LOOKING AT QUANTUM FIELD THEORY WITH UPPER SECONDARY SCHOOL STUDENTS IN MIND

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1 INTRODUCTION

The contribution concerns the first results of a project aimed at exploiting the educational potential of Quantum Field Theory (QFT) within a global reconstruction of physics addressed to secondary school teachers and students.

On the basis of other studies we have carried out [1], the project moves from the curiosity of searching for answers to the following questions:

- How the concept, *object,* changes when moving from classical to contemporary physics?
- How the concepts of *field* and *interaction* are shaped and conceptualized within contemporary physics? What makes quantum field and interaction similar and what makes them different with respect to the classical ones?

The project is moreover designed in order to explore "extreme territories" where physics education research has to face the problem of establishing its own identity [2] with respect to other research fields. In particular, the whole work is framed within a more general "meta" or methodological research framework aimed at:

1. searching for an *educational glance* at a theory that cannot be taught as it is at the secondary school level: What are the peculiarities of an educational glance at QFT with respect to other possible perspectives, for example, high level theoretical physics, foundations or philosophy of physics?
2. searching for a way of looking at the formalism without getting trapped in it, but being able to exploit its constitutive role: What does it mean to attach to the formalism a constitutive role when it appears to be so far beyond the reach of secondary school students? Can research in physics education find sensible ways of entering the formal structure, also in these extreme cases, and defend its own specificity as research field with respect to popularization?

2 SEARCHING FOR AN "EDUCATIONAL GLANCE" AT THE QUANTUM FIELD THEORY

There are many possible ways of looking at QFT that can somehow justify an educational engagement [3]. For example, the following features of QFT can deserve the attention of physics education researchers too:

- QFT is a theoretical background legitimated by the experimental successes of the Standard Model;

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- QFT can be considered *the* fundamental theory;
- QFT can represent, for several reasons, the conceptual completion of quantum physics.

None of them has been chosen as primary feature to define our perspective. In other words, none of the following arguments has been chosen to frame or orient our analysis (at least not as the *main* ones or the *only* one):

- Effective predictive capability;
- Hierarchical organization of physics;
- The need to find solutions for problems that quantum physics cannot solve.

Besides epistemological reasons, the choice is mainly due to the fact that these issues appear to be too internal to highly refined physical discourses and therefore inadequate for secondary school teaching for the following cultural and educational reasons:

- their articulation requires sophisticated technical languages, therefore the risk of not being able to go beyond pure statements can be very high;
- they seem to have a weak potential for outlining a sufficiently wide cultural horizon where to situate technical problems, with the risk of reasoning trapping on them and loosing the sense of the whole cultural game we are trying to play. We instead believe that a wide cultural horizon should be explicitly outlined in order to characterize the educational reconstruction of QFT as a process of *"bringing physics into culture"* [4, 5].

Therefore the educational perspective we have chosen is looking at QFT as: *the most recent format in which physics, through the concepts of quantum field and quantum interaction, conceptualizes "continuum" and manages its formal structures as well as re-conceptualizes "the relationship between continuum and discrete".*

3 SPECIFIC RESEARCH PROBLEMS

QFT is an impressive building of linguistic engineering, made out of very fine materials and assembled by refined craft-like experience. In its usual presentation in university textbooks it appears as a tangle of formal structures, a "quarrel" between general and particular, new and old, physical and epistemological aspects.

The first specific research problem we are addressing represents the phase of conceptual clarification: entering the tangle and outlining the *essential conceptual structure* of QFT, when analysed from the specific perspective chosen. The specific aims of this phase (the steps of the work) are:

- to identify the *minimal conceptual structure* of continuum (towards the concept of quantum field) and of discrete (towards the concept of interaction);
- to analyze the *basic elements* of such structures so as to disentangle the different formal languages involved (to understand, for example, where

and how the quantum formalism comes in to make the quantum field different from the classical ones);
- to re-organize the contents so as to highlight what is *invariant* and what is *different* when moving from classical to quantum concepts;
- to find out *practicable routes* to access the basic element shaping the minimal structure.

At present we are still far from the stage of educational transposition: It will represent the second research problem to be addressed after the conceptual clarification.

In the next sections we illustrate the research choices for situating the analysis within a cultural framework shared with other Italian research groups, as well as the first results of the analysis of the formal structure of continuum, aimed at pointing out what we call "the skeleton of continuum".

4 RESEARCH CHOICES

The analysis we are carrying out is situated within the research framework developed through collaborative work of the Italian research groups of the Universities of Bologna, Milano-Bicocca, Napoli, Roma "La Sapienza", "Roma Tre", Torino, as a follow-up of the national project F21 (coordinated by P. Guidoni).

According to the shared framework, the following research criteria have been chosen:
- to look at QFT, as every other physical theory, as the coherent re-organization of some *framing ideas* like "space", "time", "matter", "state", "interaction", "physical process", whose evolution and meaning expansion can point out elements of continuity and discontinuity between classical and modern physics.
- to analyze the "debate" between continuum and discrete by following the evolution of the interplay between modelling *physical objects* (systems, fields, particles,…), their *interactions* and the *space-time structure* (movement, propagation, …).

The analysis of QFT, then, is meant to highlight the role of the above framing ideas, however present in the traditional teaching paths, acting as transversal connections, cognitive organizers and coherence constructors in the knowledge development [6].

We indeed share with the other researchers that a "framing ideas approach" can overcome some of the major shortcomings of school teaching such as: the exceeding amount and the fragmentary character of the notions and concepts contained in the curricula; the absence of curricular continuity in the transition between the different school levels and between the different "chapters" in which Physics is traditionally organized [7].

