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Entangled Bodies in Education from Hybrid Ecologies to Quantum Literacies for a PostDigital Knowledge

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Abstract: The spread of generative artificial intelligences, wearable sensors, experimental quantum networks, and data analytics platforms is redefining educational landscapes. In this context, the body is not a peripheral to be digitized, but a semantic vector capable of inscribing and transforming flows of meaning. This contribution analyzes three dimensions that co-constitute the classroom as a socio-material ecosystem: the cognitive-affective, the techno-algorithmic, and the eco-material. To these is added a fourth interpretive axis, that of quantum literacies, based on entanglement and superposition, which open up new teaching and assessment practices. Schools and universities are thus configured as laboratories of living semiotics, capable of orienting technological innovation toward inclusive and sustainable forms of post-digital citizenship.

Keywords: Body, Semantic vector, Hybrid ecologies, Embodied pedagogies, Quantum literacies.

1. Introduction

In recent years, the educational landscape has been immersed in an unprecedented transformation, driven by the simultaneous emergence of generative artificial intelligences, wearable sensors, experimental quantum networks, and data analytics platforms (Ascione, 2024). These technologies are not merely additional tools but forces capable of reshaping the modes of production, transmission, and negotiation of knowledge. Schools and universities thus find themselves operating within a landscape in which learning no longer travels exclusively through symbolic languages or classical bit streams but takes shape as a dynamic interweaving of human bodies, algorithms, and environmental materials (Di Tore, 2024), interacting with qubits in states of superposition (Rossi, 2024). In this scenario, the body can no longer be understood as a biological peripheral to be digitized nor as a simple object of measurement, but as a semantic vector (Digennaro, 2021), a medium capable of inscribing, modulating, and transforming flows of meaning. Pedagogical research is therefore called to expand its scope and to investigate how to integrate new socio-material ecologies (Peters et al., 2022) and embodied pedagogies (Rode & Stern, 2023) within an inclusive and sustainable perspective (Lecce & Di Tore, 2025). On the one hand, learning ecologies demonstrate how learning extends beyond the boundaries of the

physical classroom to incorporate distributed communities and computational infrastructures; on the other, embodied pedagogies highlight how the body, mediated by sensors and dashboards, becomes a generator of attention, decision, and meaning. To these perspectives must be added the urgent need to explore the contribution of quantum technologies, which introduce new paradigms of information security, representation, and cooperation that can be reinterpreted in educational terms. The objective of this article is to outline an integrated reading of the body in education as a node where four directions converge: the cognitive-affective dimension, the techno-algorithmic dimension, the eco-material dimension, and the fourth interpretive axis of quantum literacies, based on the principles of entanglement and superposition (Nishanth et al., 2022; Oikonomou et al., 2025). Through this perspective, schools and universities are reconfigured as laboratories of living semiotics, able to cultivate post-digital citizenships capable of inhabiting contemporary eco-social complexity and of orienting technological innovation toward more just and sustainable forms of planetary coexistence.

2. The body as a semantic vector

The concept of the body as a semantic vector represents a turning point in contemporary pedagogical reflection. It is no longer a matter of considering the body as a biological entity to be measured or as a support to be digitized, but of recognizing it as a living infrastructure of meaning, capable of generating, modulating, and transforming learning processes. From this perspective, the body actively participates in the construction of collective semantics: gestures, postures, breathing rhythms, prosody, and micro-expressions contribute to creating a shared context that shapes communication and cognitive processing (Digennaro, 2021). Corporeality thus becomes a medium intertwining cognitive, affective, and relational dimensions, allowing the classroom to be read as a dynamic ecosystem. Recent studies have emphasized how the valorization of the body in education is central to developing authentic and inclusive forms of learning. Research on learning ecologies highlights that learning is never an individual and isolated process, but takes place within networks of relations that include human and non-human actors, as well as digital and material environments (Peters, Guitert-Catasús, & Romero, 2022). Within these ecologies, the body is not a mere receptor of stimuli but an agent contributing to the construction of shared meanings, making the educational experience a profoundly situated process. At the same time, embodied pedagogies have shown that bodily data collected through sensors, biometric bracelets, or computer vision systems are not limited to measuring phenomena but generate new practices of attention, memory, and decision. Rode and Stern (2023), for instance, demonstrate how digital tracking of physical activity contributes to creating pedagogical frameworks in which the body becomes a co-author of the learning process. This orientation connects to broader approaches in embodied cognition, according to which cognitive functions emerge from the continuous interaction between body, brain, and environment (Barton & Barrett, 2025). Assuming the body as a semantic vector therefore implies a double movement: on the one hand, recognizing the materiality of bodies and their cultural, motor, and experiential diversity; on the other, critically interrogating the technologies that mediate them. Not all bodies respond in the same way to sensory and digital stimuli, and this is why instructional design must be oriented toward a universal design for embodiment capable

of including different ages, abilities, and cultural backgrounds (Joshi, 2023). Within this framework, the body becomes not only an object of detection but also a co-designer of its own educational pathways, able to actively influence the criteria and practices that define contemporary learning.

