitive.

To re-emphasize a point made already: my aim in this paper is not to talk about the historical uses of intuition, or the role that the capacity to visualize may play in developing and refining our best physical theories. Rather, my aim in this paper is to explore whether intuition is deployed in contemporary physics, and, if it is, the *ways* in which contemporary physicists make use of their intuitions (*that*).

2 Are intuitions used in physics?

My first aim in this paper is to answer this question. This aim might seem rather trivial. One might think it obvious, particularly given the forgoing survey, *that* intuitions are used in physics. However, we should keep in mind that the focus of the paper is *intuition that*. Nothing in the preceding has established that physicists use intuitions of this form and seemingly obvious theses can be false. Since it is an open empirical question as to whether or not physicists use their intuitions (*that*), we should look at some data.

There are a number of ways in which one might attempt to ascertain whether or not intuitions are deployed in physics. The route taken here is to interrogate a large number of scientific papers and look for the use of the term 'intuitive'. There are a number of potential pitfalls with such an approach, some of which are discussed in the course of the paper. One worth mentioning at this stage is that this approach may actually underplay the extent to which intuition is involved in physics. There may be some cases in which intuition is deployed in the arguments deployed by physicists, despite the fact that none of 'intuitive' or 'intuition' appear. Although I concede that this is a weakness of the current approach, it's a weakness I'm happy to bear given the wider dialectic. The presumption in a significant portion of the philosophical literature seems to be that science proceeds either without recourse to intuition, or that the appeals to intuition that are made are of only one very specific kind. By showing the range and extent of the use of explicit *mentions* of intuition, I hope to do something to overturn that presumption. If it turns out that the *implicit* use of intuition then far outstrips the uses of intuition that I identify here as explicit, then so be it.[14]

[14] I also do not chart, here, the extent to which intuitions are deployed in consideration of thought experiments in the sciences—for the most part, because in none of the cases that I read were intuitions being discussed in this context. See, Reiner and Burko (2003) for discussion of the role of thought experiments in physics.

Another weakness of the current approach is that it takes physicists self-reports seriously and there might be a concern that we ought to avoid doing so. For instance, we might worry that although physicists *report* as using their intuitions (in the ways described in more detail in Sect. 3), they are not in fact—at the point of inquiry—*using their intuitions*. Instead, when it comes to completing the final report that we see in a journal, the word 'intuition' is inserted. Were we to *interview* physicists, we would find that they are not using their intuitions in each of these scenarios. The fact that this paper makes no attempt to *interview* subjects or examine their behavior 'in the lab' in any way, means that we cannot be entirely confident that scientists really are using their intuitions.

I accept that this is a weakness of the current project and make no claims to certainty. My thought is simply this. This paper presents *prima facie* evidence that scientists are using their intuitions. It would seem that, in the face of this *prima facie* evidence that physicists do use their intuitions in a wide range of different contexts, and to a number of different ends, the onus is on my opponent to show that the term 'intuition' is not being used to correctly report the behavior of physicists. This paper is only intended as a first-step in the analysis of the role played by intuition in physics—a point I return to in the conclusion.

To be clear on another matter: it is no part of the aims of this paper to suggest that physics *should* make recourse to intuitions or even that it is permissible for *good* physics to make recourse to intuition. It is entirely in keeping with the aims of this paper that we conclude that, although many practicing physicists do make recourse to their intuitions, this is a deplorable epistemic practice that is in need of stamping out. The aim of this paper is to establish that we have good *prima facie* evidence for thinking that it is relatively common practice for practicing physicists to use their intuitions.

I should also be clear that there may well be a significant difference between the 'folk intuitions'—unreflective judgments of commonsense—and the intuitions of physicists—post-theoretic judgments, born of great experience. I'm not too concerned by this. Were I, for instance, looking to defend the way in which some metaphysicians appeal to intuition-as-common-sense to support their views, then this might be a problem worth devoting our attention to.[15] However, that is not the aim of the paper. The aim of the paper is to show that intuitions are used (quite explicitly) in physics and to give a sense of the ways in which intuition is appealed to and the frequency of those appeals. The other project—of connecting this material to work on intuitions in metaphysics and other areas of philosophy—must wait for another paper, if it is to be carried out at all.

The scientific peer review process often has publication in a leading journal as an important end-point for a tightly focused research project. Were appeal to intuition no part of scientific practice, it is reasonable to assume that talk of intuitions would not appear in peer reviewed scientific papers.

