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Article

Culturo-Scientific Storytelling

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Abstract: In this article, we reflect on the functions of outreach in developing the modern scientific mind, and discuss its essential importance in the modern society of rapid technological development. We embed our approach to outreach in *culturo-scientific thinking*. This is constituted by embracing disciplinary thinking (in particular creativity) whilst appreciating the epistemology of science as an evolving dialogue of ideas, with numerous alternative perspectives and uncertain futures to be managed. Structuring scientific knowledge as an assemblage of interacting and evolving discipline-cultures, we conceive of a *culturo-scientific storytelling* to bring about positive transformations for the public in these thinking skills and ground our approach in quantum science and technologies (QST). This field has the potential to generate significant changes for the life of every citizen, and so a skills-oriented approach to its education, both formal and non-formal, is essential. Finally, we present examples of such storytelling in the case of QST, the classification and evaluation of which correspond to future work in which this narrative approach is studied in action.

Keywords: storytelling; narrative; outreach; quantum; physics; technologies; culture; future

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1. Introduction

One of the greatest challenges facing our "society of acceleration and uncertainty" [1] is the need for resources to tackle the problems which arise from scientific and technological advancement, such as climate change and information management [2]. The most sustainable form of resources are people [3]: a population nurtured with the skills needed to navigate and support an ever-changing world. Educated citizens can contribute to science themselves, by employment in research, through citizen science methodologies [4], and through policy making [5]. Equally, such skills are necessary for them to be effective, efficient, and creative problem solvers in their own employment or social context [2].

It is also well understood that public awareness and acceptance of science is crucially important [6–8], particularly in those emerging areas which are rapidly developing and have an enormous potential to influence society in the coming decade, such as the focus of this article: quantum science and technologies. Many may know of and appreciate the mechanism of natural selection, although even this most famous of theories is fraught with misconceptions among the general public [9,10]. Yet how many are aware of the quantum nature of the matter of which we are all made, and how its properties can be leveraged to produce powerful computers [11], generate ultra-secure communication [12], and perform life-saving medical imaging with the utmost precision [13]. Within the coming decade, there will be an overwhelming scale-up of quantum technologies across the world [14]. The present public, particularly the young people currently of high school age, will be expected to compose the workforce of this emerging quantum industry [15]. As a result, it is crucial that awareness and acceptance of quantum science and technologies is as widespread as that of natural selection, and that the population are given the opportunity to engage with and understand them. In doing so, they may become informed and eventually active participants in the resulting technologically and culturally advanced society.

The contribution of public communication for this goal is well demonstrated by its prime position in research and study programs [16–21].

Scientists the world over are starting to appreciate and take responsibility for this duty [22,23]. However, the majority (even the most educated and enthusiastic for public communication) have not been offered guidance on how best to structure their activities, based on research of the education community—where much more thought has been put into every aspect of activity design.

These considerations have led to the emergence of the pilot Quantum Technologies Education for Everyone (QUTE4E [24]) devoted to outreach of emerging Quantum Technologies. The central philosophy of the project is that every citizen should have access to the essential concepts of QST, regardless of age and social or cultural background. The emphasis on education for "everyone" naturally calls for the design of generaliseable guidelines which educators can exploit to conceive of engaging narratives for outreach of quantum technologies, and the essential concepts of physics on which they rely, in a captivating and language-accessible manner.

In developing guidelines, we must first ask what outcomes we would want from our storylines. An inspiration is the collective writings of Howard Gardner, such as *Five Minds for the Future* [25]. Within this work, he poses the timely questions: What characteristics are we educating ourselves to? What "minds" do students need in order to be aware and skillful citizens in the future? Gardner's classification is into the disciplined, synthesising, creative, respectful, and ethical, but is not specific to the sciences. In this article, we reflect on the functions of outreach in developing the modern scientific mind, associated with rapidly developing fields such as quantum technologies. We consider how, with a suitably designed storytelling, outreach has the potential to bring about these positive transformations for the public.

