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New Ways to Reimagine Quantum Physics by Bridging the Gap Between Teaching and Outreach

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We have developed different tools to reimagine quantum physics representations in teaching and outreach. We first describe the “Quantum Made Simple” project, a set of graphic animations, which display basic quantum phenomena in a coherent graphical language. We discuss the design choices we made and why teachers, researchers, or laymen should eventually use these animations. We then present “Quantum Design”, a collaborative project with designers to engage the general public with quantum metaphors. We discuss why these projects are hard to classify into categories a spectrum ranging from education to outreach and even art. These boundaries raise questions regarding how the fields of design, outreach and education sometimes overlap. We propose that this inter-disciplinary approach may help to provide new ways to present fundamental physics to the general public and also to the students.

1 Introduction

In the academic world, students encounter quantum physics sometimes at the end of high school in scientific sections and then in undergraduate physics courses in university. It is often taught in a traditional format combining formal courses and training exercises. Recently, a large community of physicists and science education researchers have used new technological tools to reimagine this teaching, developing simulations, remote or virtual labs, interactive screens, new visualizations or online environments (see for example the two sessions about quantum physics in the *Multimedia in Physics Teaching and Learning 2015 conference).*

Similar evolution has occurred in the field of outreach and informal science. Quantum physics is still being presented in traditional formats such as popular talks, books, articles or TV documentaries. The past ten years, however, have seen new formats and media emerge (Masserant, 2014) including short, engaging talks like Ted conferences, new types of videos like the Youtube channels Minute Physics or Veritasium, serious games (Lieberoth, 2015), new print formats, and finally artifacts (various types of creations) involving art or design (Bobroff, 2014).

Surprisingly, these evolutions in the education and outreach fields have occurred in parallel with no strong overlap. In fact, respective objectives, target audiences and prescribers are different and should not be confused. But a dialog and best-practices exchange between the fields of education and outreach could be mutually beneficial. Teaching could benefit from the strategies deployed in the outreach world on how to engage and captivate an audience. Likewise, outreach could benefit from the academic approaches in terms of scientific content and education tools, especially on more advanced topics, which are usu-

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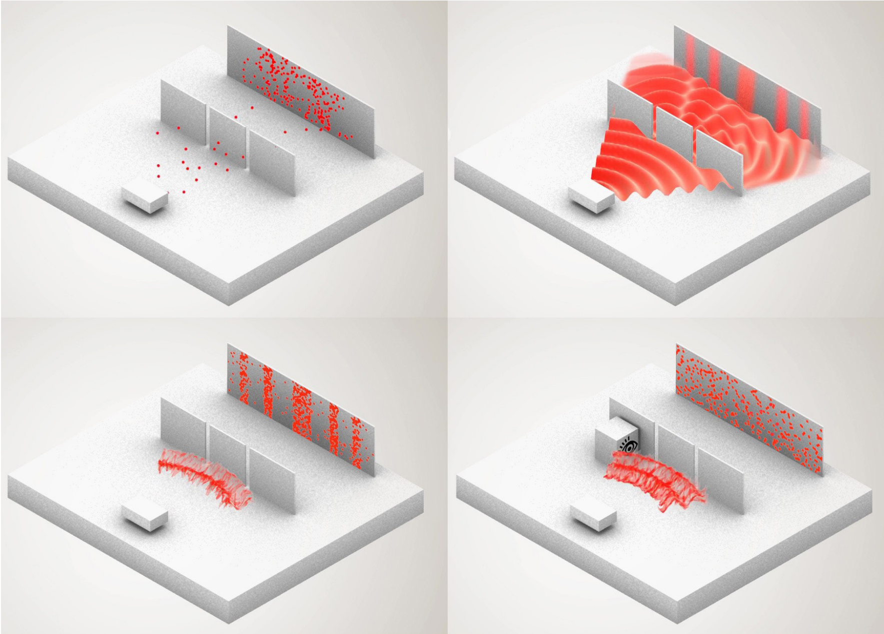

Fig. 1. Screenshots of the double slit experiment animation, displaying 1) particles 2) waves 3) quantum wave functions and 4) the same with an observer at one of the two slits (resulting in the destruction of the interference pattern) (full animation available at http://www.QuantumMadeSimple.com)

ally not even addressed by the outreach community. In addition, the academic world is not operating in isolation: physics students also use outreach resources in parallel with their courses, and may find it hard to reconcile these two points of view on the very same topics.

