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**Is the Transition from Classical  
to Quantum Mechanics  
Truly an example of a Kuhnian  
Revolution?**

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# The background

- What to make of **quantum mechanics**?
  - We can use the theory for their experiments but they have trouble understanding what it means.
- **Prototypical example of a paradigm shift**:
  - The world-view that seems to be depicted by quantum theory seems to be **radically different** from the one of classical physics.
    - While according to classical mechanics the world is made of particles, waves and fields, the quantum world seems to be populated by mysterious objects that can be particles and waves at the same time, and in general by entities that appear to be able to be in more than one places at once.
- In this paper I wish to **challenge the necessity of this view**:
  - I argue that classical mechanics and quantum theories are not necessarily as radically different as they have been depicted so far.
  - In fact whether we actually have a paradigm shift going from classical to quantum mechanics is going to depend on what we understand quantum mechanics to be.

# Kuhnian Revolutions

- Thomas Kuhn:
- Normal science:
  - It is based on a **paradigm**: a set of theories, methods, metaphysical and epistemological theses that scientists, at a certain point in history, accept. The paradigm dictates what puzzles science will work on, and what counts as an adequate solution to those **puzzles**, how science should be practiced, and what the aim of science is.
  - Paradigms often have **anomalies**: predictions not fulfilled, inconsistencies and so on. Normal scientists substantially ignore these problems since they believe that can be ultimately be solved within the framework of the theory, even if they currently have not. At a certain point, though, there are too many anomalies, so that the paradigm becomes fractured.
- Revolutionary science:
  - It involves **sweeping away the whole old paradigm**, its theories, methods and standards, starting from scratch.
  - Revolutionary scientists paint over the canvas, to draw in a new outline, which new normal scientists will go on to fill in within the **new paradigm**.

# Kuhnian Revolutions

- Many have claimed that also the **shift from classical to quantum mechanics** can be viewed in Kuhnian terms.
- Here I will argue that the thesis that our world-view and the relationship between physics and metaphysics radically *have to change moving from classical* to quantum mechanics, is false: **they may have changed in practice, but they did not have to change.**
- In contrast, I will show that it is possible to construct quantum theories completely compatible with the “old” classical paradigm.

# Classical Theories

- Classical Mechanics (CM) is not a very controversial theory:
  - The world is made of **particles**.
- The clear metaphysics of the theory grounds a scheme of explanation that **arguably** allows to determine the properties of macroscopic physical objects in terms of the behavior of the fundamental objects in the theory:
  - In CM any physical body (gases, fluids, and solids) and their macroscopic properties can be satisfactorily described in terms of **collections of particles**.
  - It seems reasonable that even if we move from an ontology of particles to one of fields, also in three-dimensional space (CED), things will not fundamentally change in this respect.

# Classical Theories

- **Granting that reductionism is possible**, this is how it is supposed to work:
  - why a table is solid: because it is composed of particles that interact electromagnetically such that it is impossible for another object to penetrate them.
  - Why a pair of glasses are transparent: because the electromagnetic forces acting between the particles composing the glasses, that are such that incoming light-rays will completely pass through them.
  - Why water is liquid: because there is a very weak interaction between the particles of water, and this allow water to change shape with the container.
  - Why gases expand: because they are composed of non-interacting particles colliding with one another.
  - Why air is compressible: because it is composed by non-interacting particles, so that it is possible to reduce the distance between them almost as much as we want.
- These examples show how in the classical framework we have a clear and **straightforward scheme of explanation of macroscopic phenomena**:
  - given the particles at the microscopic level, one can employ what now are standard methods to determine the properties of familiar macroscopic objects.

# Quantum Theories with the Observer

- Too bad it seems we have to **abandon** such clear scheme once we consider quantum mechanics:
  - we need to **change our paradigm**, otherwise we seem to have too many unexplained and unexplainable anomalies.
- Several extremely **strong assertions** have been made about quantum theories:
  - it is impossible to be realist if quantum mechanics is true,
  - the observer can create part of reality,
  - the “old,” classical way of understanding the world we just described is not suitable any longer.



