About the Meaning of „Understanding“ in Modern Physics

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Abstract

For nearly 100 years, physicists have been trying to „understand“ quantum physics. Up to today no satisfying answer could be given concerning the surprising behavior of nature, especially if looking into microscopic scales. This article identifies an approach towards an answer to the questions arising from the quantum physics effects, which are preposterous to common sense, by first going one-step back: “understanding” as a terminus is defined, as well as the terms analogy, model, concept and theory. In addition, the role of mathematics for the understanding of physics is addressed. This generates a more accurate basis. The limitations of our mind and senses due to the fact that we are living in a mesoscopic world are taken into account. This may lead to an identification of our limits of insight. As an outcome, models may have to be replaced by concepts to achieve a different level of understanding compared to the “classical” expectation.

1. Introduction

Compared to classical physics, up to the end of the 19th century the meaning of “understanding” physical phenomena has changed drastically. Classical physics has been understandable in a very intuitive and uncomplicated way. Our direct sensual experience allowed us to set up models with an unquestionable character. “Only” the right mathematical description had to be found. This stayed valid even for more complex phenomena such as electromagnetic waves – the model of “waves” and its mathematical description could be derived from an existing analogy in the fluidic area. Such comparisons have led to correct results and because of that the same mathematical methods can be used. That is why “models” have been widely accepted and taken as examples that show how to understand nature and their physical description. However, modern physics has revealed that things are not as simple as this.

Well known, but not always fully acknowledged, is the change in use of models when entering atomic physics. Obviously, simply extending our experience and sensual perception to smaller scales does not lead to a correct description of reality. The planetary model of an atom with electrons on defined orbits does not explain some very fundamental phenomena and measurements, starting with the stability of an atom. Accelerated electrons emit synchrotron radiation and therefore loose energy. So, how can it be that an atom is stable? Scatter experiments show a small, hard, positive core and a big “cloud” representing the electron presence. Therefore, it does seem to be similar to a planetary system. However, it does not behave as could be expected from our experience and the classical physical laws.

During the beginning of the quantum physics development, a way out of this contradiction was to introduce postulates, such as the following: electrons do not emit synchrotron radiation if they are on certain orbits [1]. That´s it. It is a fact, it is accepted as such, and there is no explanation to it. But if it is accepted, calculations can be made and the correct results can be derived. The problem still is, nothing has been understood at all.

Has there been any progress on this since the early 20th century? Yes, of course, a lot. Moreover, with absolutely astonishing answers. But, up to now, we did not make it to fully understand what is behind, for example, this simple question of the atom’s stability. Instead, we got used to it rather than learned to understand.

Before I will further discuss "understanding" in modern physics, I will try to answer the example of the question on the atom's stability from today's view – it is worth it.

The first step towards an understanding is to acknowledge that physics is not scale invariant. This means the physical description of phenomena needs to change with the scale, also saying, there is an absolute scale in the universe. This is not a guess or an assumption, it is evident. The maximum length in the universe is its diameter – around 90 billion lightyears or $8.5x10^{26}$ m. As minimum length the Planck length may be taken – $1{,}616 \cdot 10^{-35}$ m. At bigger scales, gravity and the structure of space and time are dominating physics. In medium scales, classical physics is the most suitable way to describe nature (emergent phenomena, not fundamental elements), and in small scales less than 10^{-6}m, quantum mechanics provides the best way to make calculations and predictions. These different theories are also needed because of the different forces and their area of domination – because of their different reach.

A clear indication of the non-existance of scale invariability in nature (physics) is the evidence of Heisenberg's uncertainty principle [2]. First step, well known of course, have been Planck´s investigations on the black body emission, leading to the exploration of the "help constant" h, better known as Planck's constant. In fact, on one hand, this fundamental nature constant then led to the "first quantization" and therefore to quantum mechanics. On the other hand, it became clear that the universe has an existing absolute scale, with a fundamental unit given by the Heisenberg uncertainty principle: $\Delta x \times \Delta p \geq \frac{\hbar}{2}$.