3. Towards quantum literacies

In recent years, pedagogical debate has begun to question how the principles of quantum mechanics can contribute to renewing the notion of literacy in education. Quantum literacy does not merely consist of transferring knowledge of physics to students but aims to provide conceptual and metaphorical tools for interpreting the complexity of educational processes. It situates itself within the trajectory of new critical literacies that have accompanied the digital society—from media literacy to digital literacy—but distinguishes itself through an emphasis on three fundamental dimensions: the simultaneity of possibilities, the instantaneous correlation between events, and the probabilistic nature of decisions (Nishanth et al., 2022). From this framework, two main trajectories emerge. The first is entanglement literacy, which proposes reading the classroom as an interconnected system in which the action of one individual immediately influences the entire context. In educational terms, this means recognizing that what a student does—for instance, a contribution in a discussion or the choice of a work strategy—has effects that propagate throughout the group, generating dynamics of cooperation and shared responsibility. The second is superposition literacy, which values indeterminacy as a didactic resource. In a classroom understood as a laboratory of possibilities, alternative hypotheses are not prematurely discarded but can coexist, be recorded, and simulated before collapsing into common decisions. This approach overcomes the binary rigidity of traditional testing and encourages students to explore multiple scenarios, fostering creativity and critical thinking (Oikonomou, Savvas, & Iatrellis, 2025). At the practical level, interesting experiences are emerging. Some STEM laboratories have begun to use quantum simulators to introduce the concepts of superposition and entanglement through problem-solving activities in small groups (Lemo et al., 2025). Digital twin platforms make it possible to experiment with multi-state decisions, supporting the idea that educational reality is not linear but probabilistic. For example, students and teachers can construct parallel decision maps and visualize in real time how different choices produce different outcomes. Assessment is also open to these innovations: rather than reducing performance to a single result, it becomes possible to record the path of generated hypotheses, discuss the criteria adopted, and document cognitive and collaborative processes (Nita et al., 2023). Alongside these opportunities, significant challenges remain. The complexity of quantum concepts requires careful pedagogical mediation to avoid misunderstandings and oversimplifications, and teacher training becomes crucial for integrating quantum literacies responsibly. Moreover, access to simulators and advanced infrastructures is not uniform, with the risk of widening the gap between well-resourced schools and those less equipped (Joshi, 2023). For this reason, quantum literacies should be understood as critical literacies rather than mere technical introductions, with the aim of fostering a deeper understanding of the interdependencies between knowledge, technology, and society.

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4. The three dimensions of the classroom as a socio-material ecosystem

Rethinking the classroom as a socio-material ecosystem means recognizing that every educational process is constructed through the co-presence of bodies, technologies, and material infrastructures. This perspective, consolidated by the literature on learning ecologies (Peters et al., 2022), invites us to move beyond the vision of the classroom as a neutral space, highlighting how practices, tools, and environments are intertwined in the generation of meaning. The classroom thus becomes a relational place in which three dimensions intersect dynamically: the cognitive-affective, the techno-algorithmic, and the eco-material. The first dimension is the cognitive-affective, which centers on the role of gestures, postures, breathing rhythms, and micro-expressions in the educational process. These bodily elements, often underestimated compared to verbal language, contribute to the construction of a shared collective semantics. Eye coordination, prosodic management, use of space, and motor synchronization in group work are not merely indicators of internal states but actual producers of context and meaning (Barton & Barrett, 2025). In this dimension, the focus shifts to the body's ability to create affective resonance and generate belonging, aspects particularly relevant to educational inclusion (Joshi, 2023). The second dimension is the techno-algorithmic. Here, bodily patterns are translated and interpreted by systems of computer vision, biosensors, and neural networks. Wristbands that detect heart rate variability, cameras that estimate posture, microphones that analyze prosody, and dashboards that aggregate signals into indices of attention or collaboration are concrete examples of how the body is rendered legible by digital devices (Rode & Stern, 2023). These technologies do not merely record but retroactively shape teaching practices, influencing cognitive and motor habits. Generative platforms, integrated with the data collected, can propose personalized activities, study recommendations, and learning pathways, also providing explanations of their choices in a process of continuous negotiation between students, teachers, and systems (Zawacki-Richter et al., 2025). Finally, the third dimension is the eco-material, which draws attention to the physical and often invisible infrastructure that makes digital mediations possible. Lithium mines for device batteries, energy-intensive data centers, photonic interfaces, and cryogenic systems required for quantum processors constitute the material backdrop on which educational practices rest (Buccini, 2023; Lemo et al., 2025). This awareness encourages us to consider the environmental and energy impact of technologies not as an external element but as an integral part of education itself. Attention to the ecological costs of educational choices thus becomes part of citizenship training, fostering critical sensitivity and planetary responsibility. Interpreting the classroom as a socio-material ecosystem therefore means holding together affective corporeality, algorithmic mediation, and material infrastructure, recognizing how each of these dimensions participates in the co-construction of meaning. Only an approach that values their interaction makes it possible to envision educational practices that are genuinely inclusive and sustainable.