The journals published by the American Physical Society include many of the leading publications in physics, with high impact factors (2010 impact factors[16] listed in

[15] See, e.g., Markosian (2004, p. 48).

[16] For the uninitiated: the impact factor of a journal is an indication of the number of times that its articles are cited. To calculate the impact factor of a journal in 2010, one would count the number of citations of

parentheses after the journal title, where available[17]): *Physical Review Letters* (7.621), *Review of Modern Physics* (51.695), *Physical Review A* (2.861), *Physical Review B* (3.772), *Physical Review C* (3.416), *Physical Review D* (4.964), *Physical Review E* (2.352), *Physical Review X, Physical Review Special Topics: Energy Beams* (1.661), *Physical Review Special Topics: Physics Education Research* (2.302), and *Physics*.

But we must be cautious. *Physics* is dedicated to highlighting research in physics; *Physical Review Special Topics: Physics Education Research* is dedicated to exploring pedagogical issues around the teaching of physics. Thus, one *might* take the view that neither should be included in a search looking for the ways in which intuitions are deployed in physics itself—rather than the highlighting of particular issues in physics or the teaching of particular topics in physics. One might also worry that, without data concerning its impact factor, *Physical Review X*, which is published solely on-line and is an 'open access' journal, should be excluded from being counted as a journal that is representative of the field. I'm not persuaded by these concerns. However, in the interests of leaving the findings prone to as few objections as possible I have not analyzed the use of intuition as it appears in any of these three journals.

The search carried out took the following parameters. The key word 'intuitive' was searched for in each of *Physical Review Letters, Review of Modern Physics, Physical Review A-E*, *Physical Review Special Topics Energy Beams*. To get a sense of the proportion of research that at least *appears* to be making some recourse to intuition, a second search was carried out to obtain the total number of papers published in these journals. The results are tabulated below. It should be recorded here that a search for 'intuitive' returned mentions of the term 'intuitive', but also the terms 'intuition' and the term 'counter-intuitive'. Because both terms indicate an appeal to intuition *in some way*, I have counted these as an appeal to intuition in Table 1.

The data is suggestive The percentage of papers that make recourse to intuition, in some fashion or another, is roughly steady at between 7.2 and 9.3 %. Although we do not yet have a complete data-set beyond 2010, there seems to be a steady increase in the proportion of papers that make some recourse to 'intuitive'.[18]

So *prima facie* this gives us some reason to think that intuitions are used in physics. If (roughly) 9 % of papers in these illustrious physics journals used the word 'intuitive' in 2010, then we have some reason to think that intuitions are being used *in some way* in physics.

Footnote 16 continued
papers from that journal that appear in 2008 and 2009, and then divide that number by the total number of items that appeared in the journal in 2008 and 2009. I don't claim for an instant that impact factors are an infallible measure of the importance of a given journal, though particularly high impact factors do seem to be associated with journals in the sciences that are especially well regarded—e.g. *Nature* and *Science*. My more meager claim is that these impact factors *suggest* to the non-physicist that these are internationally significant journals. To give the reader some comparison with philosophy: the *British Journal for the Philosophy of Science* has an impact factor of 1.048; *Synthese* has an impact factor of 0.676—again, as taken from the journals' websites.

[17] These were taken from journal homepages.

[18] It is possible that some of the uses recorded in these papers are instances of *intuitions of*. However, as we shall see in the sections that follow, all of the uses of intuition that I am able to pin-point seem to be instances of *intuitions that*. That being the case, I think that we have reason to be skeptical of the claim that *intuitions of* are being reported in physics papers—though I don't claim that evidence to be conclusive.

Table 1 The proportion of articles mentioning intuition

Year	Total number of items	Number of items returned in a search for 'intuitive'	% of papers that include 'intuitive'
2001	15175	1129	7.44
2002	15709	1138	7.24
2003	14987	1164	7.77
2004	16433	1195	7.27
2005	18314	1477	8.06
2006	17964	1456	8.10
2007	17921	1409	7.86
2008	19205	1649	8.58
2009	18801	1666	8.86
2010	19192	1776	9.25

But the question remains of how far we should endorse this *prima facie* appealing line of thinking. There are a number of ways in which an opponent could reply. For instance, one might speculate that the uses of 'intuitive' that are appearing in scientific journals appear in a very particular context (or contexts) and that in such a context it's perfectly clear that physicists aren't *using* their intuitions, so much as mentioning the intuitions 'of the folk' to set them aside. One can easily imagine a case in which a physicist describes a result or theory as being quite surprising and hence, 'not very intuitive or commonsensical', but then also goes on to describe the theory is true.