It may be interesting to note that in between the discovery of Planck's constant [3] and Heisenberg's uncertainty principle in 1927, in 1913 Bohr made his postulates to develop the earlier mentioned atomic model based on classical physics (except for these postulates). This model was able to explain the hydrogen atom and its basic spectrum quite well. The used mathematics is very easy to understand and very convincing, however, compared to "true reality", this model is completely wrong. We will keep this in mind for later discussion.

The uncertainty principle gives an astonishing answer on the question for the reason of the stability of atoms: the question is wrong. In more detail the answer is, you are not allowed to ask a classical question if quantum mechanics is to be applied. Because of the coupling of position and momentum there is simply no way of treating an electron like a particle in the specific case of being located as exact as an atoms diameter. The problem still is, just by knowing the question is wrong, you don´t know what the right question is to get a satisfying answer.

The follow-on developments have been the mathematical description of quantum mechanics by Heisenberg, Jordan and Born [4] and Schrödinger [5,6], in two different, but equivalent mathematical ways concerning the results. One of the main outcomes is, against the classical deterministic view, only predictions in the frame of probabilities are allowed in quantum physics. Later on Bell via his famous inequality [7] and following experiments gave proof that quantum mechanics is a correct mathematical description of nature (even if it is not a local realistic theory), compared to a theory with hidden variables to allow staying with determinism. Therefore: we don´t have a classical path for an electron, because of this Maxwells laws are not applicable, we don´t have electromagnetic radiation due to this → we do have a stable atom. That´s it in a nutshell.

Surely true. But somewhere on this track I think we lost the point to understand the nature of atoms and quantum physics. What we have is a valid and widely proofed mathematical description and the stunning finding, that the fundamentals of nature are preposterous to common sense. The theory of Quantum Electrodynamics is giving absolutely accurate results, compared to measurements with today's achievable measurement accuracy. This is today's situation. Question: is there any possibility to reach a point, that we would say „yes, I have understood quantum mechanics“ in a classical way - which means, we think we have got a few fundamental and basic ideas which clearly explain the experimental results? Or aren't we able to reach this point for some specific reasons? I will discuss in the following sections. But maybe, we are in the latter position, if you look for a famous physicist like Feynman: "I think I can safely say that nobody understands quantum mechanics." [8].

2. Definition of understanding

The terminus "understanding" is widely discussed within the philosophical society. As examples, I will just list two references: "Explaining Understanding", a collection on this topic from different contributors [9], and, specifically more relevant as this is dealing with quantum theory, the problem of realism and addressing the misuse of classical analogies for the explanation of quantum phenomena: [10].

However, even if the philosophical aspects of understanding are to be discussed, within this article we need a short and more practicable approach. I admit – I put a topic into two pages where plenty of books are available on, so this is just scratching the surface of this matter, but enough for the purpose.

I will start with the goal of physics:

"Physics is a science with the goal to understand inanimated nature." - If you agree to this, we obviously have to define what "understanding" means. "Physics is a science with the goal to identify mathematical laws, which describe nature in the correct way, and to use them for our purposes.“ - If your view on physics is like this, you are reading the wrong paper, you don´t have the main problem discussed herein at all. By the way – both definitions about the goal of physics are valid and split physics into two major contributors, namely fundamentals of physics and applied physics.

Therefore, before we can judge whether we understood something or not, we need this definition of what "understanding" is. And, as already mentioned by giving the references above, this is a bit tricky.

"Understanding" is neither a physical nor a terminus of any other exact science. This terminus cannot be measured, there is no percentage between "I think I have got a vague idea about the basic principle" and "I fully understood" to be determined. However, if we would like to conclude whether something has been understood or not, we need to define this terminus somehow in the way of exact science. In other words, we do have to make this terminus impartial.

