Critique of the history of quantum mechanics and why it matters

Erik Deumens[*]

March 19, 2023

Abstract

Quantum mechanics is almost a century old. However, there is no generally accepted formulation that equals classical theories in conceptual clarity and coherence of ideas. We observe that the recent worldwide attention to quantum information science challenges the status quo and, at the same time, brings a possible path out of the century-long impasse. A critical analysis of the history and development of quantum mechanics, including these recent developments, shows that the intense debate on aspects of the theory may be caused by the mixing of two scientific activities. These activities are: (1) gathering and organizing data from and developing intuition about quantum phenomena, and (2) building a theory from which the observed phenomena can be derived by logical and mathematically rigorous deduction.

This is note # 1 in a series of notes to untangle quantum mechanics for a general audience and experts alike.

URL https://people.clas.ufl.edu/deumens/files/pap-critique.pdf

Intuition and theory There are two aspects or components to the scientific endeavor: The first consists of observation of the phenomena relevant to the subject of scientific inquiry. The second is the development of hypotheses and eventually a full-blown theory to describe, organize, and systematize said phenomena. The true value of the theory then shows up in the ability to predict phenomena, to find solutions to problems, and to engineer systems.

We start with a well-known example, namely the mechanical phenomena of the world of every-day living and the theory of Newtonian mechanics, and then look at the history of the discovery of quantum phenomena and the development of the theory of quantum mechanics (QM). Then we will see how the development of QM led to the state of the

---

[*] Quantum Theory Project, University of Florida, ORCID 0000-0002-7398-3090

theory today, almost 100 years later, without a strong consensus among the experts in the community. This situation is unique to QM in the history of physics.

The history of Newtonian mechanics provides a beautiful and familiar example of this structure. As people grow up, they learn how to navigate the physical world we live in. They also learn language, social, and technical skills and much more. In the context of this note we focus on the mechanical phenomena to move the human body and to manipulate objects using that body. This lifelong experience gives people a strong intuition about motion, acceleration, and forces. Then, sometime around the age of 15 to 20, people may learn about Newton's Laws in the theory of Newtonian mechanics. Some people only learn a simple version, while others, such as physicists, engineers, and athletes, take a deep dive into the subject. Notice that there is a big gap in time between the development of the intuition and the learning of the theory. Also notice that humanity survived and evolved for thousands of years without the theory of Newtonian mechanics.

Quantum phenomena were first recognized as a new class of phenomena in 1900. Physicists claimed to have a full-blown theory shortly after 1926. However, unlike other theories, even initially controversial ones like Einstein's special and general relativity, there is no consensus among physicists, even today 100 years later, about the status of QM unifying theory. There are a number of "interpretations" with competing claims, but no approach solves all problems and addresses all concerns satisfactorily for everyone interested. At the same time, QM is used successfully to accomplish numerous things in our technological society, from building computers to developing new meterials and chemicals; all accomplished without a universal theoretical consensus.

Excitement about quantum information science In recent years, there is a strong worldwide interest in everything quantum caused by the challenge of building quantum computers and the promise of quantum information science. The National Quantum Initiative Act of 2018 [1] in the United States is one example of the broad scope of the current interest in things quantum. The Nobel Prize in physics being awarded to Aspect, Clauser, and Zeilinger "for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science" provided a timely confirmation.

One important side effect of this increased interest is the need to develop a quantum workforce, which was the topic of a workshop in January 2023 [5]. The workshop showed that, in the past 5 years, various groups, organizations, and institutes have developed materials to teach quantum mechanics to a broad public, including high-school students. The reception of these teachings by the students has been very positive, and they did acquire a good understanding of the basics of quantum phenomena and quantum mechanics. The most well-known and widely recognized one is the online course by Prof. James Freericks of Georgetown University in Washignton D.C. [4], taught every summer since 2017. The course has been recognized as the 7th best Massive Open Online Course (MOOC) of all time [3].

A closer look at what is being taught so successfully to these students shows that the material is what the physicists, philosophers, and mathematicians working on the foundations of QM call the "core" of QM [7]. The core contains the parts of QM that are close to the observation of the phenomena and include the basic formalism to describe and analyze the data from observations and experiments. The core of QM is generally accepted by all experts working in QM. It excludes all material from the controversial "interpretations" that go beyond the core to address the questions of why and how the phenomena come out the way they are observed.