2. Theoretical Framework

2.1. The Structure of Disciplinary Knowledge

All experimental sciences are fundamentally governed by the same laws of nature. Despite this, physics, chemistry, and biology, each describe their own subsets of nature with their own distinct discourses. Furthermore, the nature of the paradigmatic approaches, knowledge, and theories within fields of the same subjects are also different, such as the notion of absolute space and time in Newtonian physics, which is altogether distinct from the spacetime paradigm of relativistic physics. It was first highlighted by Schwab (1964, [26]) that a field with its own discourse establishes a disciplinary structure. Both in education and research, this structure is firmly respected to this day [27]. It is visible clearly in the titles of courses (e.g., "Fluid Mechanics" [28]), textbooks, (e.g., "*Introduction to Quantum Mechanics*" [29]), and scientific journals (e.g., "*Laser Physics*" [30]). To model this disciplinary nature, these fields can simplistically be considered separate collections of knowledge organised into a central nucleus of core defining principles, and a body of working theories and applications.

In their 2005 work, Tseitlin et al. [27] highlighted that this description does not incorporate the temporal evolution of the discipline, with ever-growing boundaries where the subject is being explored and rival, inconsistent theories are held. Such a viewpoint considers the historical development of the field to be of great importance [31,32]. Historical approaches to the field can be of great value even to modern day researchers, as these alternate viewpoints have proven many times to hold insights which can be useful to both learning [33] and to research [34] despite being outside the core paradigm. A common example in the context of QST is the Bohr Model, often cited as a historical approach to narrate the early days of quantum mechanics [33]. Rather than discarding these approaches, the discipline-culture (DC) framework formulates the discipline as a culture in itself, with its own language and discussions, whereby the alternate accounts fit into the periphery of the field. This triadic model is shown in Figure 1. The fundamental sciences each "pretend to describe the whole world" [27], whereas in reality they are better considered as a dialogue of multiple discipline-cultures, much akin to the way that numerous interacting cultures make up human society.

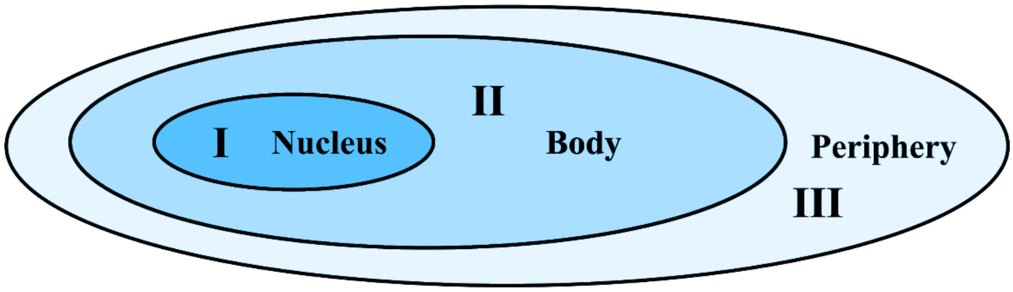


Figure 1. The structure of discipline-culture within the framework of Tseitlin et al. Adapted from [27].

2.2. Scientific Skills of the Modern Day: Culturo-Scientific Thinking

Scientific thinking is commonly understood as knowledge-seeking [35]. Inherent in this definition is a reliance on a "gap" in understanding which needs to be filled. The methodology for filling this gap is commonly known as the inquiry cycle [35]. It consists of observation, experimentation, and theory-building [36] in a continual process of refinement. From a disciplinary perspective, the literacies benefitting this methodology are the formal (mathematical), creative, and experimental [37]. It is important to note that, as Kuhn puts it: "to seek knowledge is to acknowledge that one's existing knowledge is incomplete" [35]. In order to truly think like a scientist, one must be searching for new explanations, theories, or observations of some aspect of nature that cannot be fully explained or described. It is embedded in inquiry as a cyclical process which recognises that there is more to know. Being comfortable and, crucially, self-aware of the limitations of one's theory, and that scientific knowledge is incomplete and ever-developing demonstrates advanced epistemological beliefs.