One step forward is to use "explanation" for the definition of understanding. Ernest Rutherford said: "An alleged scientific discovery has no merit unless it can be explained to a barmaid."[11]. You can read it in the way, that you haven´t understood a physical theory as long as you are not able to explain the basic ideas in your own words. Even if also "explanation" is not a scientific terminus, it becomes obvious that understanding is a process, which enables you to reformulate a theory instead of just repeating it. Don´t read it in the strict way that it has to be formulated in a way that everybody has to understand it completely – sounds nice in some probably misattributed variants of the upper quote, but you cannot expect a six year old to understand the theory of electromagnetic fields for example, independent on how you explain it. And, if you would expect a six year old to understand it, it would need to give proof for this by explaining the theory to another six year old.

"Ability to explain" is just one part for the definition of understanding concerning physical theories. This is the subjective, very personal decision to be taken by each individuum itself whether he/she has understood or not. We cannot take away this personal aspect of this terminus, but we give a help to check for this personal judgment by asking the questions "are you able to explain the theory / this aspect of a theory to me in your words, and you think what you are telling me is fully correct?" And, moreover, “do you feel comfortable and well prepared if I start asking silly questions to you about the theory?”

Fortunately, there are other more objective aspects to judge whether a physical theory has been understood or not by the (physical) community. This is

- availability of a mathematical basis for the theory (a mathematical model)

- availability of a set of basic ideas, which are shared, explained, and discussed in the community

- availability of physical models and analogies to support understanding of basic ideas

- agreement in the physical community about what has been understood and how to interpret it

Some remarks:

1. Of course, before we can start discussions on the understanding of a physical theory, proof has to be given that the theory fulfills Poppers [12] definition of a scientific theory at all. In specific, out of a theory predictions for experiments or measurements are needed, to be able to falsify the theory. If this is not the case, we talk about a possibility in best case, but not about a scientific theory.

2. I will discuss in more depth the role of using models and analogies below. This is currently handled in a way that it leads to a lot of confusion.

3. Agreement in the physical community can be used as a measure on the degree of understanding reached. The better the agreement, the more we tend to accept something as “understood”.

