Alma Mater Studiorum · Università di Bologna

Scuola di Scienze
Dipartimento di Fisica e Astronomia
Corso di Laurea in Fisica

The Second Quantum Revolution:
Designing a Teaching-Learning Activity on the Quantum Manifesto to *Futurize* Science Education

Relatrice:
Prof.ssa Olivia Levrini

Correlatrice:
Dott.ssa Sara Satanassi

Presentata da:
Roberta Spada

Anno Accademico 2018/2019

Ad Alberto

Abstract

This thesis is the final result of a work within the "I SEE Project" (*Inclusive STEM Education to Enhance the capacity to aspire and imagine future careers*), a European Erasmus+ project, coordinated by the University of Bologna and involving six partners (http://iseeproject.eu). The work I carried out led to the design of a teaching-learning activity titled "Applications and Implications of Quantum Computers in Society" as part of an I SEE teaching module on Quantum Computers.

Both the I SEE project and the activity I designed aspire to contribute to two research debates in science education: the debate on STEM Education, and its position in research, institutional and educational contexts; the debate on the young people perception of future in this fast-changing and accelerated world.

The first chapter concerns the state of art of the debate on STEM education, both on a research and an institutional level, as a way to address key-issues regarding the problematic relationship between science and society.

In the second chapter, the I SEE Project is presented and collocated within the research in STEM Education. The chapter includes a description of how the I SEE Project strives to contribute to fostering the development of so-called *future-scaffolding skills* and to design an integrated STEM approach, with a description of the Finnish and Italian modules on Quantum Technologies.

The third chapter includes the description of the activity I contributed to designing. The activity has been built to reach several goals: to guide secondary-school students to get acquainted with the terminology, perspectives and contents of relevant institutional documents like the Quantum Manifesto; to analyse and reason about the future applications and implications of quantum technologies; to get aware about the multiple dimensions (at least social, economic, political, etc.) they involve and to recognise where and how the quantum technologies can impact their personal lives.

At the end, we discuss the results of the implementation of the activity, which happened in Bologna in February 2019 with 25 secondary-school students.

Sommario

Questa tesi è la conclusione di un lavoro all'interno di I SEE (*Inclusive STEM Education to Enhance the capacity to aspire and imagine future careers*), un progetto europeo Erasmus+ coordinato dall'Università di Bologna e che coinvolge altri sei partner (http://iseeproject.eu). Il mio lavoro ha portato allo sviluppo di un'attività didattica intitolata "Applicazioni e implicazioni dei computer quantistici nella società" che è parte di un modulo I SEE sui computer quantistici.

Progetto e attività mirano a contribuite a due dibattiti nella ricerca sull'educazione scientifica: quello sulla didattica STEM e sulla sua posizione in contesti di ricerca, istituzionali e didattici; quello sulla percezione del futuro da parte dei giovani in questo mondo in accelerazione.

Il primo capitolo riguarda lo stato dell'arte del dibattito sulla didattica STEM, da un punto di vista sia di ricerca che istituzionale, come modo di affrontare temi chiave che riguardano il rapporto problematico tra scienza e società.

Nel secondo capitolo, viene presentato il progetto I SEE e collocato all'interno della ricerca nella didattica STEM. È fornita una descrizione di come tale progetto contribuisce a promuovere lo sviluppo delle cosiddette *future-scaffolding skills* e a disegnare un approccio STEM integrato, con una descrizione dei moduli finlandese e italiano sulle tecnologie quantistiche.

Il terzo capitolo include la descrizione dell'attività che ho contribuito a sviluppare. Essa è stata costruita per raggiungere diversi obiettivi tra cui guidare gli studenti di scuola secondaria a familiarizzare con la terminologia, le prospettive e i contenuti di documenti istituzionali come il Quantum Manifesto, e rendersi conto delle tante dimensioni coinvolte, riconoscendo dove e come le tecnologie quantistiche potranno essere d'impatto nella vita del singolo.

Infine, si discutono i risultati dell'implementazione dell'attività avvenuta a Bologna nel febbraio 2019 con 25 studenti di scuola secondaria.

Table of Contents

Introduction

This thesis is the final result of almost a year of work within the "I SEE Project", a European Erasmus+ project, coordinated by the Research Group in Physics Education of the Department of Physics and Astronomy of the University of Bologna (http://iseeproject.eu). The work I carried out led to the design of a teaching-learning activity titled "Applications and Implications of Quantum Computers in Society" as part of an I SEE teaching module on Quantum Computers.

The I SEE project and, more specifically, the activity I designed aspire to contribute to two important research debates in science education: the debate on STEM Education, its meanings, roles and current implementations in research, institutional and educational contexts; the debate on the young people perception of future in this fast-changing and accelerated world. Indeed, one of the research questions the I SEE Project aims to answer is the following: How to promote an image of future where the irreducible *uncertainties* become sources of imagination for *possible scenarios*?

The thesis is divided into three chapters. The first chapter concerns the state of art of the debate on STEM education. Firstly, the chapter focuses on how the research on STEM Education problematises the meaning of "STEM" and suggests several definitions of *integrated STEM approach*. Secondly, the chapter analyses how international and national institutions—in particular the European Union, the Organisation for Economic Co-operation and Development (OECD), and the Obama Administration of the United States of America—refer to STEM education to address key-issues regarding the problematic relationship between science and society, such as the big institutional problem of how to promote responsible citizenship through science education.

In the second chapter, the I SEE Project is presented and collocated within the research in STEM Education. After recalling the conceptual origin of the project, the chapter includes a description of how the I SEE Project strives to contribute to fostering the development of so-called *future-scaffolding skills*. Then, after describing the way I SEE designs its own integrated STEM approach, the chapter describes the Finnish and the Italian modules on Quantum Computers.

The third chapter represents the core of my work since it includes the description of the activity I contributed to designing. The activity has been built to reach several goals, such as: to guide secondary-school students to get acquainted with the terminology, perspectives and contents of relevant institutional documents like the Quantum Manifesto (de Touzalin et al., 2016); to analyse and reason about the future applications and implications of quantum technologies; to get aware about the multiple dimensions (at least social, economic, political, research, educational, ethical, environmental) they involve and to recognise where and how the quantum technologies can impact their personal lives.

At the end, we discuss the results of the implementation of the activity, which happened in February 2019 with 25 secondary-school students at the Department of Physics and Astronomy of the University of Bologna.

Chapter 1

The Institutional Urgency of a New Science Education

In the last decade, great attention has been paid to Science Education, not only by educators and researchers in the field but also by institutions, policy makers, and business organisations.

To name a few, the United Nations Educational, Scientific and Cultural Organization (UNESCO) identifies ability in science and technology as “the key element in economic and social development” as well as promoting science education at all educational levels, and scientific literacy in society in general, as “a fundamental building block to building a country’s capacity in science and technology” (UNESCO, 2017). In 2011, the Obama Administration in the United States of America established the Committee on Science, Technology, Engineering and Maths Education (CoSTEM), in order to coordinate federal programmes in support of STEM education.

Even the European Union is one of the institutions and governments of the world that realised the importance of science education. As a matter of fact, this issue is included into one of the nine pillars of the “Horizon 2020” programme, a section called “Science with and for Society” (SwafS). Its aim is “to build effective cooperation between science and society, to recruit new talent for science and to pair scientific excellence with social awareness and responsibility” (European Commission, nd*a*).

All these institutional efforts have two elements in common: (1) The use of the acronym “STEM” with regards both to the scientific world in general and to scientific education, (2) The evidence of the tight relationship between scientific education and society, a relationship that is considered on different levels, from the simplest, such as the importance of science literacy, to the apparently less obvious—for instance, the claim that science education is important for building an inclusive society and responsible citizenship.

In the following sections, these two points will be analysed in greater detail.

1.1 What Does STEM Mean?

"STEM" is an acronym coined in 2001 at the U.S. National Science Foundation for indicating scientific subjects in education (Hallinen J., 2017). STEM disciplines are indeed Science, Technology, Engineering and Mathematics. But since its birth, STEM has had a strong political and institutional value.

According to Gonzalez and Kuenzi (2012), the term "STEM education" refers to teaching and learning in the fields of science, technology, engineering, and mathematics. It typically includes educational activities across all grade levels, in both formal and informal settings. But, as Kennedy and Odell (2014) state, "STEM education has evolved into a meta-discipline, an integrated effort that removes the traditional barriers between these subjects, and instead focuses on innovation and the applied process of designing solutions to complex contextual problems using current tools and technologies" (p. 247). Hence, the real shift from Science Education to STEM Education takes place when STEM is considered not as the combination of single topics from different subjects, but as a whole, as "an approach to teaching that is larger than its constituent parts" (National High School Alliance, nd, in Kennedy & Odell, 2014).

This led to the birth of STEM Education as a distinct branch of research in Science Education with its own peer-reviewed research journals, such as the "International Journal of STEM Education" and the "Journal for STEM Education Research". One of the main challenges in STEM education research is giving a definition of "integrated approach to STEM education". Let us now summarise some of the research questions and conclusions attained by the academic community so far.

Let us first define integration. According to Honey, Pearson and Schweingruber (2014), integration means "working in the context of complex phenomena or situations on tasks that require students to use knowledge and skills from multiple disciplines" (p. 52). Converging on science education, a continuum of increasing levels of integration can exist within a STEM practice. Vasquez (2014/2015) subtly identifies the following four levels:

i. *Disciplinary*, when students learn concepts and skills separately in each subject (no integration at all);
ii. *Multidisciplinary*, when students learn concepts and skills separately in each subject but in reference to a common theme;
iii. *Interdisciplinary*, when students learn concepts and skills from two or more disciplines that are tightly linked so as to deepen knowledge and skills. Students are not aware of which discipline the concept they are applying belongs to, and do not ask about it;
iv. *Transdisciplinary*, when, by undertaking real-world problems or projects, students apply knowledge from two or more disciplines and help to shape the learning experience. It is

the highest level of integration, as students develop interest for the challenge they are dealing with.

Moving on to the various definitions of integration in STEM education, Sanders (2009) defines integrated STEM education as "approaches that explore teaching and learning between/among any two or more of the STEM subject areas, and/or between a STEM subject and one or more other school subjects" (p. 21). He also points out that STEM practices are exemplars of a constructivist paradigm of education. In psychology, *constructivism* refers to the assumption that the mental representations human beings hold of reality depend on the specific characteristics of our perceptive system and on the functioning of our mind. In education theory, one of the ways in which this concept can be translated is *social constructivism*—whose father is Lev Vygotsky—, which is the claim that cognitive development depends essentially on learning processes that are conditioned by social interaction (Gagliardi & Giordano, 2014). Hence, integrated approaches to STEM education rely on the constructivist theory of knowledge and cognition, as they are intrinsically based on the provision of "a context and a framework for organizing abstract understandings of science and mathematics" and they encourage "students to actively construct contextualized knowledge of science and mathematics, thereby promoting recall and learning transfer" (Sanders, 2009, p. 23). Moreover, the so-called "STEM practices" are problem-based and enquiry-based teaching practices, the latter being, according to the OECD (2016b), science activities: (1) that lead students to study the natural world and to explain scientific ideas by engaging in experimentation and hands-on activities, and (2) that challenge and encourage them to develop a conceptual understanding of scientific ideas. This kind of science instruction is more and more correlated to positive outcomes in students' achievements (OECD, 2016b; Costa & Araújo, 2018). Social interaction, achievement, interest, motivation and self-efficacy are all considered critical for learning (Sanders, 2009) and fundamental to characterise an integrated STEM module.