What this reply correctly identifies is one of the weakness with such a broad approach. The trouble with any such broad analysis as this is that it tracks only the number of times that some particular term is deployed; it fails to reveal to us any of the details of the *way* in which the term is being deployed. If we're to meaningfully explore the role of intuitions in physics, we'll need a detailed sense of the various different ways in which intuitions are being appealed to.

There is an obvious way to remedy this. The remedy is simply to list all of the different ways in which 'intuitive' is being used in the above. But as obvious as this remedy is, it is also a little less than practical. Tracking the several thousand appearances of the term is well beyond the scope of this paper.

3 The many and varied uses of intuition in physics

The next search carried out took the following parameters. Having performed the keyword search described above, a number of the items returned in that search were read, in order to get a feel for the variety of ways in which it is common to see intuition deployed. Where particular types of use of the term 'intuitive' were made again and again, these were noted. The common features of these uses were recorded. In the section that follows, I specify these. To be clear: it is no part of the claims made here that this is an exhaustive list. As we shall see in Sect. 4, there are a variety of uses. Rather, in this very informal search, these uses were the ones found to be most common.

3.1 Intuitive results

To begin, there are a number of cases in which a *result* is described as being intuitive. Here is García de Abajo (2010, p. 267—my italics)

> In practice, electron beams are polychromatic. However, a trivial extension of the above formalism for typical beams with random phases between different energy components leads to the *intuitive result* that the loss probability is the average of Eq. (17) over the incident beam spectrum.

Second, here is another case, this time involving Quantum Cryptography. Let us consider three protagonists Eve, Bob, and Alice.

> … if Eve performs a measurement providing her with some information …, then, because of the perturbation, Bob's information is necessarily limited. … Suppose Alice sends out a large number of qubits and that n are received by Bob in the correct basis….the sum of Eve's and Bob's information per qubit is less than or equal to 1. This *result is quite intuitive*: Eve and Bob cannot receive more information than is sent out by Alice![19]

Some of the mathematics has been removed from the above—simply to avoid districting the reader (and intimidating the author). But the emphasis being given by 'intuitive' seems to indicate that the authors think a particular *result* intuitive.

Third, and finally, here is another case, this time from the study of the way in which liquids behave in close proximity to a solid wall.

> we have used TIR-FRAP to directly probe the velocity of a simple liquid within 80 nm from a solid wall. A series of experiments with hexadecane sheared against various modified sapphire surfaces have shown that the boundary condition for the fluid velocity depends both on the interfacial energy and on the surface roughness at molecular scales, in agreement with *intuition*… and MD simulations.[20]

Once more, this seems to be a case in which intuition is being applied to a result.[21] Three aspects of these uses are worth bringing out.

First, although this is only very tentative, in each case, there seems (to this reader, at least) to be some positive import attached to describing the result as intuitive. More fully, they seem to imply that it is *good* that the result accord with intuition.

Of course, there is no reason given for us to think that it *is* a good thing if the result accords with intuition and it may be that I'm reading in an implication that simply isn't intended. Nonetheless, I find it very hard to read the quoted passages without taking away the message that the match between the checking and the mapping of the abstract theoretical structure is a good thing.

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[19] Gisin et al. (2002, pp. 186–187—my italics).

[20] Pit et al. (2000, p. 983—my italics).

[21] See, inter alia, DeWolfe and Giddings (2003, p. 066008-1), Bunandar et al. (2011, p. 104005-7), and Bergvall et al. (2011, p. 155451-6).

To be very careful, I don't want to read too much into this. I don't want to say, for instance, that this shows that all of physics proceeds by nothing more than whim and intuition. The point intended is only very narrow. In the passages quoted above, it seems (to me, at least) that the use of 'intuitive' is intended to indicate that the results accord with intuition, *and that is a good thing*.

3.2 Intuitive explanations/theories

What each of the aforementioned uses of 'intuitive' or 'intuition' has in common is that they describe a *result*, not a *theory* as being intuitive. As we shall now see, it is common for particular explanations to be described as intuitive. Since, I assume, these explanations are parts of theories, and it is the theories that do the explanatory work, this is a shorthand way of saying that a theory is intuitive.