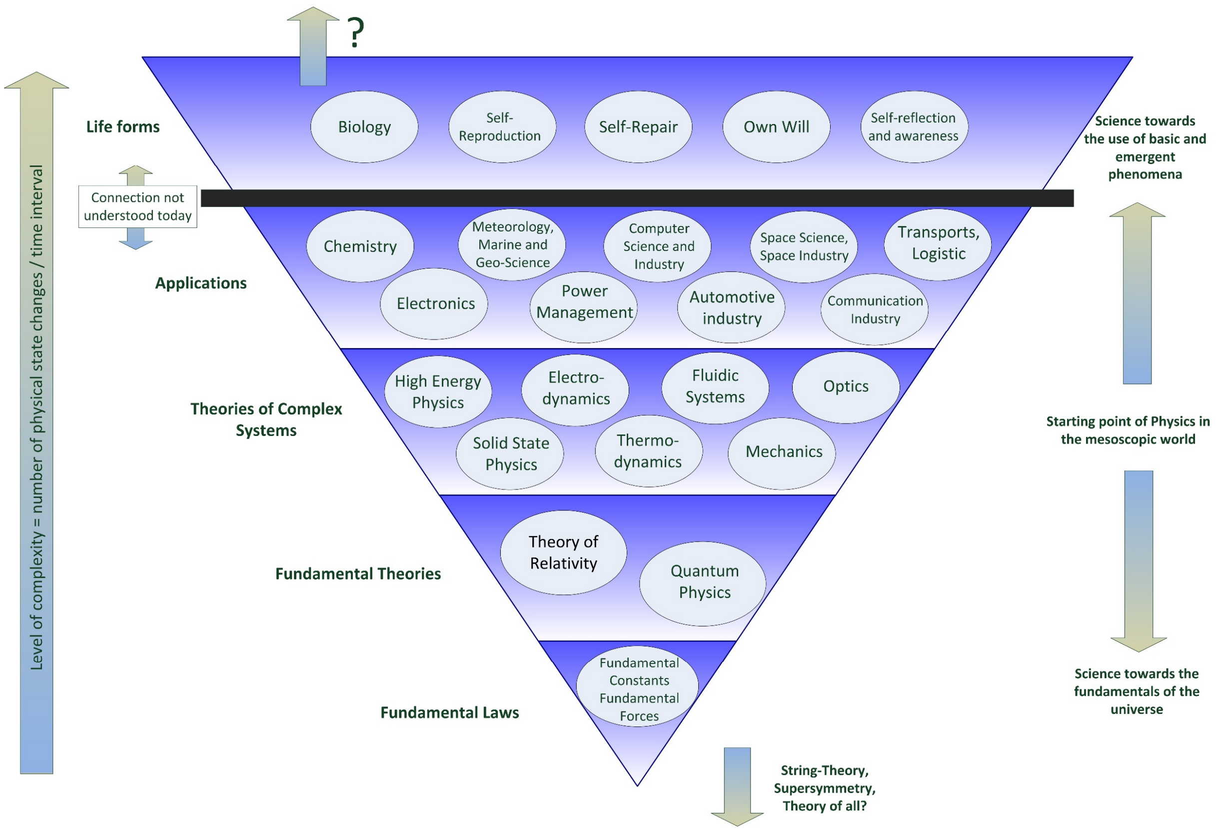

Fig. 1: Physics and Complexity

4. Complexity and understanding: Physical laws are arranged like an inverted triangle (Fig. 1). A few fundamental laws and natural constants describe simple and "pure" systems. More complex systems show emergent phenomena, which can be described in simplified (i.e. approximations for example) laws for the specific case. Asking the question "why is it like this" on a complex level is answered with reference to the level below. If this answer can be given, the phenomenon is understood. Interestingly, on a very complex level (live forms) we cannot give this answer today. Repeatedly asking this question, you end up at the fundamental level. The problems in defining "understanding" only occur on this fundamental level, as on higher levels something is understood if it can be logically explained with reference to the level below.

With this definition or maybe better clarification of understanding, even if it is not perfect, we are now able to apply it to modern physics.

3. Analogies, models, concepts, and theories vs. understanding

We have mentioned it beforehand: nature does not behave according to common sense. Is this really a surprise? In fact, it is not. It would be a surprise if nature would always be as we expect it based on our limited range of experience. Limited means: With our senses, we are only able to access directly the mesoscopic world in a limited scale. Our development according to Darwin just needed this range to "survive as the fittest". Therefore, our senses and the structures of thinking are useful for mesoscopic physics, but do not help if leaving this range [13]. By using objective measurement devices, we are able somehow to make microscopic as well as large-scale events and effects visible to the mesoscopic world of our senses. However, we tend to find explanations according to our sensual abilities. We invent analogies and models for a translation and loose the possibility to accept nature "as it is" by doing so. This is a famous way to make "understanding" nebulous and to lose track on the path to gain knowledge.

Analogies can be helpful, no doubt. However, they should be named as such. If I find different physical effects similar in some aspects, analogies may help in finding the right mathematics or may lead to reuse of mathematical methods already developed. Often, if a good analogy is found, a process called "it suddenly dawned on me" is started. This subjective sensation should not be mixed up with understanding – in the best case it can be a step towards understanding, but the proof is still missing.

To be more accurate, I will define "analogy", "model", "concept" and "theory" as understood within this paper.

Analogy:

An analogy does not claim to describe something "as it is". Analogy means: I can treat this (in some aspects) like another phenomenon, because it behaves like it or at least similar to it. An analogy usually connects two or more phenomena. It is an aid to classify phenomena, but per se no mean to understand them. If results of a calculation made according to an analogy are not according to measurements, usually it is said: the analogy does not cover this aspect. However, the analogy stays valid and can be used further for other cases.