In this article we describe some collaborations where teachers and researchers from the academic world collaborate with outreach specialists, designers, illustrators and graphic designers to create innovative media about quantum physics (Bobroff, 2013). We focus on two typical examples of this process: first, a set of pedagogical animations designed with graphic and web designers, and secondly, a set of artifacts (design objects, devices, videos, books…) conceived with designers to make the quantum world more tangible and appealing. We will also discuss how these productions compare to more conventional outreach or teaching approaches and how they were used in both outreach and education contexts. This illustrates how bridges can be built between the outreach and education fields.

2 Quantum physics animations: the "Quantum Made Simple" project

In 2012, quantum physics was introduced in the French official curricula for scientific courses in the last year of high school (Lautesse, 2015). During training sessions organized in our lab, physics teachers complained about the lack of simple visual tools to depict basic quantum phenomena in a consistent way. We therefore decided to create the "Quantum Made Simple" project to address this need (accessible at www.QuantumMadeSimple.com).

The "Quantum Made Simple" project consists of a set of thirteen pedagogical animations in 3D about quantum physics provided in a website as well as a Youtube channel and used in various Wikipedia articles. These animations address both fundamental quantum properties (e.g. duality, quantization, spin, tunneling, etc.) and more recent research topics (e.g. graphene, decoherence, etc.) or research techniques (e.g. photoemission, pump-probe techniques, crystallography, etc.). The animations were developed thanks to a collabora-

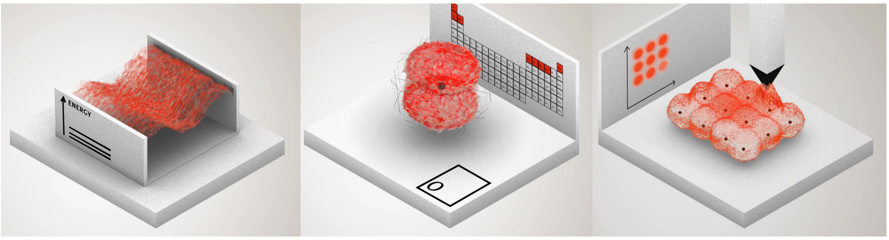

Fig. 2. Wave function representations in three different animations displaying 1) quantization in a box 2) atomic orbitals 3) scanning tunneling microscope (full animations available at http://www.QuantumMadeSimple.com).

tion between physicists from our university - researchers in condensed matter, optics, atomic and quantum physics - and graphic, web and sound designers (the DaFox agency).

Figure 1 shows a typical example, the animation of a double-slit experiment, which demonstrates the wave-particle duality. To represent the wave function, we chose red matter that behaves like a wave, but which is textured. This illustration helps to explain the difference between standard waves and particles. In order to ensure consistency between animations, the same red matter was used for wave functions in all contexts, as shown in figure 1 and figure 2: a free moving electron in a double-slit experiment, an orbital in an atom, or metallic delocalized electrons in a metal. The animations are displayed in an isometric framework. The horizontal plane is the basis for the quantum phenomena while vertical planes display physics measurements or mathematical spaces (energy levels, periodic table, STM imaging, reciprocal space...). They last from one to two minutes and are accompanied by a light subtitled legend. On the scientific side, the animations were not computed from exact simulations and do not represent rigorous treatments of quantum physics. They were developed as an easy-to-understand approximation of quantum phenomena for outreach. However, each animation was conceived with physicists who tried to be as accurate as possible, given the graphic constraints of representation and duration. For each animation, many round trips between the designers and the physicists were necessary. For each topic, an expert in the field of interest was included in the creation process. For example, David Clement, a physicist working on Bose-Einstein Condensation (BEC) in Alain Aspect's team participated to the conception of the BEC animation. After two years of use by various physicists all around the world, no major criticisms about the chosen representations were received.

As far as dissemination is concerned, all animations are gathered in a website with additional small articles introducing each effect, its applications and its use in recent fundamental research. (For example, the tunneling effect is used in both tunneling microscopes in fundamental physics and in electronic components for flash memory in industry.) Download is available in high resolution with captions in French, in English, or with no caption in case the explainer wants to develop their own oral support. Animations are also available on YouTube and in the sharing site www.commons.wikimedia.org under a creative commons license —which allows anyone to copy, redistribute, remix or transform the videos. They were incorporated in about thirty articles in the French and English versions of Wikipedia (see, for example, the entries "laser", "atomic orbital", "quantum decoherence", "Scanning tunneling microscope", etc.). The animations were broadcasted to physics teachers through specialized Internet forums, talks in teachers' conferences, teachers' trainings, Wikipedia and by word of mouth. Beyond teachers, the animations are now used in science museums (for example in an exhibit about quantum physics at the Science Museum of Virginia), in outreach talks, in popular science websites (for example futura-science.com), in science festivals (for example the World Science Festival in New York) and in the media. More surprising, they are also used for teaching quantum physics at university, usually as an accompanying visualization to a more formal approach (for example at Ecole Polytechnique in France or Aarhus University in Danemark). We even found out that a French textbook at undergraduate level uses snapshots of these animations to explain quantum phenomena, such as the electron band formation in a metal (Ribeyre, 2014). These were a-posteriori and unexpected uses of these animations.