The previous comments stress the fact that an integrated STEM approach is multi-faceted and encompasses real-world and problem-based learning. A definition that fully embraces this assumption is the one by Vasquez (2014/2015): "STEM education is an approach to learning that removes the traditional barriers separating the four disciplines and integrates them into real-world, rigorous, relevant learning experiences for students (Vasquez, Sneider & Comer, 2013)". The act of removing barriers separating the disciplines can be made in different ways and on different levels, to the extent that even this has become a research question in STEM education. Some of the literature argues that STEM practices lack full integration of all four subjects together, with prevalence of Science and Technology and to the detriment of Engineering and Maths (English, 2016). Indeed, according to Kelley and Knowles (2016), the creation of authentic contexts for STEM integration "can be as complex as the global challenges that demand a new generation of STEM experts" (p. 1).

In regard to this, the 2014 STEM Task Force Report of the United States of America says that the disciplines "cannot and should not be taught in isolation, just as they do not exist in isolation in the real world or the workforce" (p. 9). But the research question arising here is the following: As long as STEM works on the integration of four different subjects, with different styles of thinking and approaches, should STEM, in the end, valorise or abandon disciplines? On the one hand, there is the demand of institutions and corporations to shift education from a discipline-oriented approach to a skill-oriented approach (Kennedy & Odell, 2014). On the other hand, there is the traditional disciplinary approach that, among all the disadvantages, has the perk of affirming the epistemological differences between the subjects.

Another open question in STEM education research, risen by Li, Schoenfeld, diSessa et al. (2019), is whether STEM has its own domain-specific thinking, as STEM is formed by four different disciplines with four different epistemologies and ways of involving cognitive components.

1.2 The Institutional Standpoints About the Relationship Between Science Education and Society

One can see why STEM education is far more than a convenient integration of its four disciplines (English, 2016), and it is not by chance that politics and markets have been devoting more attention to STEM.

As a matter of fact, this new approach to science education was not originally born from the academic necessity of re-organising knowledge—the main reason of the birth of new fields of study—yet it was born due to an economic demand both from corporations, institutions and the labour market.

Institutional reports and policy briefs from OECD (2016a), the European Union (2015; 2018; Costa & Araújo, 2018) and the Obama Administration (CoSTEM, 2013; STEM Task Force Report 2014) all insist on the value of science education for achieving both economical and societal objectives. I identified the following areas and I am going to analyse them in the next paragraphs:

i. STEM education is essential for improving knowledge in science, technology, engineering, and mathematics across K-12 students, especially in light of the latest PISA results on science literacy among 15-year-olds.
ii. Future workforce calls for STEM skills and competences, and there is a skill gap between future jobs and current STEM graduates. Not only STEM education can give them to students of today, but it can also stimulate interest in STEM careers.

iii. STEM education, and the shift from STEM to STEAM with it, is considered critical for addressing societal problems and building responsible citizenship.
iv. STEM education is critical for building an inclusive society.

1.2.1 The Need for a Scientifically-Literate Society

The Programme for International Student Assessment (PISA) is a triennial international survey promoted by the Organisation for Economic Co-operation and Development (OECD) that aims to evaluate education systems worldwide by testing skills and knowledge of 15-year-old students (PISA, 2018); it evaluates the level of pupils on three areas: Science, Reading and Math. The 2015 PISA survey involved 72 different countries and a sample of 540 000 students. Science literacy was its specific object and it is defined as follows by OECD (2016c):

> "Scientific literacy is the ability to engage with science-related issues, and with the ideas of science, as a reflective citizen. A scientifically literate person is willing to engage in reasoned discourse about science and technology, which requires the competencies to:
>
> i. Explain phenomena scientifically – recognise, offer and evaluate explanations for a range of natural and technological phenomena.
> ii. Evaluate and design scientific enquiry – describe and appraise scientific investigations and propose ways of addressing questions scientifically.
> iii. Interpret data and evidence scientifically – analyse and evaluate data, claims and arguments in a variety of representations and draw appropriate scientific conclusions."
>
> (p. 22, box 2.2).

PISA 2015 also divides scientific knowledge into three elements (OECD, 2016c):

i. *Content knowledge*, knowledge of the facts, concepts, ideas and theories about the natural world that science has established.
ii. *Procedural knowledge*, knowledge of the procedures that scientists use to establish scientific knowledge.
iii. *Epistemic knowledge*, an understanding of the role of specific constructs and defining features, which are essential to the process of knowledge-building in science.

I took the definition of science literacy as a starting point not only because the majority of institutional literature refers to it, but also because it deeply resonates with the intent of STEM education to develop both content and epistemic knowledge in students, as enquiry-based practices are fully included in the PISA analysis (see OECD, 2016b, p. 69).

PISA indicates 13% as the OECD average for low achievers in science, reading and mathematics, meaning that they fail to reach basic competences in science. As far as the 28 Member States of the EU, the Education and Training Monitor published by the European Commission (2018) highlights that 20.6% of pupils across the European Union are low achievers. The U.S. share of low achievers is 13.6%, thus not significantly different from the OECD average. The countries with lowest percentages of low achievers are Macao (China, 3.5%), Viet Nam (3.5%), Hong Kong (China, 3.5%) and Estonia (4.7%) (OECD, 2016b).

In the light of these data, the European Commission (2018) highlighted the need to improve science education. The European Education and Training Monitor aims at reaching a maximum of 15% of low achievers as the target for 2020.

As for the U.S., the latest report is dated back to 2013 and refers to the 2009 PISA survey, emphasising the fact that the U.S. was not leading the world in science and mathematics (CoSTEM, 2013). The above may suggest the relevance that surveys like PISA can have in the context of policymaking in some Western countries: for instance, PISA 2015 has collected data on students' expectations towards science-related careers.

1.2.2 STEM Knowledge, Competences, and Skills for Tackling the Workforce Problem

Kennedy & Odell (2014) define STEM literacy in the words of the Nobel Laureate Leon Lederman, saying that "STEM literacy" in a knowledge-based economy is the ability to adapt to and accept changes driven by new technology work with others (often across borders), to anticipate the multilevel impacts of their actions, to communicate complex ideas to a variety of audiences, and perhaps most importantly, to find "measured yet creative solutions to problems which are today unimaginable". They also claim that scientific literacy is an essential constituent of the overarching goal of STEM education, which is to prepare all students for post-secondary studies and the 21st century workforce.

As a matter of fact, the STEM workforce issue is a common thread in the development of STEM education, as it was the main cause of engagement in the STEM approach in an institutional context, and it is currently a significant challenge for both the EU and the U.S. According to CoSTEM (2013), the President's Council of Advisors on Science and Technology estimates there will be one million fewer STEM graduates over the next decade than U.S. industries will need. As for Europe, EU Skills Panorama (2014) highlights that from 2003 to 2013, the number of people working in STEM occupations grew by 12%, three times as much as total EU-28 employment, and that STEM occupations now account for 7% of all jobs. According to Joyce (2014), by 2020 more than 800 000 technology jobs will be unfilled due to skill gap, and even lower level positions will require increasing levels of STEM knowledge and competence. Furthermore, the so-called "STEM skill gap" also refers to the "growing disengagement of young people towards STEM subjects in schools and decreasing interest in STEM careers" (Joyce, 2014, p. 2) especially in secondary schools. STEM shortages are already evident in Austria, Flemish Belgium, Czech Republic, Germany, Hungary, Italy and the UK. The areas where the problem is more acute are engineering and ICT.

The way the European Union chose to tackle this emergency is by the renewal of STEM education and its framing into the European Key Competence Frameworks. In order to talk about this, it should be noted that the institutional literature pays great attention to the distinction between knowledge, skills and competences (Joyce, 2014; European Commission, 2016):

i. *Knowledge* is the outcome of the assimilation of information through learning.
ii. *Skill* means the ability to apply knowledge and use know-how to complete tasks and solve problems (and can be cognitive or practical). Skills can be *cognitive*, *methodological* or *social*.
iii. *Competence* means the proven ability to use knowledge, skills and personal, social and/or methodological abilities, in work or study situations and in professional and personal development. Competences are seen more broadly than skills, are they refer to the ability of a person to use and apply knowledge and skills in an independent and self-directed way.

This definition is part of the European Key Competence Framework and the European Qualifications Framework; these are two important starting points for coherently implementing objectives and recommendations in order to achieve a skill-oriented education for Europe, especially in higher education. Then, another European Commission report in 2016, "Developing future skills in higher education" (European Commission, 2016), linked the development of knowledge, skills and competences to the acquisition of social and civic competence, as well as to employability for graduates, in accordance to the objectives of the 1999 Bologna Process for Higher Education. The latest publication regarding this issue is the 2018 "Council Recommendation on Key Competences for Lifelong Learning" (Council of the European Union, 2018). Its objective was to update the 2006 European Reference Framework of Key Competences for Lifelong Learning, which originally defined eight competences:

i. Communication in the mother tongue;
ii. Communication in foreign languages;
iii. Mathematical competence and basic competences in science and technology;
iv. Digital competence;
v. Learning to learn;

vi. Social and civic competences;
vii. Sense of initiative and entrepreneurship; and
viii. Cultural awareness and expression.

Moved by the claim that young people cannot be equipped anymore with a fixed set of skills and knowledge and that "they need to develop resilience, a broad set of competences, and the ability to adapt to change", the Council of the European Union chose to recommend the development of a competence-oriented education, which focused especially on digital and STEM competences:

> "In order to motivate more young people to engage in science, technology, engineering and mathematics (STEM) related careers, initiatives across Europe started to link science education more closely with the arts and other subjects, using inquiry-based pedagogy, and engaging with a wide range of societal actors and industries. While the definition of those competences has not changed much over the years, the support of competence development in STEM becomes increasingly relevant and should be reflected in this Recommendation." (p.15).

The Recommendation says also that Member States should "support the development of key competences paying special attention to […] fostering the acquisition of competences in sciences, technology, engineering and mathematics (STEM), taking into account their link to the arts, creativity and innovation and motivating more young people, especially girls and young women, to engage in STEM careers".

The use of the word "competences"—i.e. "the proven ability to use knowledge, skills and personal, social and/or methodological abilities"—is not accidental, as it refers to the final objectives of the STEM integrated approach, which is a no-nonsense idea of tackling the need for a skill-oriented education.