Model:

If setting up a model, the idea is to propose a way how to understand phenomena. A model reflects reality as far as possible and without any contradictions. A proven model generally is the agreement in the physical society that a phenomenon has been understood. A model depicts a physical phenomenon. Remember: this is possible for emergent phenomena, but seems to be very complicated if talking about the fundamentals of physics. If results of a calculation made according to a model are not in line with measurements, the model is wrong and has to be dismissed or at least to be corrected.

A model consists of a set of ideas describing the physical topic, and the mathematical background to make calculations and predictions.

Concept:

The difference between a model and a concept basically is, that the concept does not depict the phenomenon. The basic ideas behind do not refer to any direct sensual experience in the mesoscopic world. As for a model, a concept is based on ideas about the physical phenomenon and a mathematical background. It is a closed logical system. If a concept exists, we could call it an “indirect understanding”.

Theory:

A theory is a valid description of physical phenomena. Usually a theory is based on analogies, concepts, or models. Calculations made based on a theory need to be in agreement with measurements as long as the range of validity of the theory is not exceeded (examples: Newtons mechanics as long as relativity is negligible, gas equations in a certain temperature range etc.). A theory primarily aims on the use of physical laws and interrelations, not on the understanding of the phenomena. Preconditions on a physical theory are well described by Popper (see reference above).

Applying these definitions on quantum mechanics means that we don´t have models yet, but only analogies and concepts. Bohr´s atomic model may have been a model intentionally at the very beginning, but immediately turned into an analogy to a planetary system. Acknowledging that the wave–particle duality is not a model, but two different analogies makes very clear, that Feynman´s citation above is right: nobody understands quantum mechanics today. However, we do have very good theories on this matter.

Let us stay for a moment with the particle-wave duality. We know that particles under certain circumstances behave like waves and vice versa. In fact, particles and waves are the same like a coin showing one or the other side (to use an analogy). By knowing both sides we obviously did not get the full understanding: a model is missing, which by using a set of basic ideas gives us “coin” instead of “two sides of something”. Astonishingly up to today, nobody was able to present a model like this. Probably this is due to the fact, that mesoscopic phenomena are emergent phenomena and that microscopic, fundamental phenomena are completely different to this. Therefore, we are not able to find a “closed” analogy in the mesoscopic world, which could be used as a starting point to develop a model. Our evolution hinders us to think different and to open up our mind for radically different approaches. Nevertheless, what we have is a concept, called the second quantization and quantum field theory. This concept removes the contradiction between particles and waves, it naturally introduces it as necessary outcome of very basic assumptions. “The rest of my life I would like to spend thinking about what light is.”, said Einstein, a man, who definitely gave proof that he was able to change the point of view for making progress in the understanding of physics. Obviously, his opinion was that the concept could be improved.

Being more precise in the usage of the terms analogy, model, concept, and theory would probably help to avoid misunderstandings in physics. Especially in trying to explain complex theories to ordinary persons, the use of analogies, often wrongly named as models, seems to be an inflationary trend. It looks like a correlation: the less known about the physics, the more use made of (misleading) analogies. Unfortunately, this has an effect on the way of thinking of the physical society as well. We have not understood quantum mechanics yet, so can it really be helpful if analogies like strings, branes and so on are used in a way as if they have a real equivalent in nature?

4. Mathematics vs. understanding

Again, nature does behave preposterous to common sense, as we have seen. However, there is a reliable fundament without any doubt: logic. If nature would not be strictly logic, mathematics would not work as the right tool to describe it. Indeed, up to now there is not a single evidence that nature does behave contrary to mathematical logic. It does not always behave as a mathematical theory is predicting, but in such cases, this is because the theory is not suited to describe this aspect of nature, and not because there is a violation of a logical chain.

Mathematics is a tool to make the logic of physics (nature) visible and usable. If we have not understood the logic of nature, any mathematical theory on physical phenomena is just a guess, or a possibility, if the results are fitting to observations. Mathematics by itself can only present a possible solution, but does not allow concluding that this solution is necessarily the one exactly reflecting the physical "truth". However, finding a mathematical solution or theory often helps in making progress on the way to understand the physics behind.