In terms of audience, the QuantumMadeSimple.com website has had about 60 000 visitors this year, and the more successful animations were seen about 20 000 to 45 000 times each on Youtube. The largest audience, however, was probably reached with Wikipedia's articles displaying the animations even though it is hard to assess quantitatively. As an example, the "laser" English Wikipedia article is visited about 700.000 times per year.

From informal feedback over the past two years, we attribute this success to practical and design reasons. From a practical perspective, various users said that the animations were convenient because they were easy to download, available with and without legends, displayed no introductory credit panels or embedded logos, and were not too long.

On the design side, cognitive studies have tried to establish what the ingredients are for an animation to be effective (Wouters, 2008). First, contrary to conventional wisdom, dynamical animations are not necessarily superior to static graphics for learning (Lowe, 2003; Tversky, 2002). Mayer's cognitive theory of multimedia learning further shows that information is processed verbally (spoken and written) and non-verbally (pictorial) (Mayer 2001) and the two add positively. Thus, a verbal accompaniment to the animations is a key feature for pedagogy, when a supportive pedagogical agent guides the students and provides explanations (Wouters, 2008 and ref. therein). These cognitive studies imply that our quantum animations are not providing a sufficient pedagogical role alone, for example when being seen on Youtube by individuals. They are likely to be more effective when used by a teacher in his course or by a scientist in an outreach talk. Appearance and graphic design are also crucial as has been stressed in studies on both cognition (Shah, 2003; Weiss, 2002) and the science of communication (Bucchi, 2013). Whether it is called "cosmetic appeal" or "style", this aesthetic quality of the animations is often underestimated, and not easy to assess since it depends on the public and the on-going fashion. However, this notion of "nice looking animations" was often quoted as an important ingredient for the success of our animations, especially among the young adult audience.

These animations are at the frontier between education and outreach, both in their content and use in high schools, universities, science outreach centers and public events. They therefore have to be analyzed both by education, cognitive, and communication studies to tackle not only their pedagogical value but also their "engaging" nature.

3 Collaboration with designers: The "Quantum Design" project

While the former animations were more focused on the pedagogical side of outreach, we turn now to the other side of the spectrum, the "quantum design" project (accessible at www.designQuantique.fr). The "quantum design" project is the result of a collaboration between physicists and a French design school, ENSCI-Les Ateliers. The same partners had already undertaken a project about superconductivity (Bobroff, 2014a). After being introduced to quantum physics and having visited labs and discussed with physicists, design students were asked to produce artifacts and design projects but left with freedom to choose the format and purpose. The projects were supervised by professional designers in collaboration with the physicists. Contrary to usual collaborations between scientists and artists focusing on a specific technology or topic, this project explored a wide variety of formats (videos, devices, design objects, live animations, books, photos), subjects (basic phenomena and applications) and approaches (pedagogical, artistic, design-oriented). These productions offer a more intuitive, aesthetic and tangible approach to the quantum world, one that supplements the more pedagogical "Quantum Made Simple" animations.

A sociological and semiological study was carried out about this project's resulting

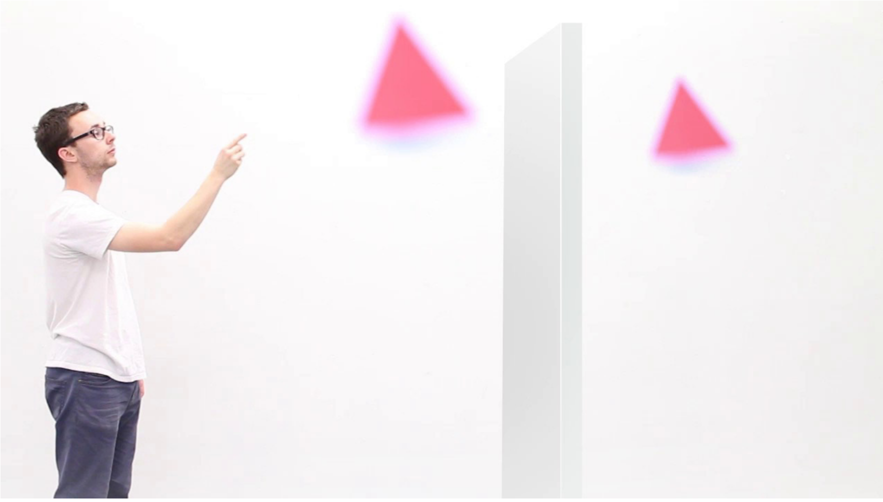

Fig. 3. Snapshot from the video "quantum thing" by the designer Paul Morin, which depicts a man manipulating large-size quantum wave functions, and in this image experimenting quantum tunneling.