Moving on to the U.S. Obama Administration, a strategic plan was made in order to direct federal investment towards the improvement of STEM education (CoSTEM, 2013). Given the importance of a STEM-literate society and the need to better prepare students for today's jobs and those of the future. In the words of the former President of the United States Barack Obama:

> "We want to make sure that we are exciting young people around math and science and technology and computer science. We don't want our kids just to be consumers of the amazing things that science generates; we want them to be producers as well. […] We've got to make sure that we're training great calculus and biology teachers, and encouraging students to keep up with their physics and chemistry classes... It means teaching proper research methods and encouraging young people to challenge accepted knowledge." (p. 1)

The U.S. is tackling this challenge through the following strategic priorities:

i. Improve STEM Instruction;
ii. Increase and sustain youth and public engagement in STEM;
iii. Enhance STEM experience of undergraduate students;
iv. Better serve groups historically underrepresented in STEM fields; and
v. Design graduate education for tomorrow's STEM workforce, by the means of fellowships and traineeships for students with high potential, but also of giving students more autonomy at the beginning of their academic career and encouraging them to set and meet more ambitious goals in research, education, and service.

In particular, the coordination approaches for improving STEM education are:

i. Building new models for leveraging assets and expertise; and
ii. Build and use evidence-based approaches.

The following government, the Trump Administration, did not leave the question pending, as the STEM shortages in workforce still exist (for further information, see The White House, 2018).

1.2.3 STEM for Addressing Societal Challenges and Building Responsible Citizenship

Another issue in which STEM education can be crucial is the relationship between science and society. Too often science is seen as something separate from all other subjects or disciplines in education, disconnected from people's lives beyond school (SiS.net, 2016). Moreover, the loss of trust in science is more and more evident in our contemporary world. Not only promoting a culture of scientific thinking can bring people and science together again, yet it can also contribute to give citizenship competences. In particular, the STEM approach can allow to learn how to critically reason upon crucial issues for the future—such as global warming, artificial intelligence, industry 4.0 or the Internet of Things. As a matter of fact, by the means of integrated STEM practices, science, technology, engineering and mathematics are not anymore neither isolated nor monolithic, they cannot exist without a surrounding context permeated by the other subjects, whether they are the other letters of the acronym or "arts" or "all the others". The gathering of STEM subjects with arts or all the other subjects within an integrated approach is called "STEAM". The research literature always refers to STEAM as "Science, Technology, Engineering, the Arts and Mathematics. The European Union, instead, gives to this acronym a unique meaning—"Science, Technology, Engineering, Mathematics and All the others"—in order to highlight the insertion of STEM disciplines into an all-round interdisciplinary context, a possible way to address non-scientific challenges with a scientific approach (European Commission, 2015).

The report by the expert group on science education within SwafS *"Science Education for Responsible Citizenship"* (European Commission, 2015) clearly links the importance of science education to the purpose of addressing societal challenges: It states that meeting the main objective of the European strategy—a smart, sustainable and inclusive growth—is connected to the ability of our societies to educate smarter, more creative and entrepreneurial individuals and to generate new knowledge to adapt to technological change. Therefore, knowledge *of* and *about* science are considered "integral to preparing our population to be actively engaged and responsible citizens, […] and fully aware of and conversant with the complex challenges facing society" (European Commission, 2015, p.14).

If it is assumed that tackling the range of future global challenges can be easier if all societal actors understand the issues and their consequences and are actively involved in helping identify and monitor society's responses (European Commission, 2015), science education becomes essential. The report identifies several areas where science education can make a difference, which are considered to be critical for the future of European citizens. Scientific education is indeed not considered limited only to the school years, yet it is seen as an integral part of society, as "an essential component of learning continuum" (European Commission, 2015, p. 8). According to this vision, science education should not just inspire children to aspire to careers in science and all sorts of professions that underpin our knowledge and innovation-intensive societies and economies; it can help promoting a culture of scientific thinking as well, in order to inspire citizens to use evidence-based reasoning for decision-making, as well as giving them confidence, knowledge and skills to actively manage the increasing complexity of scientific and technological issues. Furthermore, from an economic perspective, it can nurture an innovative Europe-wide environment, where companies and other stakeholders from around the world would want to invest. Lastly, science education can empower responsible participation in public science conversations, debates and decision-making for tackling the big challenges facing humanity today, by means of the promotion of Responsible Research and Innovation (RRI)—which is "an approach that anticipates and assesses potential implications and societal expectations with regard to research and innovation" (European Commission, nd*b*). Several objectives were identified in order to construct a series of recommendations for European and National implementation (see European Commission, 2015, pp. 28-34).

STEM education is also considered critical for building inclusive societies both by the EU and the U.S., especially as far as gender equality is concerned.

In Europe, science-and-society issues are undertaken by Responsible Research and Innovation, which has six areas of intervention (European Commission, 2014):

i. Public Engagement in science;

ii. Gender Equality;
iii. Science Education;
iv. Open Access and Open Science;
v. Ethics in Research and Innovation;
vi. Harmonious governance models for implementing RRI.

Inside the RRI framework, gender aspects in science education involve two main focus of interest: (1) Gender inclusive participatory approaches for challenging stereotypes and encouraging equal participation of boys, girls, men, and women in science activities and careers; (2) The Integration of Gender Analysis into Research (IGAR), which aims to avoiding gender bias in the science production (SiS.net, 2016). Science education can tackle this issue by facilitating the entrance of girls in academic research and careers, as well as encouraging synergies between STEM subjects and the arts and humanities, in order to make visible the role women can play in making these links. Moreover, emphasising the presence of positive female role models at all levels of education can also be a step forward towards gender equality, at all levels of education.

In the U.S., the gender cause goes side by side with the ethnical issue concerning minorities within the U.S. population. According to CoSTEM (2013), STEM participation and achievement statistics are especially alarming when it comes to women and minorities, categories which are highly underrepresented in STEM. Just 2.2% percent of Hispanics and Latinos, 2.7% of African Americans, and 3.3% of Native Americans and Alaska Natives have earned a first university degree in the natural sciences and engineering by age 24. Likewise, only 25% of women—which constitute 46% of the overall workforce—hold a STEM job, even if women constitute the majority of students on college campuses and student diversity is increasing as a reflection of the demographic change among minorities. The report stresses the importance of the presence of minorities and women in science and gives three reasons: the sources for future STEM workforce are not sufficient; the demographics of the population is dramatically shifting; and diversity of ideas and perspective in STEM is a strength that benefits both diverse groups and the Nation as a whole. The solution that is being implemented is to emphasise education at critical transition points from P-12 to post-secondary education and from the latter to the STEM workforce, when it is statistically more probable that underrepresented groups drop out of the so-called “STEM pipeline”, the educational pathway for STEM students. Finally, there have been several presidential initiatives to accentuate the importance of role models—also by recognising the presence of female “hidden figures” in the history of American scientific progress—and education for minorities and girls in STEM, such as: STEM for All, Change the Equation, and the Women in STEM mentoring programme (The White House, nd).

All that emerges from the institutional literature about STEM is a leap towards the future and a vision of education as a means of training new generations for tomorrow. The I SEE Project, which I will outline in the next chapter, focuses precisely on this: giving *future-scaffolding skills* to young generations through STEM education.

Chapter 2

The I SEE Module on Quantum Computers as a Way of Joining STEM Education and the Future

2.1 The I SEE Project and its origins

As an EU-funded initiative, the I SEE Project finds its place within the institutional urgency of using STEM education as a way of building an inclusive and responsible society. I SEE (Innovative STEM Education to Enhance the capacity to aspire and imagine future careers) is indeed a triennial project coordinated by the Department of Physics and Astronomy (DIFA) of the University of Bologna. It involves a strategic partnership between four European countries (Finland, Iceland, Italy and the UK) with a total of seven partners (I SEE, 2019):

i. Two universities, the University of Bologna and the University of Helsinki;
ii. Three secondary schools, the "A. Einstein" scientifically-oriented secondary school in Rimini (Italy), the Helsinki Normal Lyceum (institutionally part of the University of Helsinki), and the Hamrahlid College of Reykjavik;
iii. The NGO "Eco-Schools Iceland" and the Association of Science Education (UK);
iv. The Fondazione Golinelli in Bologna.

The premise of the project is that of creating "an approach in science education that addresses head-on the problems posed by global unsustainability, the uncertainty of the future, social liquidity and the irrelevance of STEM education for young people and their future" (Branchetti, L., Cutler, M., Laherto, A., Levrini, O. Palmgren, E.K., Tasquier, G., & Wilson, C., 2018, pp. 11).

Concretely the project foresees that the approach is applied in the development of teaching modules for upper secondary school (16 and 18-year-old students) on advanced STEM topics (e.g. climate change, artificial intelligence, quantum technologies). Besides teaching modules, I SEE has been producing guidelines for teachers, policy recommendations and research-based case studies on the impact of the modules on students' learning and on their perception of the future.

The philosophy of the project and its general aims ground their origin in the book that Benasayag & Schmit wrote in 2004 where they, very clearly, claimed about the deep change in the young generations in their perception of the future.

Indeed, according to Benasayag & Schmit (2004), the Western culture has always been characterised by the vision of future as progress, as a “not yet” that discloses the hope and promise of a future realisation by the means of the progress of knowledge. Nowadays, instead, we witness the shift from a boundless trust to an equally extreme diffidence towards the future, resulting in a pessimistic mood surrounding the latter. This prevailing uncertainty could be also the result of an unfulfilled promise: indeed, scientist positivism promised that deterministic knowledge would have solved every human problem, until the complete domination of nature. This idea collapsed when the development of rational knowledge did not give birth to a universe only disclosable by deterministic models, therefore leading to a sense of powerlessness and uncertainty, but also to the possibility of existence for other non-deterministic paradigms of rational thought.

Two sociologists, Hartmut Rosa and Carmen Leccardi, depict the situation in particularly effective ways. Rosa (2010), theorist of the social acceleration, identifies different dimensions of such acceleration in society: technological acceleration, acceleration of social change, and acceleration of the pace of life. In particular, technological acceleration refers to new forms of organisation and administration which are intended to speed up operations. This culminated in the shrinking of time and space in the individuals’ mind. Carmen Leccardi (2009) analyses “time” as social institution and links the society of acceleration with the increasing uncertainty of young people facing the transition to adult life. The young live their life phase in a social atmosphere where the right to choose who one wants to become goes hand in hand with the difficulty in finding points of reference in the biographical construction that can avoid uncertainty.

One question that arose to researchers in science education within this global situation is the following (Levrini, O., Tasquier, G., Branchetti, L., & Barelli, E., under review): Can science teaching contribute to developing skills for managing (rationally and emotionally) uncertainty towards the future and for projecting imagination forwards? If so, how?