Arguments for the value of advancement in this area are numerous [27,38,39]. Within physics, epistemologies have been shown to influence conceptual understanding and attainment in high school [40] and university [41–44] settings. Such is the recognition of their impact that many measurement tools for these dimensions have been developed and become common features of evaluations of university programs [45,46]. As a result, features of educational activities which ensure that epistemologies are advanced have been identified, including incorporation of the historical and philosophical features of topics alongside scientific knowledge [47–49].

Knowledge-seeking could, at first glance, imply that scientific thinking is geared towards a completely objectivist perspective. However, this is not the complete picture. Einstein was aware that scientific concepts are "free creations of the human mind" [50], open interpretations of nature which are not unique. It is clear within the DC framework, where alternative interpretations are not discarded or incorrect, but are simply lying in the periphery, no less valid than those accepted paradigms in the nucleus and working theories in the body. What may be considered objective scientific discoveries fundamentally rely on theories which are themselves creations [51]. Creativity, then, is an essential component of the scientific process. It can be observed within the method of inquiry (through theory-building) [35,52], and is a routine skill of the working scientist in experimental design, problem-solving, hypothesis forming, and modelling [51,52]. The importance of narrative in science education is also well-understood [53,54]. Narrative thinking has been proposed as the vehicle by which not only scientists, but experts in all fields, make sense of information [55,56]. Since science is a creative endeavour, to seek and make sense of knowledge, in a sense, may involve unfolding a story in one's own head. Within those fields which are rapidly developing, such as quantum technology, there is a unique opportunity to present a narrative which highlights the forefront of scientific knowledge and understanding, and the possible future trajectories both of the field itself, but also of the field's impact on society. Doing so may enable students to develop the ability to model the future and manage uncertainty, based on understanding of the past and present. This concept has been formalised recently by Levrini et al. into future-scaffolding, a synthesis of skills including recognition of causality, scenario-thinking, and multi-perspective problem-solving [57]. In two rapidly evolving contexts, climate change and QST, teaching approaches carefully designed to foster future thinking have been shown to positively impact these skills [58,59].

Present education systems were not formulated taking these significant societal changes into account [57,58]. As a result, it is becoming increasingly important to design both formal and non-formal education which can support participants in actively engaging with not only research and development, but also the resulting social and cultural transformations. Clearly, and particularly in QST, citizens must think to the future [57,58]. In addition, contributing to rapidly developing society requires not only an appreciation of where technological development may lead us, but also an understanding of how these changes occur through research advancement. This requires a knowledge of how science is constructed through inquiry, and the ever-evolving nature of the resulting discipline-culture.

Ultimately, the skills supporting this cognizance may not exist in isolation. Individuals who are able to think scientifically and creatively, with an understanding of the ever-evolving nature of their field and its uncertain future, may be well described as possessing *culturo-scientific thinking* skills. Operationally, these skills may be constituted with scientific thinking, epistemological advancement, and future-scaffolding.

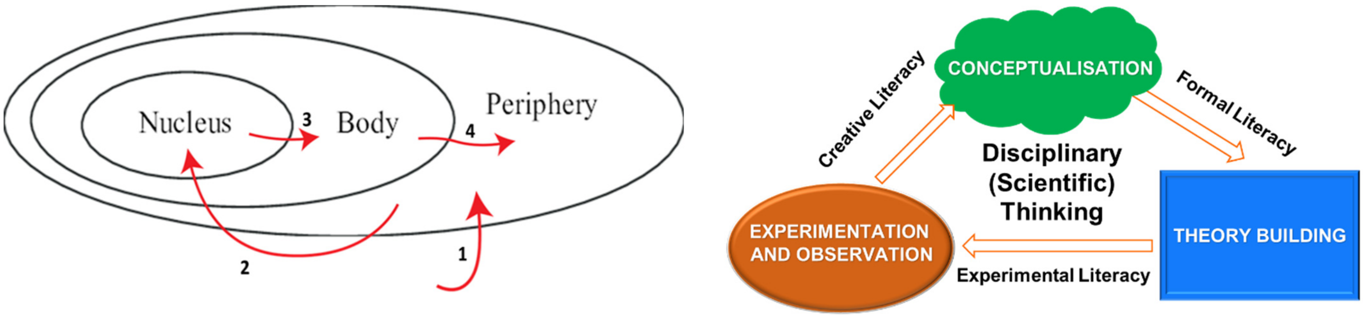
3. Storytelling for Culturo-Scientific Thinking