artifacts (Jutant, 2015). It was based on a study of the creative process itself during the workshops, on interviews of the various actors (students, teachers, a physicist) and on the analysis of the artifacts. It revealed that the designers' productions prompt reevaluation of not only the outreach contents but also the format and process of outreach itself. Indeed, we found that such collaborations produce new types of multimedia and outreach projects, both in their format, by the way they represent physical properties, and in the way they are presented to an audience.

Some projects exploit and question the scientific representation in pedagogical artifacts. For example, "quantum thing" consists of a set of videos, which show a man handling an animated form with blurred edges representing a quantum object, as shown in Fig.3. By simple manipulations, it is shown what wave collapse, tunneling, entanglement or quantization could look like at our scale.

Another family of projects investigates the construction of analogies between quantum physics and the everyday world. For example, the "quantum apartment" displays daily life situations based on quantum metaphors, for example a woman waters her plants, and her downstairs neighbor observes water leaking directly from the ceiling.

A third set of projects explores the communication medium itself. For example, the project "Tutu Quanta" is a demonstration setup used in front of the public by a mediator; a set of tools (cardboard sheets, plastic cubes, mirrors, ink, oil, bubbles) are used to perform small manipulations that illustrate the formal representations of different quantum properties, such as atomic orbitals or wave-function collapse. This demonstration setup is packaged in a box that evokes a small theater.

A fourth type of project investigates the relationship between art and science. For example, "an approach under influence" is a set of devices inspired by quantum physics but with no intention of pedagogy or outreach use: wallpapers, animated lights, children's books, clothing, materials, containers, handbags...

These projects cover a full and continuous range from pedagogical tools to artistic or pure design objects in which it is difficult to draw a line between outreach, science and art. Even though these objects cannot be directly transferred into an academic framework, they help explore new types of visualizations and setups beyond the classical modes usually used for displaying physics.

4 Exploring new formats for outreach and teaching

In the past five years, we have developed many other outreach projects about quantum physics: folding activities, comic strips, postcards, experimental devices, websites, and videos… (accessible at www.PhysicsReimagined.com). All the projects involved collaboration between physicists and professional creative people (designers, illustrators, web designers, science explainers, artists…). These collaborations provided better insight into some potentially key ingredients for successful collaborative outreach or education projects. First, these collaborations are possible when physicists acknowledge their lack of expertise in design, graphics, web design or related areas. As an obvious consequence, these collaborations therefore imply a first stage of discovering each other's field of expertise. Time spent visiting each other's place of work in addition to small initial workshops without high expectations promotes discussion of respective skills and to ensure good relationships. Thereafter, the scenario and content of the production should not be unilaterally decided by the scientist alone but built with the designers, taking into account practical aspects. Designers must first get curious and engaged about the physics at play, forcing the scientists to find the proper explanatory tools and metaphors, which is both a constraint and an advantage of these collaborations. During the process of production, the scientist should clearly acknowledge its limits and not interfere with the design and aesthetic choices of the designer, provided the scientific meaning is not in question. Finally, from the outset of the project, strong emphasis should be placed on the future dissemination strategy, taking into account practical considerations such as formats, translations, logos, copyrights…

We want to stress a side-benefit of such design-science collaboration: these design and applied art schools have a long history in innovative project-based learning methods (Blumenfeld, 1991; Findeli, 2001). This inspired us to develop similar project-based courses in our own physics curricula. We created two new coursesteachings for third year physics undergraduates, one about outreach in physics and one about low-cost open-source tools for physics labs. Surveys could show their effectiveness in teaching physics differently (Bobroff, 2016; Bouquet, 2016).

In conclusion, this interdisciplinary production process helped us explore new types of media and designs to present quantum physics in a different light. We do not claim they should replace more traditional and rigorous approaches, but rather that they should be considered as one possible gateway to engage students with quantum physics. We also think that educators and teachers could learn a lot from designers and scientists about how to design efficient and engaging teaching media.

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