To answer this question, the I SEE Project developed an approach that aims at combining STEM education with Futures Studies, an interdisciplinary field that investigates the way people think about the future. As a matter of fact, the future is simultaneously intrinsic to science, to societal challenges, and to the process of personal engagement. It is intrinsic to science in the way the process of modelling *per se* is intrinsic to science and it is nowadays deeply debated, for example, within applied physics where the science of complex systems is taken as a point of reference. Indeed, the science of complex systems laid the foundations for an epistemology that puts concepts such as uncertainty, emergence, feedback, projections, and probability at the centre (Gammaitoni & Vulpiani, 2019). Such an idea of science enriches and somehow counterbalances the deterministic, Newtonian one, where the future is exactly determined by the initial conditions of a system, so that future is not only certain but also exactly predictable. This deterministic conception of science and time strongly influenced the western culture and the myth of progress that stayed at the basis of our culture since the Enlightenment (Rosa, 2010). Moreover, this is the kind of idea of science that emerges during secondary school, as Newtonian and deterministic science is the most taught part of science in schools. However, science and, in particular, the 20th Century physics elaborated new and probabilistic models of systems evolution that, if treated in class, could contribute to shape a richer idea of science where other kinds of paradigm are foreseen. One of the main characteristics of the I SEE modules is the analysis and enrichment of the Newtonian perspective and the introduction of the basic concepts of the science of complex systems.

The future is intrinsic to societal challenges, as our incoming future is asking different and new competences and skills for dealing with the complexity of tomorrow, such as strategic thinking and planning, creative thinking, the capacity of managing uncertainty, and modelling and argumentation.

Eventually, even the sphere of identity and personal engagement is linked to the future, in the way it implies that people cope with their values, desires, irrational fears, and images of possible worlds.

Thus, guiding students to deal with uncertainty can mean to highlight the development of other non-deterministic—probabilistic—perspectives in science and to provide them with conceptual and epistemic tools elaborated by science and futures studies to develop scenarios and futures thinking. Giving such an epistemological knowledge to students means making them not only able to understand the structure of scientific knowledge but eventually to make them conscious about its worth in society for solving present and future problems (Barelli, 2017), by involving them personally and making them cope with their own sets of values and beliefs.

2.2 *Futurizing* Science Education: the structure of an I SEE module

At the heart of the I SEE project in Branchetti et al. (2018) there is the claim that *futurizing* science education is an interesting challenge that is worth addressing. The use of this term is not accidental at all, as it is a counterpart of the notion of *defuturizing* introduced by Bergmann (1992) to mark how the political discourse was depriving the future of some its main features—uncertainty, possibility and impossibility—to reduce people's anxiety.

The I SEE project addresses the problem of making the futures in the STEM topics explicit by reformulating the paradigm implemented by Sadler, Foulk and Friedrichsen (2017) within the research on Socio-Scientific Issues (SSIs). The SSI approach stresses on the importance of exploiting societal relevance of scientific contents, in order to make the students develop both scientific knowledge and critical, all-round thinking on the various aspects involved in the problem. To this purpose, they claim the need to introduce in teaching Socio-Scientific Issues that are defined as scientific topics that have a strong social significance: They are in general controversial topics, for which there is not a unique solution or a univocal answer and for which ethical and social values are involved. Examples are genetic engineering, climate change, and animal testing for scientific purposes. The Sadler et al. (2017) teaching-learning approach involves three phases consisting of:

i. Encountering the focal issue;
ii. Engaging with science ideas, science practices and socio-scientific reasoning practice;
iii. Synthesising key ideas and practices.

The I SEE project took the same three-phase structure of the SSI teaching-learning model, and the explicit aim to integrate science contents and their social relevance (Branchetti et al., 2018). However, there is a deep difference between an SSI and an I SEE topic, since the latter has to be future-relevant. This means that an I SEE topic, unlike an SSI, has to refer explicitly to the future and project itself onto it, in its implications for future society and by revealing the future-oriented nature of science.

Said that, an I SEE module involving an advanced and future-relevant STEM topic is structured as follows (Fig. 2.1):

i. Encountering the focal issue and the structure of future thinking;
ii. Engaging with STEM contents and linking conceptual knowledge with epistemological knowledge and practice, and inquiry practice;
iii. Fostering the interaction between science and the future (“bridging” activities);
iv. Synthesising the ideas and putting them into practice through future-oriented and action competence activities.

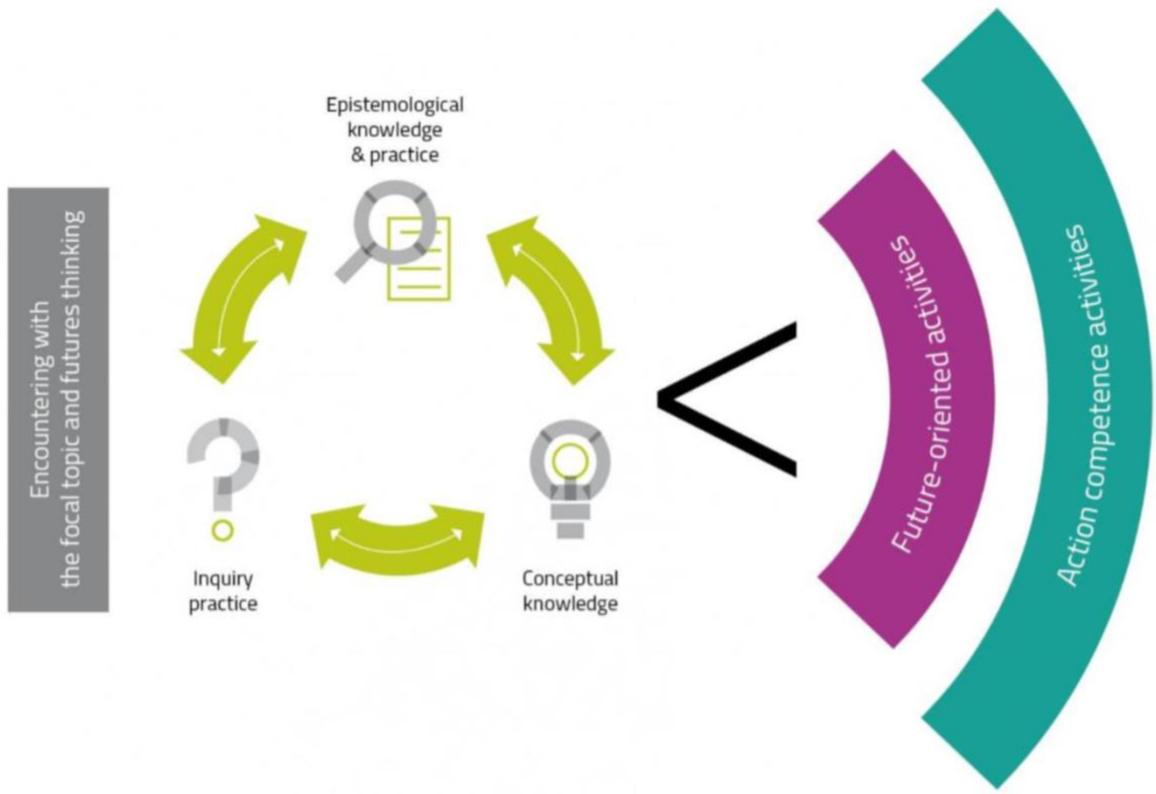


Figure 2.1: Structure of an I SEE module.

The future is present throughout the three phases of the module. During the *encountering activities*, the students are introduced to social issues and problematic aspects of the topic, so that the focal issues are characterised by the connections to STEM and the future. The second phase properly presents science and future in their interaction. While the elements of the topic are introduced, strong visibility is given to the three dimensions of science: (1) *conceptual knowledge*, where scientific contents are presented as a reconstruction for education; (2) *epistemological knowledge and practice*, in order to be able not only to model, argue and explain, but also to grasp the shift in the different epistemological paradigms; (3) *inquiry practice*, in order to use and acquire inquiry skills such as formulating hypotheses, designing inquiry, and moving from models to experiments and vice versa. Studies in the field have shown that including these three features in the science contents may foster a deeper and meaningful learning (Tasquier, Levrini, & Dillon, 2016), especially as far as modelling, explanation and argumentation are concerned (Chinn, 2018, pp. 206-226).

In the future-oriented practices, the future plays different roles. First of all, this is the moment where the future-oriented discourse of science is actually highlighted and put into practice. Secondly, some futures studies concepts allow to make explicit some societal matters within the STEM topic, by reading it again from a different perspective, as well as enlarge imagination about the future. The latter is made in two directions: the social one, involving how students conceive and imagine the future of society, and the personal one, involving how single students place themselves in the future, allowing to imagine and aspire to future careers in STEM. Some of the powerful concepts the Futures Studies provide revolve around the fact that the future should not be thought as singular, but as plural. Different futures exist; some of them are more *probable* than others, some are *plausible*, some are *possible*, some are *desirable*. Each and every future is imaginable by depicting *scenarios*, which are "stories about distinct futures" (Miller, 2006, p. 98). Such a vision opens up to a positive way of conceiving uncertainty, not as something to fear, but as something that discloses a world of possibilities. All these futures are visually represented through the so-called "futures cone" (Fig. 2.2).

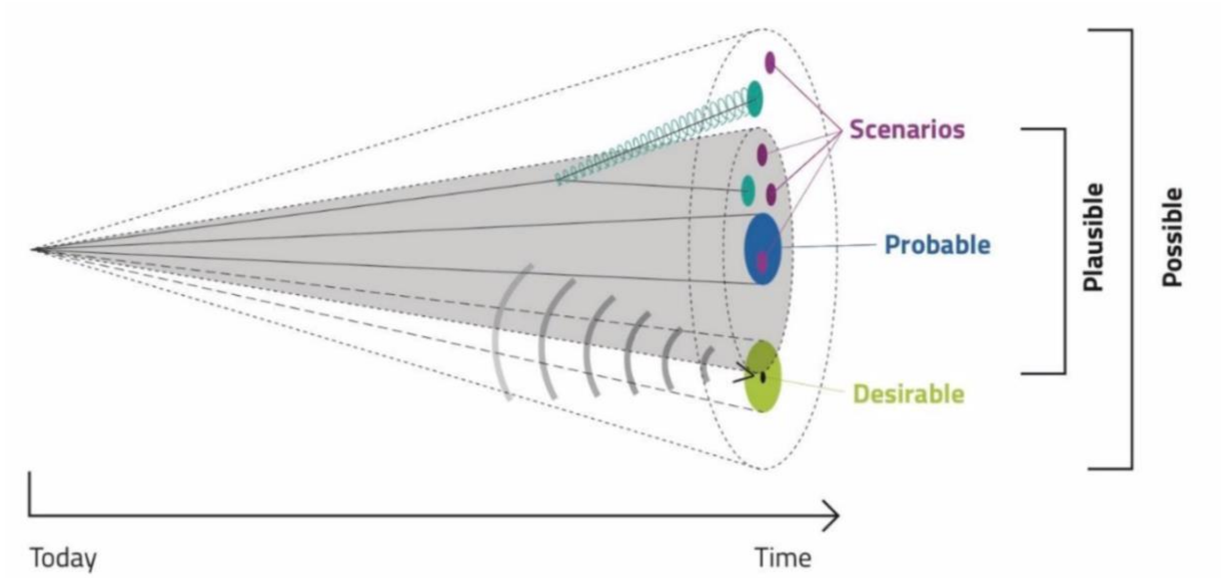


Figure 2.2 Futures cone.