In the following case, we see mention of both the idea of an 'intuitive picture' and the idea that a theory may be intuitive. I return to the case of 'intuitive picture', below.

> Under what conditions might one expect to find more complicated superconducting states becoming energetically favorable? An intuitive picture is linked with the existence of a strong on-site Coulomb repulsion. This favors the formation of a Cooper pair with a large amplitude of the wave function at finite distance, rather than at the origin, in order to reduce the Coulomb repulsion energy. This can be achieved by the electrons in the pair having finite relative orbital angular momentum. Since a strong on-site repulsion is a key ingredient in strong electronic correlation, this accounts in a physically *intuitive* way for the close relationship between strong correlations and unconventional superconductivity. These considerations apply even when the net attraction among the electrons is attained by spin fluctuations.[22]

This may require some unpacking. What is required is an explanation of the close relationship between strong correlations between pairs of electrons and unconventional cases of superconductivity. The view taken by Mackenzie and Maeno (M&M), in the above, is that this accounted for by a strong on-site repulsion. This explanation is intuitive. Because this explanation is a part of a theory of superconductivity, I assume that this means that M&M are committed to the theory being intuitive, also.

3.3 Intuitive pictures

The next sense of 'intuitive' deployed refers to pictures. Let us return to the case cited in 3.2. Thus,

> Under what conditions might one expect to find more complicated superconducting states becoming energetically favorable? An *intuitive picture* is linked with the existence of a strong on-site Coulomb repulsion. This favors the formation

[22] Mackenzie and Maeno (2003, p. 660—my italics).

> of a Cooper pair with a large amplitude of the wave function at finite distance, rather than at the origin, in order to reduce the Coulomb repulsion energy.[23]

In another paper we find,

> As discussed above, the electronic charge density in any real material is more complex than that implied by the muffin-tin approximation. Inside the muffin tins the charge density is not perfectly spherical, and in the interstitial region the charge density is not constant. Instead, it is often common to find a buildup of charge between neighboring atoms, where there is significant bonding. This same effect can be *intuitively pictured* as a consequence of overlapping atomic charge densities, which also naturally leads to a buildup of charge between neighboring atoms.[24]

Finally:[25]

> Rotational motion is the most prominent mode in nuclear structure, and it appears in a large number of nuclei. In this Letter, we shall discuss the rotational motion in the ground-state (rotational) band of even-even nuclei with relatively low rotational frequency. The *intuitive picture* of such low-frequency nuclear rotation is that the nucleus is deformed in an ellipsoidal shape, and this ellipsoid rotates about an axis.[26]

So, this first use of 'intuitive' to describe a picture seems, from context, to mean something along the lines of a 'picture that seems right' or, a 'representative that seems correct'. The ubiquity of talk of 'pictures' in physics is unsurprising given the similar ubiquity of graphical representations and models and the historical importance that has been attached to the visualizability of a particular physical model of reality.[27]

3.4 Intuitive understanding

It is reasonably common to see particular types of understanding described as intuitive. In a discussion of the chemical composition of Ultra High Energy Cosmic Rays (UHE CR), Ahlers and Taylor,

> discuss exact analytic solutions of the evolution equation of ultrahigh energy cosmic ray nuclei. We introduce a diagrammatic formalism that leads to a systematic analytic expansion of the exact solution in terms of second order effects of the propagation. We show how the first order corrections of this expansion can improve the predictions of secondary spectra in a semi analytical treatment.[28]

[23] Mackenzie and Maeno (2003, p. 660—my italics).

[24] Rehr and Albers (2000, p. 663—my italics).

[25] See, inter alia, Swingle (2010, p. 050502-1), Shen (2007, p. 179702).

[26] Otsuka (1993, p. 1804—my italics).

[27] See, de Regt (2001). There is an obvious connection here to *anschaulichkeit*, discussed in Sect. 1.1. Teasing out the precise nature of this connection is a project for another day.

[28] Ahlers and Taylor (2010, p. 123005-1—my italics).