# Quantum Theories with the Observer

- How did it happen that people get convinced of these things?
- Let us briefly recall the **history** of the development of quantum mechanics:
  - At the end of the 19th century, the Newtonian picture of the world was commonly accepted, even if there were several puzzles;
  - Some of them suggested the idea of quantization;
  - Other results suggested instead a change in the ontology:
    - Some experiments were taken to show that particles sometimes behave like waves.
    - But particles and waves are **incompatible ontologies!**
    - So, it appears that we need to **revise our ways of understanding** and describing reality:
      - particles and waves are **obsolete concepts**, inadequate to represent the quantum reality, and should therefore be abandoned.
    - In addition, since in the quantum world superpositions are possible, the laws of **classical logic** such as bivalence **do not hold any longer**:
      - a particle can be here and not here at the same time, so we need to develop **a quantum logic**.

# Quantum Theories with the Observer

- An attempt to **save the classical paradigm**, Louis de Broglie's wave function:
  - Let us associate such wave to each particle as a "guide field" whose evolution was later described by Erwin Schrödinger.
- De Broglie's idea was quickly abandoned:
  - Due to some heavy criticism by Wolfgang Pauli at the 1928 Solvay Congress.;
  - Due to some other results (such as Heisenberg's uncertainty principle, and von Neumann's theorem) which were taken to show that quantum theories had to be **about the wave function**, and not about particles.
- Also, if we attempt to interpret quantum mechanics realistically as a theory about the wave function we fail:
  - Schrödinger's **measurement problem**: if the wave function completely describes physical systems, and it evolves according to the Schrödinger equation, then macroscopic superpositions which we clearly never observe are produced.

# Quantum Theories with the Observer

- Early proposed solution of the measurement problem:
  - Wigner and von Neumann: the observer's conscious observations “collapse” the wave function to one of the terms of the superposition .
    - Unsatisfactory, but the common understanding was that the situation left **no other escape**.
    - If this is the case, then:
      - 1) the wave function is collapsed in one of the terms of the superpositions by an observer; or
      - 2) there are two distinct and fundamentally irreducible worlds, the classical and the quantum one.
    - **Neither** of these two approaches **is close to the previously accepted paradigm** of CM in which the world was made of microscopic particles that compose macroscopic objects.
    - Then it seems we have a **paradigm shift**:
      - 1) Either in one world-view consciousness actively participates to physics,
      - 2) or ordinary concepts and the laws of classical logic are not valid any longer.

# Quantum Theories without Observers

- Eventually, new and less problematic proposals to solve the measurement problems were made.
- **David Bohm (1952):**
  - He revised and updated deBroglie's particle-wave theory and showed that his theory solves the measurement problem.
  - However, this theory had an unfortunate fate, since von Neumann's theorem was already taken to prove that hidden variables are impossible. This conviction was reinforced by certain presentations of Bell's inequality. As a result, Bohm's theory was dismissed for a very long time.
  - Only fairly recently it was appreciated that such interpretation of von Neumann's theorem was mistaken, and that there is nothing wrong with Bohm's theory (Bohmian mechanics, BM).
- **Hugh Everett (1957):**
  - He developed the so called many-worlds interpretation, in which the terms of the superpositions are interpreted as belonging to different worlds to which we have no access, so that everything that can happen (all superpositions) will happen, but in a different world.
- **Ghirardi Rimini and Weber (1986):**
  - They developed a theory in which the wave function does not evolve according to Schrödinger's equation but it randomly collapses in one of the terms of the superpositions not because of an observer but as a result of a physical law.
- Even if there are particles in BM, people still insisted on the **wave function as (part of) the ontology of quantum theories**. In addition, the other solutions to the measurement problem all involve the wave function in a fundamental way as well.
- In fact they seem to be focused either on accepting the macroscopic superpositions (Everett), or on eliminating them (GRW).

# Quantum Theories with Paradigm Shift

- The three examples presented above show how it is possible to provide realist interpretations of the quantum formalism that do not rely on the notion of the observer.
  - “quantum theories without observers” (QTWO)
- All these theories were naturally taken to be **theories about the wave function**.
- **Argument for this view:**
  - If in a physical theory there is a fundamental equation for the evolution of a given mathematical object, generally we think we are justified to take this object to represent physical objects.
  - In CM, the fundamental equation is Newton's equation, and it describes the temporal evolution of point-particles in three-dimensional space. We therefore conclude that CM describes the behavior of point-like particles.
  - By analogy, in QM the fundamental equation is **Schrödinger's equation**, and given it is an equation for the temporal evolution of the wave function, we are entitled to take the wave function to represent physical objects as well.