The final point of the module are the *action competence activities*, where students are asked to decide collectively a problem and investigate how to solve it, reasoning with their own perspectives, ranges of values, skills, and interests, being able to choose the future they expect and the future they want and find the way to make them correspond one another.

Action competence is one of the learning outcomes of the I SEE approach (Branchetti et al., 2018). Indeed, the project assumes that the students do not only have to open up their imagination toward future scenarios, but they also have to become agent of their desirable futures.

Besides the action competence, the I SEE approach aims to develop, as further learning outcomes, the so called *future-scaffolding skills*: Skills that "refer to the capability of organising knowledge in the present, imagining futures and moving dynamically and consciously, back and forth, globally-locally between different times and dimensions" (Levrini et al., under review). Future-scaffolding skills are divided into two categories:

i. *Future-scaffolding scientific skills*, that come from science and can support students to talk and to think about the future, e.g. concepts from the science of complex systems such as projection, space of possibilities, emergence, feedback, etc.

ii. *Future-scaffolding transversal skills*, that do not have a scientific origin but can develop within science classes in order to enable students to project themselves onto the future.

So far, four modules have been designed and tested in different contexts. They refer to climate change, artificial intelligence, carbon sequestration and quantum computing. Each of them has been tested in at least two different contexts.

In the following, the module on quantum computers is described in some detail since it is the module to which I contributed by designing an activity aimed to flesh out the applications and implications of the topic.

2.3 Quantum Computers as a future-oriented advanced STEM topic

Quantum computers and quantum technologies are a brand-new field of quantum physics, whose birth is historically dated back to the famous keynote speech "Simulating Physics with Computers" held by Richard P. Feynman at the first MIT "Conference on Physics and Computation" in 1981 (Feynman, 1982). Feynman asks the following: "what kind of computer are we going to use to simulate [quantum, ed] physics?" (p. 467). In this way, Feynman claimed that, if we want to simulate the quantum nature of the world, we cannot use a deterministic, classical computer; we should instead change the fundamental phenomenon we use to represent information, from classical to quantum, from an on-off configuration to quantum superpositions. That is, switching from a bit to a quantum bit, or *qubit*. Since Feynman's article, quantum technologies were studied and developed both from a theoretical and an experimental point of view. Nowadays, quantum technologies are a very advanced field in quantum physics, that is recently affirming outside pure research labs for applications in the entrepreneurial world. The biggest ICT corporations—such as Google, IBM, Intel, and Microsoft—are investing lots of money on quantum technologies and governments are becoming more and more aware of their importance.

Right now, we are living in the so-called "Second Quantum Revolution". According to Dowling and Milburn (2003), while the first revolution was that of lasers, diodes, semiconductors, and all kinds of phenomena that depend on the fact that light can be treated as a particle and *vice versa*. The second one, instead, is about the exploitation of the fundamental principles of quantum mechanics—the uncertainty principle, superposition, interference, entanglement, decoherence, tunnelling—for altering the quantum face of the physical worlds and "transforming it into highly unnatural quantum states of our own design, for our own purpose" (p. 4). As quantum technologies do not only concern quantum computers, but also new ways of conceiving cryptography, sensors and optimisation, the second quantum revolution could have a great impact on society, especially in cryptography and in the occurrence of inequalities (de Wolf, 2017).

Let us now show that quantum technologies are an example of advanced STEM topic. One can see that the topic is advanced as it is a very specific field of quantum physics, that is just beginning to be explored by non-scientific audience, even though such a technology is thought to have enormous potential consequences for the future and the entirety of society. Nevertheless, such an advanced topic can be reframed for a teaching-learning activity by the means of an integrated STEM approach (see § 1.1), for it contains all the S-T-E-M features. The *Science* part can be tackled by introducing those concepts of quantum physics and computer science that are necessary for understanding the functioning of classical and quantum computers. The *Technology* part takes into account all the technological advances that have been achieved by exploiting quantum phenomena. Such a topic links very well to the *Engineering* part, which involves the process of understanding how to translate quantum mechanical concepts into technological applications, just as a classical phenomenon like differences of electrical potential has been translated into a way to codify classical information, and computers were born. Finally, the *Mathematics* part can include the typical mathematics of both a classical and a quantum computer: the binary system on one hand, and the computing of quantum probabilities on the other. A recap of some disciplinary content that can be addressed through this topic is given in Table 2.1. Concepts like logic gates and algorithms are typical cross-cutting STEM concepts, because they combine mathematical, physical, and engineering aspects and they stay at the basis of technological applications.

Table 2.1: Examples of disciplinary contents that can be addressed through a STEM module on quantum technologies.

STEM subject	Disciplinary content
Science	**Physics** What does it mean to make an experiment in quantum physics? How does the relation between the experimenter and the experiment change? Differences between a classical and a quantum system: states observables and measurements. The uncertainty principle and non-commuting observables. Quantum superposition. Entanglement. The representation of a quantum system. The qubit. **Computer Science** Computer science: Input → elaboration → output. Structure of a classical computer: Von Neumann architecture; CPU. Encoding, elaboration and decoding of information. The bit.

Technology	Technological applications of quantum physics: e.g. quantum computers, quantum cryptography, quantum sensors, quantum simulators, quantum networks.
Engineering	Architectural aspects in the construction of quantum technologies.
Mathematics	Computation of classical probabilities. Binary numeral system. Truth tables. Complex numbers and quantum probability.

As the future is intrinsic to science, it has to be intrinsic to quantum technologies, too. And it actually is, in two ways. The first one is that quantum physics provided a fundamental contribution to problematise the deterministic Newtonian view and to introduce non-epistemic probabilities.
Indeed, on the one hand, Newtonian physics rests on its laws of motion, whose mathematical structure implies a unique solution of a Cauchy problem by the Peano-Picard theorem. The Cauchy problem is indeed the mathematical expression of *determinism*: The knowledge of the laws of motion automatically determines each and every future state uniquely, and in a very strict way, being determined by "an inflexible necessity" (Israel, 1986). In this sense, Newton's epistemology refers to *a world of necessities and univocal predictions*, as its acme is reaching a universal, complete solution to a physical problem, and being able to determine each and every point of space and time with a single set of equations. On the other hand, we have quantum physics and the conceptual revolution it brought at the beginning of the 20th Century. In this new epistemological framework, the uncertainty principle shows that, in specific conditions where the main parameters are comparable with Planck's constant h, the position and velocity of a particle cannot be simultaneously determined, undermining the fundamental principle of classical physics. The break with the deterministic view of the world is also visible in the new conception of experiment brought up by the uncertainty principle, where the experimenter has to decide which physical quantity to observe and, in this sense, takes part in the experiment itself (Wheeler, 1986). Such a vision defines a *world of possibilities*, especially if we take into account the fact that, by the superposition principle, before taking a measurement of the quantum system, the latter comprises a plurality of possible outcomes.

The second way of how future is intrinsic to quantum technologies is immediately clear as soon as one can conceive the future of society and science with or without quantum technologies. Several perspectives were put into the design of the teaching-learning modules, as two different teams within the I SEE project developed the module, both of them targeting upper secondary school students. The module, called "Quantum Computing and the Future of ICT", was designed and developed in two different moments: the first time by the Finnish researchers of the University of Helsinki, and the second time by the Physics Education Research Group of the University of Bologna.

2.3.1 The Finnish Module

The Finnish module was designed to be implemented in approximately 20 hours, spread over two weekends. Table 2.2 shows the chronological structure of the module implementation.

Table 2.2: Chronological structure of the Finnish I SEE module.

Conceptual and epistemological activities	**Future-oriented activities** **Action competence activities**
Day One	
Electronic computer; Information as bits; ▪ Binary exercises.	Future projects; Basics of creative thinking.
Day Two	
Components of a computer; Operations of a computer; Algorithms; ▪ Electronics homework.	Back to the Future.
Day Three	
Introduction to Quantum Mechanics; ▪ Quantum exercises.	Mapping the problem; Scenarios.
Day Four	
Quantum computing.	Backcasting.

Let us go through the module by analysing it from a STEM-approach perspective. The first two days are entirely dedicated to the classical computer. As far as conceptual and epistemological activities are concerned, students learn how a computer works and is made, and how information is stored in bit-like form. Students experiment the *Mathematics* of computer information, by learning how to manage the binary numeral system and what an algorithm is. They also deepen the *Engineering* part by learning the components of a computer and how transistors can function as classical logic gates. This part involves understanding the shift from the mathematical operations with binary numbers to the truth tables in the logic gates to the use of transistors in order to create real gates. The *Technology* part involves all the applications obtained from the engineering results.

The future-related activities of this part involve the widening of imagination in students, firstly by choosing a problem involving the future that interests them and that they will carry out for the rest of the module, then by learning and putting into practice the foundations of creative thinking, in order to foster imagination to solve the problem they chose. To challenge their critical thinking, creativity, and imagination about the future, a second activity is proposed: In the “Back to the Future” activity, students have to analyse some clips of the famous 1980s movie and discuss the way the production of the movie predicted our present. Then they have to apply that same line of reasoning for imagining a summer day in 2035.

The second weekend focuses on quantum mechanics and qubits. Emphasis is given to the difference between the old theoretical system of classical physics and the new logic of quantum physics. As a matter of fact, after learning the logical operations, algorithms and hardware components of a classical computer, students learn how to replace bits with qubits. To avoid misunderstandings and to consider quantum physics as distinct from classical physics, any kind of similarity between classical and quantum physical quantities is avoided. In this way, not only there is no reference to physical quantities subject to Bohr's correspondence principle, rather quantum physics is presented as something separate, with its own physical quantities; therefore the so-called "spin first" approach is preferred, as spin is one of the few physical quantities that does not have a correspondence in classical mechanics. In this module, students learn about spin by reasoning on "physical quantities" such as colour and shape inside a Mach-Zehnder interferometer. In addition to the *Science* part, the *Mathematics* part focuses of the quantum probabilities of obtaining systems with a certain shape and colour. Quantum computing is presented in the last day of the module, by presenting the shift from bits to qubits and the question of complexity in computer science. Qubits are explained through the Deutsch algorithm. All the quantum concepts necessary to understand how qubits can be manipulated—e.g. superposition, measurement, quantum logic gates—are explained through a hands-on approach by the means of the IBM Q Experience platform[1], which allows to include the *Technology* and *Engineering* parts.

The future part here aims at giving action competences. In this part, students in groups need to revise their initial thoughts about the problem they chose and "map" it by using the Futures Studies techniques. In addition to learning how to do define a system, identify leverage points for working on it—which are the ways to think about the future and how to do backcasting—at this point of the module, they learn useful concepts from science of complex systems that can help them positively face uncertainty.

After analysing the teaching-learning module, the Finnish partners found a positive feedback as far as the future-oriented purposes of the module are concerned. Nevertheless, two critical points were pointed out (Satanassi, 2019):

i. The students were disoriented about the Deutsch algorithm. According to the teacher, they were not able to understand the kind of problem the algorithm is meant to solve and/or were struggling with the quantum formalism.
ii. The conceptual and epistemological issues and the future-oriented part about quantum computing seemed to lack a proper connection.