In the conclusion of the paper, they summarise some of their findings:

> Through the simplicity of our approach, the speed with which it may be implemented, and the *intuitive understanding* it introduces, our analytic method is anticipated to be of great benefit as a tool for future UHE CR investigations.[29]

This seems to be a case where, *that* the particular understanding generated is intuitive, is in and of itself a good thing. It certainly seems as if the intuitive understanding introduced is taken to be a part of the 'great benefit' mentioned. Similarly, in Franzosi *et al.*, we find in the abstract a description of the project:

> We discuss the possibility of exponential quantum localization in systems of ultracold bosonic atoms with repulsive interactions in open optical lattices without disorder. We show that exponential localization occurs in the maximally excited state of the lowest energy band. We establish the conditions under which the presence of the upper energy bands can be neglected, determine the successive stages and the quantum phase boundaries at which localization occurs, and discuss schemes to detect it experimentally by visibility measurements. The discussed mechanism is a particular type of quantum localization that is *intuitively understood* in terms of the interplay between nonlinearity and a bounded energy spectrum.[30]

Once more, this is case where a particular understanding is described as intuitive and—at least so it would appear—that the understanding *is* intuitive would appear to be being lauded by the authors. Finally, Kitagawa *et al.* describe their project as follows:

> Topological properties of physical systems can lead to robust behaviors that are insensitive to microscopic details. Such topologically robust phenomena are not limited to static systems but can also appear in driven quantum systems. In this paper, we show that the Floquet operators of periodically driven systems can be divided into topologically distinct (homotopy) classes and give a simple physical interpretation of this classification in terms of the spectra of Floquet operators. Using this picture, we provide an *intuitive understanding* of the well-known phenomenon of quantized adiabatic pumping.[31]

Exactly as before, this appears to be an instance of a particular understanding being intuitive and this being a virtue of the theory.

3.5 Getting intuition

This next way in which intuition is described is a little odd—at least, it sits a little outside the way in which we (as 'the folk' or as philosophers) might normally speak

29 Ahlers and Taylor (2010, p. 123005-12—my italics).

30 Franzosi et al. (2010, p. 063620-1).

31 Kitagawa et al. (2010, p. 235114-1—my italics).

of intuitions. I would not, for instance, speak of needing to think about something, or observe matters repeatedly, in order to 'get some intuition' about a subject matter—at least, not typically. That may, of course, be nothing more than a product of the fact (if indeed it is a fact) that folk intuitions do not vary substantively over time. Once we have our intuitions about a domain—and once we reach adulthood let us suppose that we have intuitions about all of the domains that we typically need—we do not then need to go out and acquire more of them. Nonetheless, it is not uncommon to see physicsts talking of 'getting intuition', or, as we shall see, 'building intuitions' from a particular case.

To give some examples of this:

> The theory of curved helium films also helps *build intuition* for the more general case of vortex lines con-fined in a bounded three-dimensional (3D) region[32]

Also,

> Although the behavior shown in Fig. 1 for each model has been reported in previous investigations …, for the sake of completeness and to *gain physical intuition* we summarize and explain these results here.[33]

Finally,

> To *get a better intuition* of the physics behind the proximity effect, we start with an analysis of the structure of the wave functions of the relevant states.[34]

3.6 Expectations

Finally, there are a number of cases in which physicsts will begin a sentence 'intuitively' and then go on to describe how they think a particular theoretical model will map onto a problem space. For instance,

> High-spin to low-spin transitions are often associated with structural changes. These magnetovolumic effects of prime importance for the structural stability of solids are related to the electron occupation of the crystal-field states. *Intuitively* one expects the d orbital extension, and thus the atomic volume, to be smaller in the low spin state than in the high-spin state.[35]

In addition,

> In magnetic memory devices, logical bits ("ones" and "zeros") are stored by setting the magnetization vector of individual magnetic domains either "up" or "down." The conventional way to record a magnetic bit is to reverse the magnetization by applying a magnetic field…. *Intuitively*, one would expect that

32 Turner et al. (2010, p. 1305—my italics).

33 Barreto (2010, p. 124020-4—my italics).

34 Sau et al. (2010, p. 214509-14—my italics).

35 Rueff and Shukla (2010, p. 869—my italics).

switching could be infinitely fast, limited only by the attainable strength and shortness of the magnetic field pulse.[36]

So far as I can tell, these are the primary uses to which intuitions are put in the literature.

4 Frequency

It still remains possible that, although each type of usage appears, occurrences of these types of use is so infrequent as to not warrant further comment. For instance, perhaps nearly all of the uses of intuition in physics are of the form ‘getting some intuition’. Maybe the other uses that I’ve mentioned are extremely peripheral, making up only a very tiny percentage of the use of intuition in physics.[37]

Even if that is not the case, any sensible analysis of the extent to which intuition is involved in physics ought to explore the relative frequency of these explicit mentions of intuition.