We believe that developing these traits at an early stage of students' careers should be considered one of the core goals of scientific outreach. Our philosophy is that students should be offered the chance to develop an interest in science and think like a modern scientist, able to actively engage with a rapidly developing society. In support of this, activities should be designed which reflect and provide opportunities for engaging with the scientific thinking process. They should enable students to themselves be scientists during the activity, by experimenting and observing phenomena, making sense of them creatively, and building theory to describe them. This element of role-play serves to centre the activity on the participants, with associated benefits for engagement [58], social development [59], and conceptual learning [60]. These benefits are well worth the effort required to engage participants with the scientific method of inquiry [61].

Scientists are always seeking new knowledge. As a result, they are continually exposed to the periphery of their discipline-culture, where there are alternative viewpoints and developing theories which are not fully understood. This characteristic is both valuable and accessible to highlight through outreach, whereby participants are puzzled with understanding the world. Thus activities should offer a means to place the participants in the realm of the periphery, encouraging their scientific thinking and highlighting the evolving nature of the field.

The *culturo-scientific* approach to outreach has been designed with these considerations in mind. We propose that activities follow the structure of the disciplinary thinking process, supporting this scientific role-play, whereas the overall narrative takes participants on a journey through the discipline-culture. Such storytelling structure (shown in Figure 2) has the potential to highlight that, particularly in the rapidly developing fields in which we focus, disciplinary knowledge is an unfolding dialogue of ideas, to which participants have the opportunity to contribute their own creativity.

The first entry to the field is through the periphery. A phenomenon is observed which is responsible for engaging students' curiosity. It may conflict with their internal working model of nature, puzzling them and offering a challenge to be met. In previous models based on the DC framework, such phenomena have been alternate theories and viewpoints which are generally considered historical in nature [62,63]. However, in rapidly developing fields such as Quantum Technologies, unexplainable phenomena can equally be future-oriented. In either case, participants are faced with the evolving nature of their field, allowing activities to support epistemological advancement.



(**a**) (**b**)

Figure 2. The *culturo-scientific* narrative. This approach explores the discipline-culture (**a**) in a journey reflective of the experiences of the scientist, whereby each topic is addressed with scientific thinking (**b**). This journey is constituted by an introduction with knowledge in the periphery (arrow **1**), later to be formalised into core principles in the nucleus (arrow **2**). Working applications can then be discussed and understood in the body (arrow **3**), before returning to the periphery to emphasise the evolving, incomplete nature of the DC (arrow **4**).

To make sense of a phenomenon, scientists must first define a core paradigm in which they can frame a model, such as the famous Copenhagen interpretation of Quantum Physics [64]. This brings us to the nucleus of the DC, presenting participants with a lens through which they can view the field. To reach an appreciation for a view of the world, even with a significant degree of guidance, demands strong creativity and is an inherently rewarding aspect of the scientific thinking process. Offering the inherently creative "eureka" or "aha!" moments is associated with a dopamine rush [65] and promotes motivation [66] and recall [67]. These serve as a means to ensure engagement and interest [68], and can be supported through thoughtful activity design.

Armed with a set of core principles, scientists are able to develop their everyday models and formal tools. These sit in the body of the DC, where the narrative focuses next. Here is where the conceptual understanding and formalistic thinking that is unique to the field is most benefitted, with participants able to address its core features. Traditionally, scientists work within this part of the framework for the majority of their time. However, what drives curiosity the most is not working with what is known and understood, but grappling with what is not. Indeed, this is inherent in the nature of scientific thinking as knowledge-seeking. As such, our narrative requires the audience to return to the limitations of their understanding, in the periphery. Observations are once again made without formal models which can yet describe them. In this cyclical narrative, the story does not end with the participant "succeeding" and believing that they now know comprehensively how to describe the world. Instead, they leave with an understanding that there will always be new features of their field to understand. Scientists are always at the edge of the periphery.