Within this framework, our specific bet is that looking at the QFT from this perspective allows the primitive questions about the comparison between classical and contemporary concepts (reported in the introduction) to be re-formulated in terms of the general cultural problem of searching for the *new* "contexts of the linguistic uses" (Wittgenstein) of the words "particle", "wave", "field" and *new* cognitively practicable declinations of the dilemma "wave-particle" (and complementarity in general).

The framework, moreover, makes it explicit to what extent the quantum field, like every other physical object, is a formal model shaped together with its interaction constraints and spacetime relationships (propagation). Just for the need of methodological clarification, we have decided to analyse the spacetime structure before and somehow apart from the interaction model. This approach is based on the idea that the analysis of the specifics of quantum field spacetime structure (necessary to outline "the skeleton of continuum") paves the way to analyzing the peculiarities of the quantum interaction (and the new specifics assumed by the discrete model).

By "skeleton of continuum" we mean the essential formal structure that should highlight what a vibrating string and a quantized field have in common. In this sense the skeleton should involve the generic idea of "shape" (expressed substantially by spacetime relations to which functions and functionals are subjected), to be related to specific physical cases through the interpretation of some parameters inside the equations or coefficients inside the relations.

5 FIRST RESULTS

Examples of good candidates to be part of the skeleton of continuum (the elements of the *minimal structure*) are:

i) the wave equations (e.g. d'Alambert, Klein Gordon);
ii) the tools of analysis (e.g. Fourier transformation);
iii) the spacetime symmetries and conserved quantities (Noether's theorem).

The first result of the study is a methodological one: we have developed criteria for clarifying the basic concepts and pointing out the elements of the minimal structure in terms of formalization of *intelligible*, *plausible*, *meaningful* requests.

A request is *intelligible* if it can be seen as expressions of "general ways of thinking"; it is *plausible* if it appears to be sensible for sketching conceptually clean routes to highlight the core of the basic elements. All the requests, taken as an ensemble, will be *meaningful* if the whole territory traced by the different routes appears to be sensible and suitable to be covered without getting trapped in the formalism. Below, we will briefly report the results of the first step of the analysis aimed at testing the effectiveness of the requests to clarify the concepts.

i) the physical core of the wave equations has been analysed by implementing the request that "a shape, during propagation, does not change or changes its profile with style". The route leading from the request to the formalized wave equation allows the following results to be obtained: the formal expression of a shape propagation is highlighted as a special relation between the second derivatives in space and time ($\Box = \partial^2/\partial x^2 + \partial^2/\partial y^2 + \partial^2/\partial z^2 - \partial^2/\partial t^2$, $c = 1$)[b)] whilst the possible modifications of the profile are related to the second term of the equation “$\Box f = 0$ ” or “$\Box f = m^2 f$ ”).

ii) the Fourier transformations have been analyzed by implementing the request of “highlighting what the various shapes have in common and what makes them different”. The implementation allows the abstract spaces that contribute to structure the whole formal construction (ordinary space-time, k-space, Hilbert spaces and Fock space) to be disentangled. In particular the analysis shows that, for example, the common aspects of a vibrating string and a quantum field lie in the formal structure of plane waves (the base of Fourier expansion), whilst the peculiarities of each shape lie in the coefficients of the Fourier expansion. Indeed a quantum field gains its peculiarities with respect to a vibrating string only when the coefficients are interpreted as quantum operators in a Fock space and no longer as the numbers indicating the amplitude of a normal mode. However, the relevant physical quantities (energy, momentum) can be expressed as relations between the coefficients, whilst the plane waves, being neutral with respect to different physical cases, progressively loose contact with phenomenological aspects while gaining meaning as leading structure.

iii) Noether’s theorem has been analysed by implementing the request that “All the observers distant in space and time must have the same «building tools»”. The route outlined by the request implementation leads to looking at the conserved quantities (energy, impulse, angular momentum…) as necessary consequences of the action invariance under Poincarè transformations.

6 FINAL COMMENTS

We are deeply convinced that physics education should accept the challenge involved in this statement by Levy-Leblond:

“Let us use an architectural metaphor. In order to construct a building, scaffoldings, supporting structures are needed. They are often built with whatever means available.

Analogously, the scientific researcher builds like a craftsman, constructing new experiments and new concepts with the tools and the ideas he has at hand. But scaffolding hides what is to be built, and in the end it has to be taken down to allow the building to be seen and for it to function. In the same way, the theoretical scaffoldings of new scientific ideas often hide these ideas and should be taken down in order to allow the real structure to be seen and its inner meaning to be evident.

Nevertheless such a critical task of cleaning and tiding up is seldom done within actual science, and rarely consciously. The conceptual level stays crammed with things whose constructive role has been relevant, but that now hide the building; The consequences are evident in epistemological analysis and, in particular, in instruction.” [4]

[b)] The problem of educational transposition will be of course addressed by taking into account that formal tools like the d’Alambert operator, or the Fock space cannot be explicitly used at the secondary school level.

In our project we have begun to pursue this idea, as we have briefly outlined in this contribution, by addressing the research problems lying both at a methodological level (concerning the search of an educational glance at contemporary physics), and at a technical one (concerning foundations of QFT).

The chosen approach seems promising for outlining a conceptual transversal structure that, by crossing different physical domains, is able to make the physical ways of conceptualising continuum and discrete explicit, as well as for pointing out the specifics of the different contests where the same words are used. Moreover, in the light of the first results of the test for evaluating the requests plausibility, it seems possible to arrive at designing a whole territory where QFT is reconstructed and its core ideas translated into accessible languages without missing their deep meanings.

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