The journal with the highest impact factor, above, is *The Review of Modern Physics*. In 2010, 38 of its published 77 papers used the term ‘intuitive’. To try and get some sense of the frequency with which the various reports of intuition occur, I shall use these 38 papers—and the use to which they put the term ‘intuitive’—to highlight the frequency with which particular uses of intuition are put.

It’s worth getting clear on the fact that *The Review of Modern Physics* is an outlier. For one thing, unlike (for instance) *Physical Review A*, *The Review of Modern Physics* publishes review articles, that provide a review of recent work in physics. It is also true that with 38 of its 77 articles in 2010 being returned in a key-word search for ‘intuitive’ *The Review of Modern Physics* is well above the average in terms of the number of items that make reference to intuition. That might seem to give us two reasons to think that the data provided here is not of use: *The Review of Modern Physics* is not representative of the field because it has such a high Impact Factor; *The Review of Modern Physics* is not representative of the field because it has papers that contain so many mentions of intuition.

In response: I do not take Impact Factor to be an infallible guide to the significance of a particular journal. There are well known concerns with attaching significance to these ratings. However, a very high Impact Factor (over 50 in the case of *The Review of Modern Physics*) is worthy of note. Such an Impact Factor indicates that the work is not *out of step* with activity in the physics community. In some way, at least, papers in *The Review of Modern Physics* represent the views and practices of those working in the field. Since I am only look to establish *that* intuitions are deployed in physics and *that* the range of uses identified above are reasonably widespread, making recourse to *The Review of Modern Physics* is reasonable. Even if the uses recorded in *The Review of Modern Physics* are not a perfect match for the ways that intuitions are used in the

[36] Kirilyuk et al. (2010, p. 2733—my italics).

[37] It’s also worth making the point again that this is only defeasible evidence that physicists are using their intuitions and it is a matter that could, and perhaps *should*, be further investigated using interviews and perhaps also by studying the behavior of specific research groups.

wider literature, it is still the case that, with such a high Impact Factor, the range and extent of use is an important part of physics.

Similar remarks can be made in response to concerns that *The Review of Modern Physics* is a statistical outlier—containing a high proportion of papers that make recourse to intuition. *Even if* papers in *The Review of Modern Physics* are not representative of the ways in which intuition is appealed to in *other* physics journals, the mere fact that *The Review of Modern Physics* has such a high Impact Factor, and so can be seen to occupy such a central position in the field, tells us something that is of interest. It may then be that we should not extrapolate from the proportion of uses of the term 'intuitive' as it appears in *The Review of Modern Physics* to a general conclusion about the proportion of the uses of the term 'intuitive' falling into each of the proscribed categories in all *other* Physics journals. Perhaps that's right. But remember: the reason for including this data is to establish that each of the uses described in Sect. 3 is significant to practicing physicists. By establishing the regular occurrence of these types of use in *The Review of Modern Physics* we go at least some way to establishing that this is so. Of course, further data on the frequency with which these uses occur in other physics journals would be interesting and useful to the wider project of understanding just how intuition plays a role in physical inquiry. It would not be a surprise, I take it, if it turned out that in different *parts* of physics intuitions were appealed to in different ways and with different frequency. There is no obvious reason to expect there to be a single homogenous practice on this score. If we can simply establish that the various different types of use described are common in *review* work, that then seems to be taken to be the corner stone of much other work, then that still serves to establish that, within physics, these different types of use of intuition are important and significant.

The papers that include a term returned by the key-word search are listed in the Appendix (at the end of the paper), and assigned a number. The number assigned to them in the appendix is then the number that appears in the 'references' column of the table. The table lists the various different types of intuition cited in Sect. 3 and details the frequency of their occurrence in each of the papers in question. The table also lists the specific point in the paper(s) at which that mention of intuition is made, in order that the reader is able to check the details for themselves.

In some cases, papers make more than one mention of intuition thus the total number of occurrences listed below is greater than 38. In some other cases, authors talk in such a way as to cross categories, for instance talking of 'getting an intuitive understanding'[38]. Where this occurs, this is double-counted as an instance of *both* a situation in which physicists are talking about getting intuition, and also a case in which they are talking of intuitive understandings. This seems apt since both categories are invoked in the language used by the physicists. This occurs in three cases and the case is marked in the 'getting intuition' row with a superscript 'd' to mark the fact that this mention of intuition is one that has already been recorded under another guise, in the row above.