This *culturo-scientific* storytelling shares features with the day-to-day journey of the scientist. It is intended that not only the overall structure, but also the outreach activities themselves, should reflect this journey, and thus each should make use of the scientific thinking cycle (Figure 2b). Creative model-building, application, observation, and refinement should be present. There is also a close analogy between this narrative and that of the temporal development of the field itself. Indeed, this is no surprise, as the DC is inherently constructed over time by the entire scientific community, each individual engaged in their own research narrative and contributing to a whole.

4. The Field of Quantum Science and Technologies

4.1. QST in the Discipline-Culture Framework

The difficulty of teaching quantum physics concepts to students in high school has been discussed extensively among the physics education community [33,69–71]. There exists a well-known "paradigm shift" [72] associated with entry to the field, which leads to numerous misconceptions developing at all stages of formal education [70,72]. In the DC framework, this can be understood as moving from the classical DC to the Quantum one, with its distinct nucleus of core principles such as the Schrödinger equation, uncertainty, and superposition [62]. Without a clear narrative to access the nucleus, it may be no surprise that these challenging ideas can lead to difficulties. This was recognised by Weissman et al. [62], when developing a high school curriculum for quantum theory, referring to the importance of stimulating a discussion which contrasts the core, quantum, principles, and their applications with peripheral, historical accounts of the subject, such as classical determinism and light waves.

Their curriculum was mapped to the DC of quantum theory, in which most of the constituents of the periphery correspond to previous accounts of the field. Of course, this structure is not complete, as quantum theory is a subset of the larger discipline-culture of QST, which also encompasses topics from emerging technologies such as fully scalable quantum computing [11], residing in the periphery as a yet unrealised development.

4.2. Culturo-Scientific Storytelling for QST

A classification of outreach programs within QST has suggested that there exist two seemingly contradictory approaches taken to outreach of the discipline-culture of quantum physics. Some activities are designed to story tell the applications of quantum technologies, often linking them with their impact on society, such as through citizen science, e.g., [73,74]. Others approach the core concepts of quantum theory and the associated unique paradigm, highlighting the fascinating differences in how the world is understood in this field as compared to other areas of science, e.g., [75,76]. We propose that, with an appropriately designed *culturo-scientific* narrative, there should be no need to observe a clash. Both perspectives bring about different values, as the core concepts correspond to the DC nucleus, whereas quantum technologies mostly live in the body of the DC structure.

A quantum technology is typically the complex result of implementing, in a highly controllable manner, a set of core concepts. The high level of technicalities involved in the resulting product cannot be grasped even by more general experts in the field, and therefore, a comprehensible and useful narrative of a quantum technology must necessarily be grounded with the inspiring, underlying principles. These concepts can be built into an engaging narrative account of the procedure, in terms of difficulties faced and problems solved, that led to the realisation of that specific technology. Additional details of the technicalities would make the storytelling abstruse and hinder learning, whereas skipping the core concepts would impoverish it into a sequence of factoids and names. Failing to include the process would convey the message that science is magic. Working outwards from the nucleus to the body is therefore essential, and naturally affords an opportunity to develop a deep comprehension which can in turn be challenged by the constituents of the periphery. At each stage of the process (within the nucleus, body, and periphery), the cycle of scientific thinking should be engaged, challenging students to develop their own conceptualisations of the science resulting in the technology.

The narrative of QST, in particular the core concepts therein, represents a unique opportunity to educate citizens of all ages to a new way of thinking in which it is necessary to rely on senses beyond everyday perception. At the borders of the classical-quantum crossover [77], no direct perceptive experience of quantum phenomena is yet available. It is important to remark on the fact that this holds for both non-experts and experts in quantum physics and impacts both on their ability to interpret nature and model its uncertain futures. Thus, intuition and imagination, in turn feeding creativity, are invaluable skills to boost for all who work in the quantum world, and indeed necessary to truly grasp the phenomena therein.