Developing quantum intuition We can consider the audience of the above efforts of quantum workforce education as "unbiased" students of QM, in the sense that they are not trained in advanced theories of physics, not even advanced Newtonian mechanics. They do not have any preconceived notion of what a theory should look like; they just take in the facts. The success of these educational efforts shows that an introduction to the core of QM teaches these students the intuition about QM. This is similar to people developing intuition about the mechanical aspects of the world from birth and before they learn any formal theory about Newtonian mechanics. None of the efforts of quantum workforce education touch upon the controversial topics of interpretation. That is left for after the training and is limited to those students who are particularly interested in such topics. We conclude from this development that there now is experiential evidence, almost 100 years after the formulation in 1926 of the theory of quantum phenomena, of a way to teach quantum intuition without getting into the controversial quagmire of interpretation.

That is not what happened historically, as we will now explore. We will see that the quagmire around the "interpretations" of QM originated from the developers of QM mixing the activity of acquiring intuition about quantum phenomena with the activity of formulating the theory about the phenomena. They did this in a disorganized way, which is not surprising. Unfortunately, they did often jump prematurely to conclusions and declared them as "final." As a result, the development of the theory of QM beyond the agreed "core" proceeded in an unscientific way in the form of multiple proposals that were often no more than unsubstantiated opinions, rather than scientifically substantiated and vetted theoretical formulations.

With quantum phenomena it is impossible to create simplified experiments that allow for precisely determined outcomes, except for repeated measurements of the same thing. As a result, probabilities and statistical methods to handle data from observations are unavoidable when dealing with quantum phenomena.

Developing quantum theory Because observations of radiation and cathode rays were experimentally shown to produce highly localized events, it was assumed that these physical systems were constituted of highly localized photons and electrons, respectively, which, using classical concepts of pointlike particles, appears like a natural assumption to account for the observed facts. The totality of quantum phenomena, however, show observations that, again using classical concepts, would clearly indicate wavelike explanations are called for. Quantum theory, it was concluded, fundamentally must be a theory of particles with wavelike properties to account for some of the observations; this is known as the "particle-wave duality."

However, in retrospect, it is clear that this conclusion was premature. The young Heisenberg in 1926 argued with his mentors Bohr and Einstein that one should let the mathematics be the guide to find the correct framework for thinking about quantum phenomena. But both Bohr and Einstein insisted on using the existing framework of classical particles and fields to construct the theory to organize the observations.

This point of view has led to a data-science driven development of the theory of quantum phenomena: the search for formulations in terms of classical particles and classical fields to explain the quantum phenomena. This approach is then limited to the use of the statistical notion of correlation to resolve conceptual conflicts arising from the simultaneous use of classical concepts that are inherently incompatible. This formulation is acceptable as the framework to describe and discuss the quantum phenomena and develop intuition about them. But it is not a theory for these quantum phenomena on par with what Newtonian mechanics achieves for mechanical phenomena in the world of everyday life.

Many researchers have looked for a theory with explanatory power to derive the quantum phenonema within a coherent theoretical framework with a rigorous mathematical formulation. That is where multiple, often inconsistent "interpretations" have been invented. None of these satisfy all requirements and therefore not a single one is convincing to everyone interested in the foundations of QM.

Data statistics and the core of quantum mechanics As we have seen above, the "core" of QM, as used by quantum scientists and engineers today, is essentially the formulation and systematic framework for quantum phenomena; it encodes the intuition of QM as has been shown by the success at teaching that material to everyone [4]. The core of QM has two main ingredients for describing the change of quantum systems:

1. the Schrödinger equation (SE) describes the continuous evolution of the quantum state $\psi(t_0) \to \psi(t)$ under the influence of the forces acting upon the system, and
2. the measurement process (Born's rule) projects the state $\psi = a_1\phi_1 + a_2\phi_2 \dots$ in a discontinuous way $\psi \to \phi_n$ onto one of a spectrum of possible states $\phi_1, \phi_2, \dots$ with the probabilities given by the square of the weights $|a_n|^2$ of the initial state; except for repeated and confirmation measurements where $\psi = \phi_n$.

In the core theory of QM, the process of measurement is simplified to an idealization that has been very successful in all classical theories of physics that come before quantum phenomena were identified. Measurement in classical physics is part of the metatheory: In principle it can be described by the physical theory, but it is not required. The measurement process can always be approximated by a conceptual shortcut that "just takes on the value possessed by the system." This is possible because, in classical physics, a physical process can always be found such that the interaction between the measurement apparatus and the system being measured is negligible in that it does not influence the result from the measurement process.