Where a result was described as 'counterintuitive' this was listed as a physicist encoding their intuitions about a result—similarly, a counterintuitive explanation was recorded as an instance of a physicist recording their intuition about an explanation.

38 Clerk et al. (2010).

Where some piece of mathematics is described as intuitive, I record this as a theory or explanation of some phenomena but include the superscript ^{m}. Finally, there is a category included in the table of those uses of intuition that do not seem to fall neatly into any of the extant categories—'other uses'.

In all of the findings I have tried to minimize interpretation on my own part. For the most part, I have recorded something as a case of an 'intuitive idea' only if the physicist uses that exact form of words. In cases where I have engaged in interpretation, the item has a * following it. I have tried to steer clear of this since I do not want to pollute the findings by importing my own (plausibly theory laden) expectations; the observations should be laden with as little theory as possible. The rule that I have tried to follow is that if I am engaging in interpretation in order to classify a usage, then the use is recorded as 'other'. The reader is welcome to check items with a * to check their interpretations of my findings. To give a flavour of the sort of interpretive activity in which I've engaged: Albino describes a problem and then describes a solution to it as particularly intuitive.[39] The solution to the problem takes the form of a theoretical explanation of the phenomena. That being the case, this is classified as an intuitive explanation, though is marked with a * so that this interpretation can be checked. Later in the paper, Albino speaks of intuitive but untested assumptions.[40] Here, the language is not sufficiently clear for a *definitive* classification to be made, so this is listed as 'other'. If it is not absolutely clear that an interpretation is correct, it has been listed as 'other' (Table 2).

A number of points seem obvious and are worthy of discussion. The first—perhaps the single most obvious—is that the data is extremely messy. In Sect. 3 I defined some broad categories of the ways in which intuitions are deployed in the writings of physicists. It's something of a surprise, then, to find 46 instances out of the 125 cited, that fail to fall into one of those categories. The thought might be: these categories can't be much good at tracking actual usage if more than a third of all talk of intuition in these papers falls out-with the categories described.

That's certainly one way one could interpret this data, but I don't think that would be the right way to interpret it. So far as I can tell, the categories described are the most commonly occurring. The remaining uses to which intuition is put are something of a smorgasbord. For instance, there are three mentions of *arguments* being intuitive[41]; two mentions of *properties* being counterintuitive[42]. There are also mentions of models being intuitively very attractive[43] and measures being intuitive[44]. The reader is welcome to check the other uses for themselves. In some cases I suspect that they *could* be classified as falling within one of the categories, but to keep matters of interpretation to an absolute minimum I have not recorded them as such.

The problem, then, is not that the range of categories described is insufficiently precise. Rather, there appear to be a lot of uses that don't fall into any of the proscribed