[1] https://quantumexperience.ng.bluemix.net/qx (Login required).

2.3.2 THE ITALIAN MODULE

In light of the Finnish module and its criticalities, the Italian team revised the module and implemented it in February-March 2019, with lessons of three hours once a week for six weeks. The team working on the development and implementation of the module was composed of the following:

i. Prof. Olivia Levrini, a researcher in Physics Education, coordinator of the activity;
ii. Prof. Elisa Ercolessi, a theoretical physicist with expertise in quantum computing;
iii. Dr. Laura Branchetti and Dr. Giulia Tasquier, two post-doctoral researchers, one in Mathematics Education and one in Physics Education respectively;
iv. Eleonora Barelli, Michael Lodi, and Giovanni Ravaioli, three PhD students in Data Science and Computation, Computer Science, and Physics, respectively;
v. Sara Satanassi, a Master student in Applied Physics who carried out her Master's thesis on this experience (Satanassi, 2019);
vi. Paola Fantini, a retired secondary school teacher with professional expertise in classical architectures and algorithms;
vii. Michela Clementi and Fabio Filippi, two secondary school teachers from the "A. Einstein" scientifically-oriented secondary school in Rimini;
viii. Me, Roberta Spada, Bachelor student in Physics.

Table 2.3 shows the structure of the module.

Table 2.3: Chronological structure of the Italian I SEE module.

Conceptual and epistemological activities	**Future-oriented activities** **Action competence activities**
Day One	
History of Computers; The Physics of Quantum Computers, part one.	Introduction to the module and its objectives;
Day Two	
The Physics of Quantum Computers, part two; ▪ Exercise on quantum cryptography.	Applications and Implications of Quantum Computers (Quantum Computing &…), part one; ▪ Homework.
Day Three	
Quantum teleportation ▪ Exercise.	Applications and Implications of Quantum Computers (Quantum Computing &…), part two;
Day Four	
Classical and Quantum Problems: Introduction to Computational Complexity; Predicting, simulating, and building scenarios; Game Theory: what interaction between the agents?	Where are we in the module? Introduction to future-oriented activities ▪ A clip from "Black Mirror".
Day Five	
/	Mapping the problem and Systemic Thinking; "Back to the Future"; Creative Thinking; Scenarios;

	Backcasting. ▪ Homework: group projects to be presented next time.
Day Six	
Group presentations about the chosen topic; Final discussion about the module and conclusions.	

The module was implemented with a group of 25 secondary school students, 15 males and 10 females. The project was carried out within the activities of "Piano Lauree Scientifiche"[2], a national project sponsored by the Italian Ministry for Education, University, and Research (MIUR), whose main objective is filling the gap between secondary school students and scientific subjects at university. Each student applied for the project individually as part of their own "Alternanza Scuola-Lavoro" project, which is a compulsory extracurricular project each student has to complete during the last three years of secondary school in order to graduate ("La Buona Scuola" Act, 13 July 2015 n. 105, clauses 33-43).

The first three days of the module are strongly characterised by conceptual and epistemological activities. After an introduction about the module and its objectives, students firstly learn about the history of classical computers, activity led by Paola Fantini, who told part of the history of computers—activating the E and the T of the STEM narrative—by telling her own professional story. The latter was a very important feature in the implementation of the module, as Fantini's story was considered a way for the students to reflect upon careers in STEM in the past and in the present, in order to imagine the future, as well as a positive way of activating personal engagement. Then, students make their first encounter with quantum physics, again with a "spin first" approach, by reflecting upon the Stern-Gerlach experiment and on the spin of a quantum particle. Quantum cryptography and quantum computing are then presented. We see why the clear distinction between classical and quantum physics was necessary at first: When presenting qubits and quantum computing, that logical distinction between "classical" and "quantum" is necessary to show that quantum computers are not only more powerful and faster, but the inner functioning of qubits allows a different approach to larger problems, for example by favouring parallel computation instead of a serial one. Great emphasis is put on telling that quantum computers cannot solve *computationally more complex* problems than classical ones, and that the logic, not the power, make the difference. Quantum teleportation is then explained on the third day as a practical application of quantum entanglement. Moreover, the activity on quantum teleportation was conceived to replace the tough part on the Deutsch algorithm without losing its important epistemological concepts (Satanassi,

[2] https://www.pianolaureescientifiche.it/

2019). As a matter of fact, this activity aims at making explicit the representational shift from the experiment narration to the logical and mechanical aspects of the quantum circuit involved. This epistemological content involves the *Science*, the *Engineering*, and the *Technology* parts of the STEM acronym. Finally, the fourth day focuses on familiarising with all those concepts coming from the science of complex systems, computational complexity, and game theory, touching the *Science*, the *Engineering* and the *Mathematics* categories. These concepts gradually introduce the future-related themes and give skills and competences to students that can empower their creative and rational reasoning about the future.

The future-related content is firstly presented by the means of the activity named "Applications and Implications of Quantum Computers", also called "Quantum Computing &…". The other future-related activities are very similar to the Finnish ones, except for the "Black Mirror" activity, where students are asked to meditate on the way the screenwriters of the famous TV series imagined the future depicted in a clip of an episode.

The final project seeks to strengthen the students' future-scaffolding and action competence skills by making them imagine and try to solve a future problem they imagine for 2040, by relating events they see in the present and they imagine for the future to their desirable, possible, plausible and probable futures, using the Futures Studies techniques.

In the next chapter, I am going to analyse in greater detail the specific activity I designed in collaboration with Michela Clementi on the applications and implications of quantum technologies in the present and in the future.

Chapter 3

"Applications and Implications of Quantum Computers in Society": An Activity on Quantum Computing and the Future

3.1 Objectives of the Activity

The core of this thesis work is the activity that I contributed to designing, whose name is "Applications and Implications of Quantum Computers in Society". As previously mentioned, the activity was designed to bridge quantum technologies with their inner future-related content, something that was pointed out at the end of the Finnish module not to be explicit enough for the students. In Annex A, the I SEE official sheet that I produced about the activity is reported. The structure of the sheet is the same for every I SEE activity and it enforces the design to keep into account some general criteria, such as the conceptual, epistemological, and social/emotional goals, and some implementation tips for the teacher.

The activity took place on the second and the third day of the I SEE module at the Department of Physics and Astronomy of the University of Bologna. As already said, the whole module and the activity involved about 25 students in their last two years of several scientifically-oriented schools from Bologna and its surrounding area. The overarching goals of the activity were to guide secondary-school students to:

i. Get acquainted with the terminology, perspectives and contents of relevant institutional documents like the Quantum Manifesto (de Touzalin et al., 2016).
ii. Reflect and reason about the present and future applications and implications of quantum technologies.
iii. Get aware about the multiple dimensions (e.g. social, economic, political, research, educational, ethical, environmental, etc.) such technologies involve.

iv. Express and highlight their inner vocational, societal and personal dimensions in the discourse, by bringing together their values and opinions in a group project and to recognise where and how quantum technologies can impact their personal lives.

The activity concretely concerns a teamwork on texts that we wrote starting from the institutional literature about quantum technologies that we analysed and re-elaborated with a very precise goal in mind: To guide students through understanding the essence of the institutional literature on quantum technologies, as well as enable them to grasp the necessity of it in our contemporary world and develop critical thinking on the topic. As already said, we also wanted students to navigate this specialised literature and to get acquainted with it as much as possible.

In the following, there is a description of the institutional reports and papers we referred to: the most important of all is the 2016 Quantum Manifesto, edited for the European Commission by a group of experts in quantum technologies. After, there is the description of the activity in terms of its structure, teaching-learning materials, and specific objectives.

3.2 The Institutional References

3.2.1 The Quantum Manifesto

The Quantum Manifesto is a document edited in 2016 by Aymard de Touzalin (European Commission, Deputy Head of Unit for the Quantum Technologies Flagship), Charles Marcus (University of Copenhagen), Freeke Heijman (Dutch Ministry for Economic Affairs), Ignacio Cirac (Max-Planck Institute for Quantum Optics), Richard Murray (Innovate UK), and Tommaso Calarco (IQST Centre, Ulm) as a call to launch a European collective initiative on quantum technologies. It has indeed been the starting point of the “Quantum Technologies Flagship” of the European Commission, a large-scale, long-term research initiative launched on April 2016 with the allocation of a one-billion-euros budget. The Flagship is located within the “Future and Emerging Technologies” (FET) programme of the European Unions and aims at bringing “together research institutions, industry and public funders, consolidating and expanding European scientific leadership and excellence” in the field of quantum technologies (European Commission, nd*c*). The Flagship will run for ten years, and its ramp-up phase—begun in 2018 and ending in September 2021—has been characterised by the implementation and funding of several projects on quantum technologies.

The Manifesto is endorsed by a broad community of European scientists, industries and research institutes, whose aim is to raise the problem of the European global competitiveness on quantum technologies and to place Europe at the forefront of the incoming second quantum revolution. According to the Manifesto, preparing Europe for the arrival of new technologies means finding the tools and funds to reach excellence in research and to foster economic development, in order to make Europe a place of commercial opportunities in quantum technologies for the rest of the world. The challenge is being addressed on four technological and scientific fronts:

i. *Communication*, involving security—with quantum and post-quantum cryptography—and the development of quantum information, i.e. the creation of quantum networks, with quantum repeaters, memories and processors, and with the final goal of an Internet-wide quantum-safe network for Europe.

ii. *Simulators*, i.e. an analogue version of quantum computers, entirely dedicated to the resolution of a single scientific or technological problem, such as the behaviour of a material, the structure of a very large molecule, or the solution of the equations of a quantum system, even in conditions that a non-virtual experiment could never be able to reach.

iii. *Sensors*, leading to several applications in medicine—biosensors and magnetic resonance imaging—and imaging technologies in general, since quantum imaging devices use entangled light to extract more information.

iv. *Computers*, the most far-reaching and challenging of quantum technologies. Currently, the most recent approaches are subject to several technological limitations, especially in putting together the highest possible number of qubits. Yet, if these limitations are overcome, a whole new era of technology and computer science would open up. Moreover, in listing the current technological developments made by multinational corporations such as Microsoft and D-Wave, the Manifesto highlights how Europe needs to put itself at the centre of this economical ferment, as it is a leader in the development of software for classical high-performance computing applications.

Besides, to stand in front of this revolution does also mean “to create a lucrative, knowledge-based industry leading to long-term economic, scientific and societal benefits” (p. 3), by seeking coordination between industry and academia, and creating a new generation of quantum technology professionals. This is very indicative of the vision pictured by the Manifesto, which sees education and science as the foundation of the future European programme on quantum technologies (see Fig. 3.1).

The prospective role of education consists of building the next generation of technicians, engineers, scientists and application developers in quantum technologies, as well as informing European citizens about quantum technologies and engaging widely with the public to identify issues that may affect societies, in order to bridge the gap between academia, industry and society.