4.3. Outreach Design for QST

As compared to formal education, outreach activities have a distinct advantage in not being limited to any formal curriculum. As a result, particularly in emerging fields such as QST, a focus on activities which are deeply engaging, such as gamified and creative experiences, can offer novel approaches and overcome some of the challenges educators are faced with in teaching quantum concepts with traditional means of instruction. To implement the *culturo-scientific* narrative should not necessarily require the production of new tools, as many exist already which can support these activities. Instead, we can classify and validate (in future work) the efforts of the community in developing activities which may support the approach, a comprehensive review of which can be found in reference [78]. These tools may enhance the experience of participants, particularly within the time limitations available in outreach activities [61]. Here, we briefly categorise the main types, and provide examples.

The first class of resources are those able to implement forms of experimental observation and/or hypothesis development and testing. For this, virtual labs [79–82] can be best suited to the learning outcomes of university and high-school students. Quantum games [83–85], such as those produced in game jams [86,87] can be preferred during activities limited in time or devoted to younger ages, to provide an operational approach focused around the more basic concepts. Although not currently in existence for QST, virtual and augmented reality-based simulations may also serve this need well. The creative induction of understanding and the formulation of new concepts can benefit from animations [88,89] and other resources supporting immersive visualisation, such as comics [90] and art-science installations [91]. Finally, tools that can support and complement forms of formal literacy in QST are conceptual labs [79,92] and quantum algorithms such as the *Qiskit* environment [93]. Particularly valuable in generating engagement are games such as *Quantum Odyssey* [94], able to provide experiences in which algorithms can be implemented in a fun and immersive environment. These "toolboxes" of existing resources able to support the disciplinary literacies of QST are shown below in Figure 3. An example of the application of *culturo-scientific* storytelling in QST is currently being studied in a series of workshops for high school students based around the Quantum Jungle [93], an art-science exhibition which functions as a tactile visualisation of the time evolution of a single quantum particle.

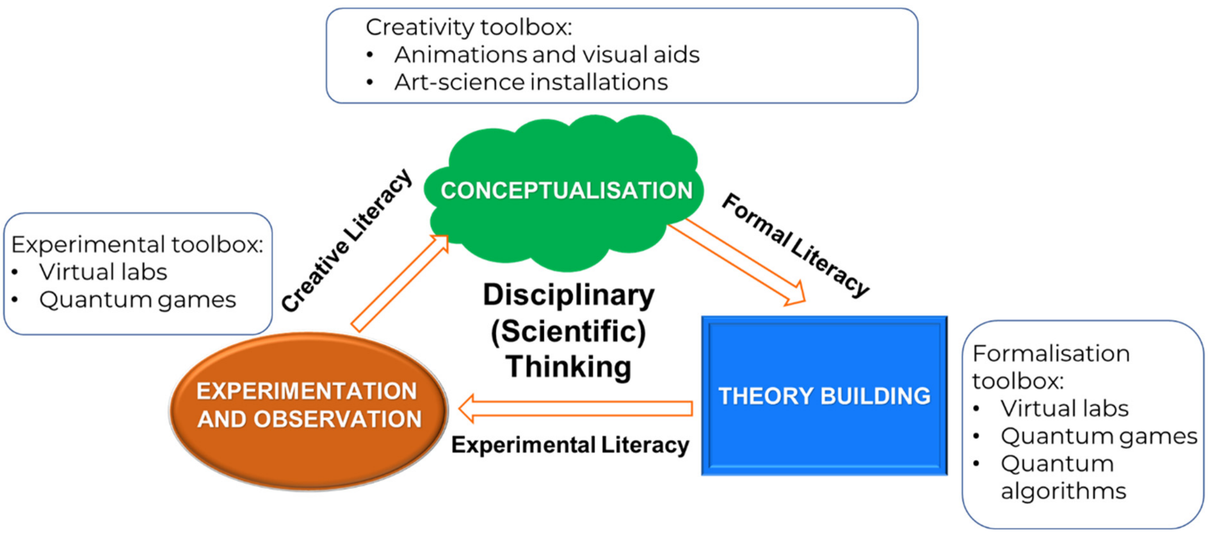


Figure 3. An example from QST of the design of outreach activities which benefit scientific thinking, utilising toolboxes supporting the creative, formal, and experimental literacies.