# Quantum Theories with Paradigm Shift

- **Problem for the view:**
  - Physical space is **not the traditional three--dimensional** space, but it is the space on which the wave function is defined, namely configuration space.
  - Clearly, we do not seem to live in configuration space: rather, it seems obvious to us that we live in three--dimensions.
  - Therefore, a proponent of such a view has to provide an account of why it seems as if we live in a three--dimensional space even though we do not. Also, she should explain how to “recover the appearances” of macroscopic objects in terms of the wave function.
- If this reading of QM is correct, then even if there are no observers in the formalism of the theory, and the laws of classical logic are still valid, we **nonetheless have a paradigm shift:**
  - we move from the classical, common-sensical view that there are microscopic objects in regular three-dimensional space (particles and fields) that compose macroscopic familiar objects, to the quantum view in which we all live together in configuration space, and we cannot use any longer the rules of compositionality and reduction as we could do within the classical paradigm.

# Quantum Theories with no Paradigm Shift

- The paradigm shift arises from taking the **wave function as describing physical objects**.
- I will argue here that it is **not necessary to go along this route**, so that we can avoid the paradigm shift.
- With a QTWO which is not about the wave function, but about microscopic *stuff in space—time*, we can develop a clear explanatory scheme, on the line of the classical one, to account for the macroscopic world.
- As a consequence, there is no quantum revolution as advertised so far: the quantum world is less crazy and paradoxical than one would have thought.
- **How is this done?**
- Let us go back to BM:
  - one could think of it as a theory about both particles and the wave function:
    - in BM we have two fundamental equations, one for the wave function and one for the particles, and they describe what there is.
  - But if we look closely to the structure of the theory we will see that this approach is contrived:
    - In BM **the wave function** has a particular role: it does not describe matter but it **describes the way in which matter moves**.
    - So, it seems more appropriate to think of it as representing **a law** or perhaps **a property**, rather than physical objects themselves.

# Quantum Theories with no Paradigm Shift

- With this understanding of the role of the wave function in BM, look to the other QTWO:
  - **GRW:**
    - GRWm: matter is described by a field in three--dimensional space defined in terms of the wave function,
    - GRWf: matter exists in space—time called “flashes,” whose rate depends on the wave function.
      - In both GRWm and GRWf the evolution of matter is determined by the wave function, which in turns evolves according to the modified GRW dynamics.
  - **Many-world:**
    - Sm: a mass density field ontology in three-dimensional space, as in GRWm, combined with a Schrödinger evolving wave function which determines the temporal evolution of the primitive variables.



# Quantum Theories with no Paradigm Shift

- In this framework, there is **no paradigm shift at all**.
- QM has the same structure as CM:
  - there is **microscopic stuff in ordinary physical space** that moves in time, and this microscopic stuff **combines together** to form the familiar macroscopic objects of our experience.
  - Because of this, also in QM we should be able to recover, at least in principle, all the macroscopic properties of physical objects using an explanatory scheme derived along the lines of the classical one.
  - An antireductionist, again, would object to this, but the point here is that within QM so interpreted the **reductionist is not worse off** than within the classical framework.

# Conclusion

- No paradigm shift is needed to account for the quantum world.
- If we like to drastically change our way of understanding the world through physics we can, but **we do not have to**.
- **First**, we do not have to cease to be realist, introduce consciousness into physics, or change the rules of classical logic if quantum mechanics is correct:
  - there are at least three quantum theories (BM, GRW and many-worlds) that account for all physical phenomena without doing anything of the sort.
- **Second**, it is commonly maintained that even if we take these theory seriously still we *need to* revise our way of understanding the world and physics itself.
- I have argued that also this paradigm shift is not unavoidable, since, while it is true that our world-view changes if we take the wave function to be a real matter field, **we do not have to do so**:
  - there are other ways of interpreting the mathematical formalism of quantum theories in such a way that we can keep our classical paradigm, or at least, a paradigm not so radically different from it.