Theory and metatheory in physics

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March 19, 2023

Abstract

In classical physics, the focus has been on developing theory to explain experiments. This tradition has been continued with quantum theory. It has become increasingly clear that properly managing metadata is as important in science as handling the scientific data. The continuing discussions about interpretations of quantum mechanics are viewed as discussions about the theory, which means they are part of the metatheory.

This is note # 3 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-metatheory.pdf

The true power of science comes from the principle that discovery is driven by data. Data is analysed. A hypothesis is formulated to provide structure to the observations recorded in the data, which eventually leads to a theory about a domain of phenomena. A second principle holds that data and experiments must be reporodicible. Therefore data must be carefully recorded, labeled, and tracked. This information about the data, is called metadata. In recent years, with the rapid expansion of the ability to collect massive amounts of data, it has become clear that metadata is crucial to the health of the scientific endeavor.

Looking at the history of theories in physics, it is possible to see a similar structure of theory and metatheory. A theory provides the concepts and laws of physics formulated in terms of these concepts to address a class of phenomena. Some of the widely known theories are Newtonian mechanics, Maxwell theory of electrondynamics, the Einstein's theories of special and general relativity, and quantum mechanics (QM). These theories, except the last one, are known as the theories of classical physics.

Classical theories have a common notion of measurement that remains undescribed as part of the theory. because it was generally accepted as so obvious that it did not

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need mention. This is similar to the fact that, initially, nobody discussed or taught about metadata; it was simply understood as good practice to carefully record your data, with Tycho Brahe setting an early standard.

It is assumed in classical theory that any concept can be measured in a way that does not influence the phenomena being studied, described, and code into laws of physics by the theory; one just needs to be sufficiently careful, which is assumed to be always possible. This is a statement in the (classical) metatheory of physics. Examples are:

1. Plantetary motion is not influenced by the light (from the Sun) that is reflected by it and observed on earth to measure the positions of planets and their changes in time.
2. Electric fields can be measured by observing the motion of small test charges; magnetic field lines can be aboserved by observing metal filings aligning.

A metatheory covers "natural" assumptions and therefore can remain silent and undeveloped until a problem is brought forth that requires investigation of these assumptions. That is what happened with data and the discussion and teaching of the principles of metadata in the last decades triggered by the rapid growth of the size data sets. The advent of quantum mechanics triggered an investigation of the measurement process. However, the problem was treated in a superficial way and because of the twists of history, further investigation was frowned upon until Bell published his theorem [2]. With the experimental confirmation by Clauser [4], Aspect [1], Zeilinger [6] (Nobel Prize 2022), the study was acceptable again, but it got derailed by a focus on the phenomena of "entanglement" rather than a deeper investigation of the dynamics of measurement.

The assumption that measurement reveals a property of the system persisted in the theoretical development of QM: Because electrons and photons caused localized excitations in detectors, it was assumed that the "particle" aspect of the particle-wave duality is the stronger property. There is no known way for fields govenred by equations like the Schrödinger equation (SE) to exhibit dynamics of concentrating rapidly into a point like action on a detector. The result was an acceptance of the mysterious behaviors found in entanglement experiments as a matter of faith. This conclusion is encoded in the unwritten, but hotly debated, metatheory of QM under the topic of the "measurement problem."

Any experiment inescapably involves very large systems, namely the measurement devices. These macroscopic systems typically have degrees of freedom that count in numbers like the number of Avogadro 10^{23}. The proposed methods cannot solve the equations with such complexity. Thus, it was natural and logical to resort to a phenomenological shortcut: namely Born's rule [3]. That rule assumes that the measurement process can be abstracted and idealized, as in classical physics, by a simple process of "recording" without delving into any details of the physical process. The success of the Born rule validates that assumption, at least for the kind of measurements physicists have been carrying out for the last century. From a philosophical and logical point of view, however, it was not acceptable, in retrospect, to declare that rule as a fundamental principle.

The conclusion that needs to be drawn from all experimental evidence in QM is that the meatatheory is not correct about measurement in QM: Measurement must be *always* be treated as a dynamical process in QM, it is never something that can be handled with the classical assumption of accepting the data at face value. The localized event produced by the imapct on a detector of the quantum field describing electrons or photons is the result of a complex dynamic process that can be, and always must be, described by the SE.

A second observation about theories in phsyics, that can be considered part of the metatheory of physics, is that scientific theory develops and matures in stages. Newtonian mechanics is a clean example, and Maxwell electrodynamics is another.

Stage 1 - Observation Tycho Brahe in 1574 published very detailed data at an unprecedented scale about planetary motion. This phase of development captures data in a systematic way.

Stage 2 – Phenomenology Johannes Kepler published his laws of planetary motion between 1609 and 1619 providing a systematic organization and description of the observations. The framework may provide a lot of explanation already, as in the case of Kepler's laws which apply equally to all planets, asteroids, and comets.

Stage 3 – Explanation Isaac Newton published the laws of force and the force of universal attraction and provided the methods to derive Kepler's laws of planetary motion, thus providing a scientific theory explaining the observations made by Brahe. Newton's laws provide an explanation because all phenomenological laws and all phenomena in the scope of the study can be systematically derived.

Using this general framework, we can ask: In what stage is the evolution of QM? QM has lots of observations gathered of the past century and it has the Schrödinger equation (SE) and methods to solve it with high accuracy for microscopic physical systems. The results from the theoretical solutions agree with all known experimental data to very high precision and thus provide the requested explanation. We therefore would conclude that QM has reached stage 3.

However, we do not have a method to solve the SE for macroscopic systems interacting, e.g during a measurement, with the microscopic systems that we can describe with the SE. For that interaction we only have a phenomenological rule, Born's rule. Therefore, in reality, the operational core of QM has not reached stage 3, but is at stage 2.5.

The work is not done as pointed out by Murray Gell-Mann [5] in 1976: "Bohr brainwashed a whole generation of physicists into thinking that the job was done 50 years ago."

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