4.4. Discussion: The Culturo-Scientific Narrative in QST

Given the significance of the choice of storytelling for QST, the inherent impact of the narrative follows, as the resulting technologies will have such an enormous impact on society [94]. Their engineering opens the way to simulate pharmacological interactions and create customised therapies [95], or to produce more efficient fertilisers that are less polluting than is currently possible [96]. Materials will be developed capable of capturing and transforming carbon dioxide emissions [97]. Numerous other transformations will come in the fields of telecommunications, artificial intelligence, and information sciences [15].

These technologies stem from different sciences, such as physics, biology, medicine, computer science, and engineering. They will have profound implications felt beyond traditional boundaries, in fields such as economics [98], judicial sciences [99], and philosophy [100]. Their effect on our everyday life can be predicted to be significant, from the manner in which we manage our health and education, to how we communicate and store information [15]. Although the expansion of QST is clearly calling for a quantum-aware population, we can predict that the increasing interdisciplinarity will also need to be reflected throughout education and research. We might ask whether we should (in future work) conceive of *interdisciplinary-culturo storytelling*, reflective of the ever-tighter and more important interaction of the scientific DCs, increasingly driving technological innovations [101].

With such impact comes the need for responsible research and innovation (RRI) in QST [102], where narrative is of great importance in conveying dimensions such as diversity and equality, openness, and public engagement. For example, Quantum Technologies are expected to revolutionise the job market, where there is already critical under-representation of women [103] and minorities [104] in scientific careers. Outreach offers an opportunity to take crucial steps towards equality and inclusion. Thus, the narrative should highlight success stories of women and other under-represented minorities contributing to and leading the development of quantum technologies. Inspirational stories along these lines should make evident that such under-representation is purely an artefact of society, and not a barrier to the next generation of female and minority scientists. Furthermore, specialist knowledge should be openly accessible to the broad scientific community, citizens, and policy makers. Participatory [105] and citizen science tools may be a powerful means of public engagement which are capable of interweaving the experiences of these groups.

Finally, we note that with activities designed with a greater focus on conceptual understanding, making use of the tools for formalisation described above (see Figure 3), the *culturo-scientific narrative* may be specialised for formal education in schools. Although the focus of the work is clearly for outreach, we propose to, in future work, study its application as an inspiring and engaging storytelling for activities in the classroom too.

5. Concluding Thoughts

In this article, we have conceived of a structure for storytelling through outreach: the *culturo-scientific narrative.* This approach takes participants on a journey through the discipline-culture of the field in question, drawing them in with unexplainable knowledge from the periphery of the field, which may be deeply at odds with their internal model. In interpreting a paradigm by which this can be understood, curiosity is engaged and participants are able to access the working applications of the field. Finally, with the dual entry and exit through the periphery, where knowledge cannot be fully explained, participants are directly exposed to the reality of being a scientist: there is always more to learn, and no discipline-culture is ever "complete". By engaging participants through this narrative, outreach offers the opportunity to act as more than an educational activity, by becoming a role-playing tool wherein students are scientists themselves for the duration, exercising scientific thinking throughout.

The resulting skills, *culturo-scientific thinking*, are of essential importance in present society, currently undergoing a second quantum revolution. Our observations echo those observed in the context of climate change [58]. Skills, not just disciplinary knowledge, should be among the goals of science education in rapidly developing fields such as QST. This approach must be incorporated into activity design and educational policies, and the *culturo-scientific narrative* represents a first contribution towards this crucially important attitude.

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