5. The fourth interpretive axis: body and qubit

Alongside the three dimensions of the classroom as a socio-material ecosystem, a fourth interpretive axis emerges that opens the way to a new educational semantics: one grounded in the principles of qubits, particularly superposition and entanglement.

While the first three dimensions describe the co-construction of meaning through bodies, algorithms, and material infrastructures, the introduction of the quantum paradigm makes it possible to rethink the very nature of decision-making and assessment processes in education (Nishanth et al., 2022). Entanglement literacy allows the classroom to be interpreted as a correlated system in which the action of each subject does not have isolated effects but is immediately reflected across the entire group. In this sense, cooperation is not merely an ethical value but becomes a structural condition of learning: what a student does "propagates" effects onto others, generating reciprocal responsibility and shared awareness (Oikonomou, Savvas, & Iatrellis, 2025). In parallel, superposition literacy values indeterminacy as a creative resource. The classroom thus becomes a space in which alternative hypotheses coexist, are recorded and simulated, before collapsing into common decisions. This perspective fosters a pedagogy of multiple possibilities, capable of transcending binary logics and stimulating critical creativity (Nita et al., 2023). The first educational applications show that quantum simulators and digital twin platforms can be used to explore multi-state decision-making scenarios. In STEM contexts, for instance, students and teachers experiment with activities in which each choice opens parallel branches, allowing them to compare alternative outcomes and collectively discuss the criteria adopted (Lemo et al., 2025). Assessment, in this framework, moves away from the hegemony of standardized testing to take the form of transcorporeal portfolios that interweave physiological traces, metacognitive reflections, and explainable algorithmic logs. In this way, the body ceases to be passively measured and becomes a co-author of its own educational pathways. However, the integration of qubits into educational processes also raises significant challenges. On the one hand, there is the risk that the collection of bodily and quantum data may lead to practices of surveillance or extractivism, with a consequent reduction of educational freedom. On the other, the infrastructures required for quantum computation carry a considerable environmental cost—from cryogenic systems to energy-intensive data centers—that cannot be ignored (Berger et al., 2021). For this reason, it becomes essential to develop ethics-by-design approaches that guarantee transparency, informed consent, and participatory audits, thus avoiding reductionist drifts. Taken together, the body and the qubit open the possibility of rethinking education as a critical practice of inhabiting complexity. Far from being technocentric futurism, quantum literacy is configured as an opportunity to build forms of citizenship that are aware of the interdependencies between knowledge, technology, and the environment, orienting innovation toward fairer and more sustainable trajectories.

6. Conclusions

The analysis conducted highlights how the body, emerging technologies, and the principles of quantum mechanics co-constitute new scenarios for contemporary education. From the reading of the classroom as a socio-material ecosystem to the potential of quantum literacies, there emerges the need to conceive education as a non-linear, situated, and interdependent process. In this perspective, bodies are not simple receptors of information but semantic vectors that produce meaning together with algorithms and material infrastructures. The opportunities arising from this framework are significant. Educational inclusion can benefit from the valorization of the cognitive-affective dimension, where postures, gestures, and affective resonances

generate belonging and motivation. The techno-algorithmic dimension offers possibilities for personalization and adaptive support through the use of sensors and generative platforms, while the eco-material dimension strongly recalls the need for critical awareness of the environmental impact of technologies (Joshi, 2023; Berger et al., 2021). To these three directions is added the innovative contribution of quantum literacies, which introduce an educational grammar based on entanglement and superposition, opening the way to more flexible assessment practices and to pedagogies of multiple possibilities (Oikonomou et al., 2025). At the same time, challenges emerge that cannot be overlooked. The collection of bodily and biometric data raises ethical questions related to surveillance and privacy protection, while quantum and digital infrastructures entail non-negligible environmental and energy costs (Lemo et al., 2025). On the didactic level, the risk of reducing quantum concepts to mere rhetorical metaphors must be addressed through solid teacher training and careful pedagogical strategies, in order to ensure that quantum literacies become authentic tools of innovation and not mere slogans. From this reflection, three concluding assumptions emerge. First, the semantics of education in the twenty-first century is the result of the co-production of bodies, algorithms, and quantum states: neglecting one of these components means losing the complexity of the formative process. Second, only a metadisciplinary mindset, capable of connecting educational sciences, the philosophy of information, data science, and applied physics, can provide adequate tools for inhabiting the digital and post-digital transition. Third, the so-called "quantum revolution" must not be interpreted as technocentric futurism, but as an opportunity to reimagine the epistemic and material infrastructures of knowledge in an ethical and sustainable way. The emerging post-digital education is therefore not a simple integration of new technologies but the construction of a laboratory of living semiotics. In this laboratory, bodies, matter, algorithms, and qubits become resources for cultivating citizenships capable of facing eco-social complexity, orienting innovation toward fairer, more inclusive, and generative forms of planetary habitability.

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