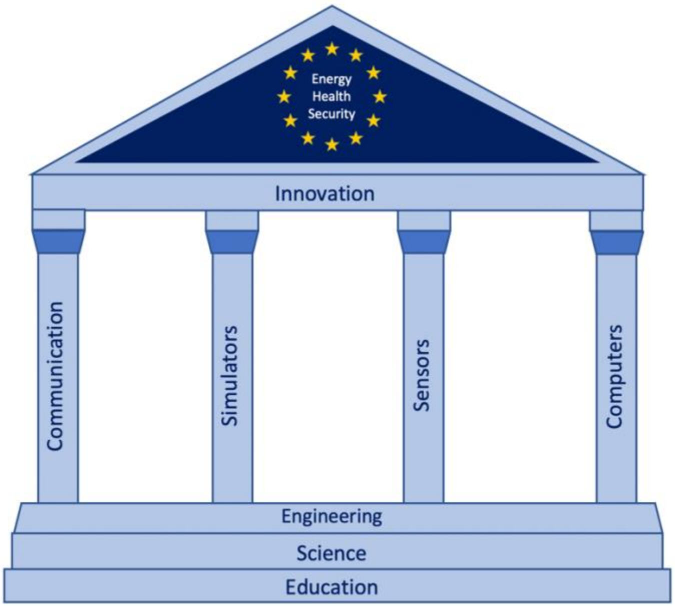


***Figure 3.1**: Elements of a European programme in quantum technologies. Adapted from Quantum Manifesto (p. 11) by de Touzalin et al. (2016).*

3.2.2 Quantum Technologies and Society

The Quantum Manifesto sets a timeline for the development of quantum technologies from 2015 to 2035, hoping to reach new technologies that could potentially modify society, such as general-purpose quantum computers, quantum credit cards, and a secure quantum Internet.

All these technological advances are considered to have a huge impact on society, especially as far as scientific research and cryptography are concerned. According to Möller & Vuik (2017), scientific computing is going to be revolutionised by quantum computing technologies in the same way the arrival of classical computers completely changed science and technology. It is projected to change, both from a hardware perspective—in terms of quantum simulators and parallel high-performance computing—and from a software perspective. The authors also imagine that quantum computers will not exist as stand-alone machines, as they need extremely low operating temperatures to work, but as processors accessible via clouds and classical computers. The increase in performance and accuracy of computers may lead to new ethical and societal problems involving the most various aspects. For instance, the authors cite the possibility that these computers can reach such a tremendous increase in efficiency that "the results of their approximations are judged as 'the true solution'" (p. 255). de Wolf (2017) identifies quantum cryptography, optimisation and simulation as the three main aspects that will lead to a profound change in society and to new ethical aspects to take into account. Cryptography is related to the problem of quantum computational supremacy, which is "when a universal quantum computer performs a computational task that is beyond the capability of any classical computer" (Howard & Montanaro, 2018), as all current cryptography is based on the solution of difficult problems that take a very long time to solve for classical computers but that could take a few minutes or hours for quantum computers. Optimisation, instead, is about improving algorithms, especially for machine learning and artificial intelligence. Lastly, simulating refers to all those computational efforts required to simulate the behaviour of a system—be it physical, chemical, biological, and so on—and making virtual experiments that could lead to new scientific and technical discoveries.

All these scenarios and possibilities highlight the future-oriented discourse of quantum technologies, as well as how much it is important to reflect upon the issue in a multi-faceted way and on different levels and scales. Based on these considerations, the Italian team of the I SEE project decided to develop a bridging activity for making explicit the future in quantum technologies and quantum computing.

3.3 The Worksheets

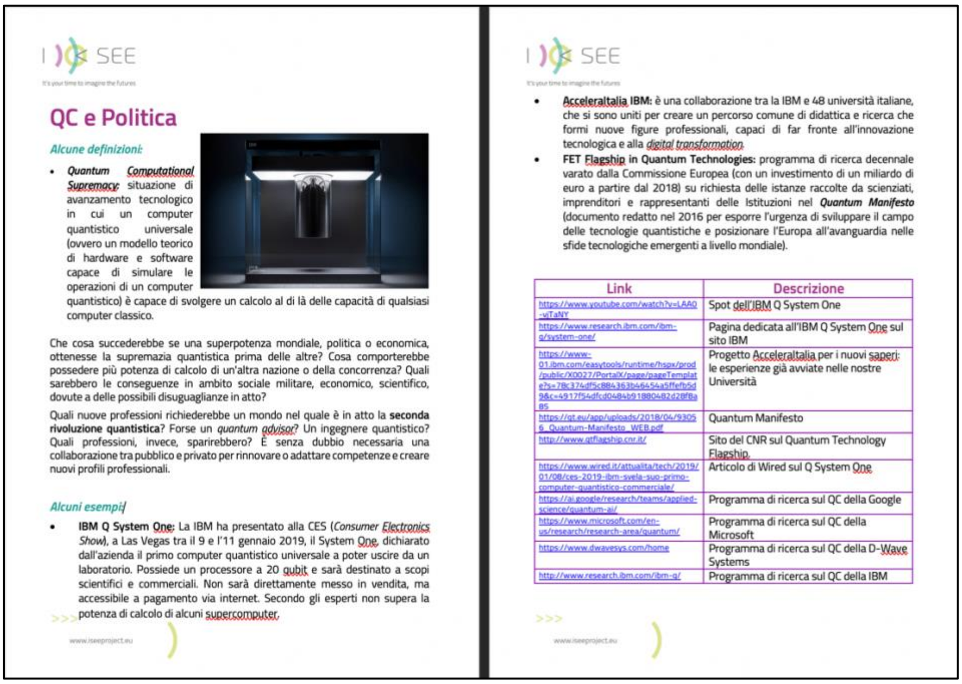
On the basis of this institutional literature, we produced four worksheets for the activity. The design of these teaching material was the result of an analytic re-elaboration of the documents that put large emphasis on developing something that could be understandable and meaningful for 16-to-18-year-old students and that, at the same time, could foster critical and evidence-based reasoning, instead of simply adding knowledge and contents. Firstly, after reading all the materials, we selected some areas that could help the students explore the impact of quantum technologies. The areas are the following:

i. *Communication*, i.e. everything that is related to ICT and that is expected to be modified by quantum technologies in this area, following the first pillar of the Manifesto.
ii. *Politics*, i.e. dynamics that can develop at national and international level as a consequence of the hypothetical emergence of quantum computational supremacy.
iii. *Scientific and Technological Research*, namely the ways in which research can evolve with quantum technologies, especially in physics, chemistry, and biology.
iv. *Society*, specifically everything that can be enhanced in everyday life by the means of quantum optimisation of algorithms—we took traffic, medicine, and online advertisements as examples.

The choice of these four topics was due to two reasons. On the one hand, we wanted to trace the way the Manifesto divided scientific and technological research into four pillars, in order to highlight that we were seeking a connection between our activity and the Manifesto. On the other hand, and most importantly, we wanted to make all the current examples of applications and implications of quantum technologies converge in contexts which were not only related to science but also to actual problems and issues involving society, so as to take quantum technology out of its mere scientific context. For instance, we wanted to students to understand that, even though quantum technologies are still on their way to be implemented, this fact does not stop institutions, scientists, and stakeholders from thinking about the future and all the possible implications and applications of this kind of technology. We believe that such an imprinting on the whole STEM activity constitutes the bridge between the central topic of the I SEE module and the future-related content.

Each worksheet presents its topic in a very structured way. First of all, there are some scientific and technical definitions introducing the area, followed by a little paragraph with some provocative questions about the topic, which are necessary in order to engage students in creative thinking about the present and the future and for making them bring their values and thoughts in the discourse. Secondly, in all the worksheets but the *Scientific and Technological Research* one, there is a list of current examples of applications of quantum technologies regarding the issue. For instance, in the *Society* worksheet, we present some examples of current applications of quantum optimisation for algorithms that are currently being develop by D-Wave with the quantum annealing techniques. We decided not to include examples within the *Scientific and Technological Research* worksheet because they were too technical and complicated, and we wanted students to focus on imagining new research and new applications rather than examining what is being developed right now. At the end of each worksheet there is a series of hyperlinks to websites the students should use as a resource for their reflection. There are mainly websites of corporations actually involved in quantum technologies, and papers and newspaper articles about the most current developments. Also, every worksheet contains the hyperlink to the Quantum Manifesto. In Figure 3.2, there is an example of worksheet.

In the following we describe how the students were guided to navigate across these materials. In particular, we describe the activity in terms of its specific objectives and the specific tasks that the students were asked to carry out as teams.


I SEE

It's your time to imagine the futures

QC e Politica

Alcune definizioni:

- ***Quantum Computational Supremacy:*** situazione di avanzamento tecnologico in cui un computer quantistico universale (ovvero un modello teorico di hardware e software capace di simulare le operazioni di un computer quantistico) è capace di svolgere un calcolo al di là delle capacità di qualsiasi computer classico.

Che cosa succederebbe se una superpotenza mondiale, politica o economica, ottenesse la supremazia quantistica prima delle altre? Cosa comporterebbe possedere più potenza di calcolo di un'altra nazione o della concorrenza? Quali sarebbero le conseguenze in ambito sociale militare, economico, scientifico, dovute a delle possibili disuguaglianze in atto?

Quali nuove professioni richiederebbe un mondo nel quale è in atto la **seconda rivoluzione quantistica**? Forse un *quantum advisor*? Un ingegnere quantistico? Quali professioni, invece, sparirebbero? È senza dubbio necessaria una collaborazione tra pubblico e privato per rinnovare o adattare competenze e creare nuovi profili professionali.

Alcuni esempi:

- **IBM Q System One:** La IBM ha presentato alla CES (*Consumer Electronics Show*), a Las Vegas tra il 9 e l'11 gennaio 2019, il System One, dichiarato dall'azienda il primo computer quantistico universale a poter uscire da un laboratorio. Possiede un processore a 20 qubit e sarà destinato a scopi scientifici e commerciali. Non sarà direttamente messo in vendita, ma accessibile a pagamento via internet. Secondo gli esperti non supera la potenza di calcolo di alcuni supercomputer.

>>>

www.iseeproject.eu

I SEE

It's your time to imagine the futures

- **Acceleraltalia IBM:** è una collaborazione tra la IBM e 48 università italiane, che si sono uniti per creare un percorso comune di didattica e ricerca che formi nuove figure professionali, capaci di far fronte all'innovazione tecnologica e alla *digital transformation*.
- **FET Flagship in Quantum Technologies:** programma di ricerca decennale varato dalla Commissione Europea (con un investimento di un miliardo di euro a partire dal 2018) su richiesta delle istanze raccolte da scienziati, imprenditori e rappresentanti delle Istituzioni nel ***Quantum Manifesto*** (documento redatto nel 2016 per esporre l'urgenza di sviluppare il campo delle tecnologie quantistiche e posizionare l'Europa all'avanguardia nelle sfide tecnologiche emergenti a livello mondiale).