39 Albino (2010, p. 2539).

40 Albino (2010, p. 2541).

41 Mitchell et al. (2010, p. 2846), Turner et al. (2010, pp. 1309 & 1310).

42 Chin et al. (2010, p. 2664).

43 Pradhan et al. (2010, p. 552).

44 García de Abajo (2010, p. 235).

Table 2 The range of intuitions

	No. of occurrences	References
Intuitive result	8	[1: p. 2498]; [6: p. 668]*; [12: p. 1785]*; [15: p. 217]; [16: p. 750]*; [16: p. 780]; [20: p. 2778]; [36: p. 2658]*
Intuitive explanations/theories	15	[1: p. 2539]*; [3: p. 343][m]; [6: p. 683]; [7: p. 180]*; [7: p. 183][m]; [12: p. 1769]; [12: p. 1771]; [14: p. 286]*; [14: p. 295]; [15: p. 235]; [18: p. 961]*; [27: p. 796]; [37: p. 1336]; [37: p. 1338]*; [38: p. 1960]*;
Intuitive picture	7	[19: p. 2294]; [21: p. 1044]; [24: p. 2850]; [38: p. 1963]; [38: p. 1967]; [38: p. 1978]; [38: p. 1980]
Intuitive understanding/intuitive way to think about	17	[3: p. 361]; [6: p. 671]; [6: p. 694]*; [7: p. 172]; [10: p. 1262]; [11: p. 1181]; [18: p. 951]; [19: p. 2295]; [19: p. 3018]; [21: p. 1068]; [22: p. 1136]; [29: p. 500]*; [31: p. 433]; [32: p. 1666]; [32: p. 1679]; [33: p. 2609]; [38: p. 1979]
Gaining intuition	16	[7: p. 171]; [7: p. 172][d]; [7: p. 174]; [9: p. 14]; [11: p. 1181][d]; [14: p. 287]; [14: p. 287]; [14: p. 302]; [17: p. 2217]: [21: p. 1051]; [27: p. 835]; [28: p. 1617]*; [33: p. 2609][d]; [36: p. 2663]; [37: p. 1305]; [38: p. 1960]*
Intuitive expectation	19	[1: p. 2490]; [1: p. 2491]; [1: p. 2498]; [3: p. 343]; [5: p. 666]*; [7: p. 181]; [14: p. 279]*; [14: p. 295]*; [19: p. 2297]; [20: p. 2733]; [22: p. 1123]*; [23: p. 1004]*; [26: p. 2676]*; [29: p. 527]*; [29: p. 540]; [30: p. 869]; [34: p. 454]*; [36: p. 2665]*; [37: p. 1343]*
Other uses	46	[1: p. 2492]; [1: p. 2541]; [2: p. 1954]; [3: p. 376]; [4: p. 1377]; [5: p. 1470]; [7: p. 173]; [8: p. 2157]; [8: p. 2173]; [10: p. 1265]; [10: p. 1272]; [13: p. 2102]; [14: p. 279]; [14: p. 283]; [14: p. 287]; [14: p. 287]; [14: p. 290]; [14: p. 294]; [14: p. 302]; [15: p. 235]; [15: p. 253]; [21: p. 1073]; [21: p. 1077]; [22: p. 1123]; [22: p. 1127]; [24: p. 2846]; [24: p. 2850]; [24: p. 2855]; [24: p. 2866]; [25: p. 1567]; [26: p. 2673]; [29: 514]; [29: p. 552]; [30: p. 892]; 31: p. 2612]; [34: p. 467]; [35: p. 905]; [36: p. 2645]; [36: p. 2650]; [36: p. 2662]; [36: p. 2664]; [37: p. 1306]; [37: p. 1309]; [37: p. 1310]; [37: p. 1314]; [37: p. 1328]
Total number of references	125	

The sum of the central column is 128, but three of these are instances of a use of intuition falling into more than one category. Thus, the total number of times the term appears in the papers is 125 and this is what is recorded in the data

categories because there are such a large number of ways in which intuitions seem to be deployed.

5 Concluding remarks

In this paper I set out to provide some evidence *that* intuition is used in physics and to give some idea of the extent and range of that use. The data provided here gives us good *prima facie* reason to think that intuition is used in physics. The tables provided give some account of the extent and range of that use.

However, the present study is only of limited value and can only sensibly be viewed as a first step into the study of the use of intuitions in physics. One question not broached here is the evidential value attached to these uses of intuitions; how bad *is it* if a theory or explanation is counter-intuitive? How good is it if a theory is intuitive? And, if these theories are good or bad in virtue of being intuitive or counterintuitive, of what value is this to a practicing scientist? Certainly, there are some cases where physicsts *seem* prepared to move from a given explanation/theory etc., x, being more intuitive than another, x*, to the conclusion that x is preferable to x*.[45] If that's right, then how (if at all) does this map onto the various ways in which metaphysicians value intuitive theories over their counter-intuitive counterparts? These are all questions that, with these results in hand, need to be pursued further.

It may also be worth repeating the kind of analysis recorded in Sect. 4 with a wider range of physics journals to see how the different types of usage appear in non-review, journals. And, in the interests of getting a feel for the role that intuitions play in science more generally, there is scope for a comparative analysis of the frequency and type of appeal to intuition in the other sciences. As noted in Sect. 1, further research should also be carried out to see whether or not practicing physicists recognize these distinct uses of intuition. We should engage in careful analysis—in the field. Interviews and studies of the behavior of working research groups would provide useful data.

Nonetheless, despite the tentative nature of the conclusions drawn here, the results are important. There is *no* other existing account of the extent of the use of intuition (*that*) in physics; there is no existing attempt to map the *range* of different uses to which intuitions (*that*) are put in physics. To be clear, this paper may only offer us a first step in providing such accounts, but first steps are important.

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