In QM this assumption is questionable. The only way to validate that assumption authoritatively is to solve the SE for the complete system consisting of the microscopic system being observed and the measurement apparatus, with both being described as fully quantum mechanical systems. The measurment apparatus, being macroscopic, typically has a number of degrees of freedom equal to Avogadro's number, which is 10^{23}. While we have developed significant expertise and experience in solving the SE equation for microscopic systems, there is no reliable way to solve the SE for macroscopic systems in terms of its quantum degrees of freedom. All approximations used for such solutions assume the validity of the classical approach to measurement or something equivalent to that assumption. To treat that many degrees of freedom, a statistical approach is called for.

Incorrect statistical quantum state The historical approach to statistical quantum mechanics, however, is based on an error. Von Neumann introduced the "statistical operator" in 1932 to describe a "statistical state" for quantum systems, also called a "mixed state." That means a state in which there are given probabilities p_n that the system is in a state ψ_n. Schrödinger pointed out in 1935 that the statistical operator is not really the description of a mixed state. A statistical mixture of quantum states does lead to a statistical operator, but given a statistical operator there is not a unique mixture that can be derived from it: the quantum states and the statistical weights in the mixture cannot be reconstructed in a unique way, there are infinitely many solutions. This statistical operator is inspired by the Schmidt decomposition [6] of the quantum state of a composite system in terms of the quantum states of the component systems. While such a construction aligns well with Born's rule, it does not constitute a probability distribution of states on the Hilbert space of quantum states.

Statistical quantum mechanics Today it is possible to formulate statistical quantum mechanics with a true probability measure on the Hilbert space of quantum states and the SE providing the flow in that Hilbert space, in complete analogy to the formulation of statistical Newtonian mechanics, which uses a probability measure on phase space.

Conclusion There is sufficient reason to doubt any and all "interpretations" of QM currently discussed in the literature. Instead we should be building on the core of QM, that captures correctly and efficiently the intuition of quantum phenomena, as shown by the success of teaching it. The path towards a solid theory of QM is to spend the effort in studying the physical process of measurement as described by the SE.

The reason this issue is important and relevant now is the challenge posed by quantum information: building a quantum computer and other quantum information devices. In such devices, microscopic systems, such as qubits, have to constantly interact with a macroscopic environment, e.g., exchanging signals with classical computers, performing error correction protocols, and executing algorithms loaded as programs of gate sequences. That process must proceed at frequencies of several MHz initially and is expected eventually to run at GHz frequencies.

To build such devices requires a solid theoretical foundation that goes beyond the phenomenological formulation in Born's rule to describe the interaction between microscopic quantum systems and macroscopic systems. Better approximations must be developed to handle the large number of degrees of freedom with sufficient accuracy to ensure correct operation of the complex quantum information devices.

References

[1] Congress, U.: National quantum initiative act - h.r.6227 (2018). URL https://www.congress.gov/bill/115th-congress/house-bill/6227. Website quantum.gov

[2] Deumens, E.: On Classical Systems and Measurement in Quantum Mechanics. Quantum Stud.: Math. Found. p. 37 pages (2019). DOI 10.1007/s40509-019-00189-3

[3] Freericks, J.: Quantum Mechanics for Everyone recognized as best MOOC of all time. Geargetown University website (2021). URL https://physics.georgetown.edu/quantum-mechanics-for-everyone-recognized-as-best-mooc-of-all-time/

[4] Freericks, J.: Quantum Mechanics for Everyone. EdX (2022). URL https://learning.edx.org/course/course-v1:GeorgetownX+PHYX-008-01x+2T2022/home. MOOC online course

[5] Sanders, B., Freericks, J., Cheng, H.P., Li, C., Deumens, E.: Workshop on quantum education for quantum workforce development (2023). URL https://faculty.eng.ufl.edu/quantum-information-systems/workshop-on-quantum-education-for-quantum-workforce-development/. Jan 30-31, 2023 at Arlington, VA

[6] Schmidt, E.: Zur Theorie der linearen und nichtlinearen Integralgleichungen. I. Teil: Entwicklung willkürlicher Funktionen nach Systemen vorgeschriebener. Math. Annalen **63**, 433–476 (1907)

[7] Wallace, D.: Philosophy of Quantum Mechanics. In: D. Rickles (ed.) The Ashgate Companion to Contemporary Philosophy of Physics, chap. 2, pp. 16–98. Ashgate Publishing Company (2008)