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State of the art of the sum over paths approach in quantum mechanics education

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Abstract. In this contribution I present an overview of the history and recent developments of the Feynman sum over paths approach for teaching introductory quantum mechanics to high school students and University undergraduates. It is argued that sum over paths has now reached full maturity as an educational reconstruction of quantum physics, and offers several advantages with respect to other approaches in terms of leading students to develop consistent mental models of quantum objects and ultimately achieving better conceptual understanding.

1 Introduction
The sum over paths approach in physics education originates mainly from two sources: Feynman's path integral formulation of quantum physics [1] and his own divulgation book "QED: the strange theory of light and matter"[2]. The latter, in fact, constitutes the first, fundamental sketch of an educational reconstruction of quantum physics based on the path integral formulation. Among the milestones of the approachs'development one can trace the undergraduate course on quantum physics "Demistifying quantum mechanics"held by E. F. Taylor at MIT [3] which had a profound impact in the international physics education research community; and the Advancing Physics project [4] of the British Institute of Physics, an advanced physics course for high schools, designed to attract students to physics, and to give them a good basis for their future progression in the subject at university level, in which J. Ogborn, A. Dobson and co-workers [5] proposed an innovative presentation of quantum physics based on sum over paths. After the turn of the millennium, interest on the sum over paths approach has grown, with several works of great interest, both empirical [6,7] and theoretical [8,9].

2 Recent developments
Recent educational research has addressed most of the open issues standing on the sum over paths approach, including devising effective educational strategies for discussing time-independent problems such as bound states and tunneling [10, 11]; improving the treatment of the uncertainty principle [11]; establishing connections with two state approaches based on spin or polarization [12]; designing and realizing tools, such as interactive simulations and tutorials, to sustain students'learning [13, 14]; pinpointing and clarifying the educational advantages of sum over paths, including reliable measures of conceptual learning outcomes [15, 16] and highlighting the importance of concepts, such as path distinguishability, which were not central in the initial educational tests of the approach, but have demonstrated extremely fecund in leading to conceptual understanding of wave particle duality, and allowing to introduce modern experimental settings and technologies [17].

3 Educational advantages
Based on the results of research literature, and several years of direct experience with using the sum over paths approach in teacher education, we can summarize the main educational advantages offered by the approach in the following way:
• On the mathematical level, the sum over paths approach allows to discuss quantum phenomena using a very simple formal language. At its heart, such possibility is due to the fact that, rather than finding solutions to the Schrödinger equation, Feynman's method constructs the Green function for the same equation, representing it as a sum of complex amplitudes computed over all possible paths. In educational practice, complex amplitudes associated to paths can be represented and added up as vectors or "little arrows", a strategy directly derived from the one used by Feynman himself, which greatly reduces the stress on student's cognitive resources while learning the basics of quantum theory.
• On the conceptual level, sum over paths has the unique peculiarity of offering students a very clear and unambiguous representation of one of the most profound quantum mysteries, namely wave particle duality. The central distinction between classical and quantum ways of computing probabilities, which is at the heart of the approach, allows both to clearly distinguish classical and quantum physics, and to make the classical limit (correspondence principle) completely transparent. Furthermore, modern educational reconstructions based on sum over paths can offer deep insight on the origin of energy quantization for bound systems, help

clarifying the meaning of the uncertainty principle, and pinpointing the siimilarities and differences in the quantum behaviour of photons and electrons. Finally, sum over paths, with the introduction of the idea of path distinguishability/indistinguishability, allows to construct a language capable to discuss modern experiments and technologies based on quantum optics.

4 Conclusions

In my overview of research on the sum over paths approach for teaching introductory quantum physics, I argue that such approach, started in the late 1980's, has reached full maturity in the second decade of the XXI century. Based on its characteristics, sum over paths can help researchers and educators improve educational outcomes in terms of conceptual understanding, and be an invaluable aid in the introduction of quantum technologies, an issue which is increasingly felt as central and urgent.

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