Mathematics is descriptive. For example, Keplers kinematics has been an empirical fit to Tycho Brahes measurements of planetary motion. The derived mathematical laws describe this motion very well, but there is no understanding, why the motion is as it is. To make this step, Newtons dynamics, starting with gravitational forces between masses, was needed. From there on it was possible to derive the Kepler equations very naturally, based on a simple model, or, if you like, based just on a few principles.

Therefore: a mathematical description of a physical phenomenon can never be an explanation for it! It seems to me that this might be mixed up sometimes in modern physics. So, if mathematical theories on physics are developed (this is needed and welcome without any doubt), they need to be coupled back to nature from time to time to give evidence that a theoretical construct has still its equivalence in nature. Mathematics is the most powerful tool for physics, but still a tool. A proven mathematical concept correctly describing the behavior of nature is just a step on the way to understand nature. It is necessary, but not sufficient for understanding.

5. Perspective

Will we be able to understand the foundations of physics in the sense of models as described in this paper?

Probably not to the full extend. Since more than 100 years, physicists are now in a situation that the application field of theories left the physical mesoscopic world. We are trying to find models, which give a clear and direct inside view of quantum physics and relativity and make it understandable. Obviously, we have to accept, that this old-fashioned way to find analogies and models according to our experience from the mesoscopic world is not working, as explained before. Moreover, the solid fundaments of physics like realism and locality are no more valid or do need a revision at least. For newer developments like the grand unified theory, dark matter and dark energy, or mathematical approaches like string theory and supersymmetry it will be the same, probably even more complicated. Our way along evolution neither allows us to live in a microscopic world and to survive in a quantum physics environment nor to be adapted to a macroscopic world, meaning on a scale of the universe´s diameter.

However, we can establish concepts. Apart from pure mathematics, our sensation and analogies it will be possible to formulate ideas, even if not in line with common sense. The ideas needed will be surprising, far away from expectations, and open up completely new views on physics. The pure number of actual riddles as named above shows that we are far from completing and closing physics, as physicists thought in the end of the 19th century. The standard model is incomplete, and the holes are getting bigger every year, as it seems.

We will have to accept, that understanding the foundations of physics will be different to what we are used to call understanding commonly. However, the ideas, as for example given in quantum physics, have to be formulated and discussed. We need concepts instead of models. A discussion on a purely mathematical basis would not help understanding nature, as we just give a description of what is around us, and it would limit the number of people involved to a minimum. We should not try to find analogies to our sensation, as this is misleading and, in fact, hindering us to understand to the possible extend. Common sense is not the way to guide us through the labyrinth of modern physics, but logic and new, independent ideas could be.

6. Conclusion

Within the discussion in this paper we have derived, that our expectations on physical models have to be revised in modern physics. For the foundations of physics, "understanding" will never be reached in the naïve way of physics before the quantum theory or the theory of relativity. We need to accept, that the best way to achieve at least an indirect understanding will be the establishment of concepts, by avoiding misleading analogies and avoiding limiting ourselves to pure mathematical descriptions.

When I started my studies of physics, I did not expect that one has to face such surprises by investigating the foundations of physics and that it would become such difficult to understand these foundations. However, this situation is demanding and fascinating for today's new generation of physicists. We should not give up trying to understand.

This article is not providing any idea for solving the fundamental questions in physics. It is just pointing out that our current and standard way in the further development of the foundations of physics obviously is a dead end. We do have to find another access to understand nature, and may be epistemology is needed and able to make this step back before physics gets a new fundament. To speak with Anton Zeilinger: a new Kant is missing.

Therefore, I will close with an appeal to physicists working on the foundations of physics:

- Feel free to find the right questions, don´t hesitate to ask for the problems we got used to instead of having solved them (What is "spin"? How to understand a quantum transition? Just to name two).
- Be aware of the risk of thinking in analogies.
- Don´t give up in trying reaching understanding in more than "just" a mathematical way.
- This is a call for "breaking the rules of thinking", which will be necessary to allow for further development of physics.

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