Link	Descrizione
https://www.youtube.com/watch?v=LAA0-vjTaNY	Spot dell'IBM Q System One
https://www.research.ibm.com/ibm-q/system-one/	Pagina dedicata all'IBM Q System One sul sito IBM
https://www-01.ibm.com/easytools/runtime/hspx/prod/public/X0027/PortalX/page/pageTemplate?s=78c374df5c884363b46454a5ffefb5d9&c=4917f54dfcd0484b91880482d28f8a85	Progetto Acceleraltalia per i nuovi saperi: le esperienze già avviate nelle nostre Università
https://qt.eu/app/uploads/2018/04/93056_Quantum-Manifesto_WEB.pdf	Quantum Manifesto
http://www.qtflagship.cnr.it/	Sito del CNR sul Quantum Technology Flagship.
https://www.wired.it/attualita/tech/2019/01/08/ces-2019-ibm-svela-suo-primo-computer-quantistico-commerciale/	Articolo di Wired sul Q System One
https://ai.google/research/teams/applied-science/quantum-ai/	Programma di ricerca sul QC della Google
https://www.microsoft.com/en-us/research/research-area/quantum/	Programma di ricerca sul QC della Microsoft
https://www.dwavesys.com/home	Programma di ricerca sul QC della D-Wave Systems
http://www.research.ibm.com/ibm-q/	Programma di ricerca sul QC della IBM

>>>

www.iseeproject.eu

***Figure 3.2**: Example of an original worksheet of the Italian implementation which took place on 12 and 19 February 2019.*

3.4 The activity

Following the path traced by the Quantum Manifesto, Michela Clementi and I decided to build the activity which is chronologically described here.

3.4.1 The Specific Objectives of the Activity

Like in every I SEE activity, the specific goals of the activity are articulated in conceptual, epistemological, and social/emotional goals.

The *conceptual goals* involved both STEM subjects—Science, Technology and Engineering—and future-related goals aiming at reaching future-scaffolding transversal skills. Not only students are expected to learn about the definitions of "Quantum Computational Supremacy" and "Second Quantum Revolution", or what is a quantum simulator; yet, they are fostered to recognise the implications of quantum technologies and to identify the current stakeholders within the Second Quantum Revolution, with a special consideration for the four pillars of the Manifesto, so as to grasp the future and present relevance of quantum technologies. Lastly, the most transversal goal, framing all the others, is understanding the relevance of the Quantum Manifesto, its objectives and its hopes, within the European context and beyond.

As far as the *epistemological goals* are concerned, emphasis is put on recognising the importance of the concept of *dimension* (political, social, economic, scientific, ethical, environmental, professional, etc.) for unpacking the relationships among the different components of a complex context and among the stakeholders, as well as on understanding the complexity of the tight relationship between science, technology, and society and recognising the different dimensions involved when contextualising the first two in the third.

Lastly, *social and emotional goals* are carried out throughout the entire module and concern the aim to guide the students to search for their own personal position within the bog issues and to see the activity as something they were actively, directly involved in. In addition to the teamworking and public-speaking skills involved in the group project, students learn to become aware of their own ethical values implied in the emergence of new technologies. The latter goal is generalised at a higher level, by aiming at citizenship competences, i.e. to comprehend the relevance of one's own role within society and to aspire to actively take part in it. Even future-scaffolding transversal skills have their key role in the activity, by showing how to share different points of view and how to cope rationally, emotionally, creatively and responsibly with their future.

3.4.2 THE MATERIALS

The teaching materials consist of:

i. The four worksheets we wrote as elaboration of the institutional literature. Every student receives one copy of all the four worksheets (See § 3.3; Annex C);
ii. A map picturing some of the life aspects quantum technologies can touch. Every team receives one copy (Annex D);
iii. A sheet with the instructions of the activity for each team (Annex B).

Each group, as we will discuss afterword, had a topic to reflect on and, hence, a worksheet to analyse. The map (Fig. 3.3 and Annex D) was designed to be a tool and a point of reference for the team to discuss their own topic. There are several ovals, each with a different dimension of the issue, and some blank spaces for adding new dimensions to the problem. The map is the core of the group project, as it is a tool for making explicit the epistemological objectives of the activity. After reading carefully the worksheet, students discuss about their topic and the different dimensions the latter is involved in directly on the map, by drawing arrows, writing keywords and sentences or adding new content. In particular each team is asked to:

i. Recognise and highlight in the map the aspects "touched or involved" by their topic;
ii. Find valuable connections between the topic and the various aspects selected in the map, by drawing arrows between their topic and the ovals;
iii. Reason about the connections.

Each connection has to be clarified and discussed by paying close attention to the different dimensions of impact. The team should also be able to say which connections are more meaningful among the others and why.

After the "inner" discussion, each team is asked to communicate their own findings in front of the class, by explaining in detail what they wrote on their map.

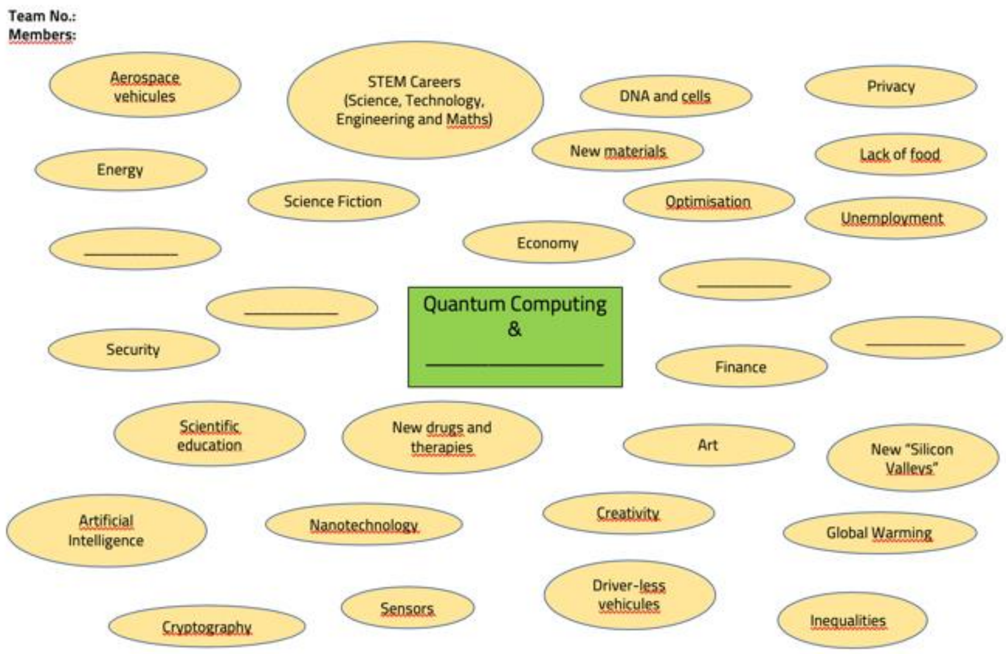


***Figure 3.3**: Map of the Italian implementation which took place on 12 and 19 February 2019*

3.5 Implementation of the Activity and Results

3.5.1 Implementation of the Activity

The activity was carried out in February 2019 and took two hours and a half overall: 30 minutes for explaining the activity, one hour for working in teams on a chosen topic, one hour for having each team presenting its results. The choice of the topic involves four different areas: (1) *Communication*; (2) *Politics*; (3) *Scientific and Technological Research*; and (4) *Society*. Each student can choose one of the four topics and then teams are formed, based on who chose what.

In the first part, we explained the activity and its close relationship with the Quantum Manifesto, by introducing its four pillars, objectives and idea of future brought up by the prospected impact of quantum technologies. We highlighted that, in the first part of the activity, the "judgement in terms of good versus bad" should be suspended and postponed after an engagement with scientific texts and a process of analysis. Thereupon, we introduced the activity and the teaching materials. In particular, we stressed the fact that the development of the activity was the result of an analysis of scientific and institutional resources, and that it was specifically designed in order for students to try to make their own analysis on the material they can find on the worksheets, aiming at the exploration of a context in which quantum technologies can be applied and can imply some effects on society.

Students were then divided into teams, depending on which topic of the four worksheets they preferred. They had one hour for working in teams on the worksheets (See § 3.3; Annex C) and on the map (Fig. 3.3; Annex D), sticking to the following instructions:

i. First of all, students had to read the map and explore the four worksheets, looking for possible applications and implications in the use of quantum technologies. By *implications* of a technology in society we mean the ways society can be influenced, shaped and transformed by technology—in this case, the quantum ones. Instead, by *applications* we mean possible uses in everyday life—and in the most different contexts—of technological artefacts that can be developed by exploiting the discoveries of a certain scientific field—in our case, quantum physics. This part of the activity is essential for the single student to grasp the content of the chosen topic and to critically imagine scenarios about it. Then, each team had to use the map to represent the found connections between quantum technologies and the aspects written in the ovals of the map. The team could also add some aspects of society in the blank spaces of the map, if it found some new.
ii. Secondly, students had to discuss together the arrows and the map, especially by paying close attentions to the different dimensions of impact on the applications of quantum computers (scientific, environmental, social, ethical, economic, political, etc.). During the discussion, they had to highlight and make more explicit the connections that the team found more meaningful among the others, by writing down some keywords that could describe the reason why the team considers those applications/implications important. This part has one main objective: each student, after reasoning on their own about the topic, can bring their own ideas, values and reflection to the team, in order for it to select and organise information, to build connections between the topics and think about how to develop all the dimensions involved in the topic.

In the last part of the activity, students had to choose the way they preferred for speaking about the results of their own analyses—a poster, some slides, a short video, or simply a little speech—and prepare at home for expressing in approximately five minutes their ideas and opinions in front of the whole class the day after.

In this first implementation, we decided to stress the analysis on computers more than on technologies in general, because all the previous activities focused mainly on them, especially the physics lecture given by professor Elisa Ercolessi during the first and the second day about the physics behind quantum computers. Moreover, as computers are something very present in everyone's life, reflecting on them could be a very direct way of addressing the problem from a societal dimension. Nevertheless, quantum technologies were not excluded and found their collocation within the activity.

3.5.2 Final Results

All students were very enthusiastic about the activity, since everyone put a lot of dedication in completing it, both during the work sessions of the module and at home. As far as the completion of the group project is concerned, students responded to the activity in different ways. One team fully understood the activity and was able to work on the connections in the map, on different levels and with a very profound critique. Some teams understood how to work on the dimensions involved and stuck to it. Some other teams developed some themes that were related to quantum computers without reporting detailed and reasoned analyses. One team took the cue from the activity and the whole epistemological re-elaboration of the institutional documents to talk about important themes the group cared very much about.

Such results show that the major criticality of this activity is the complexity of extrapolating from the institutional documents lines of reasoning that can be suitable for upper secondary-school students without overlooking the importance of developing the contents not for adding new information but for making it a starting point for critical thinking. Nevertheless, this activity has great potential and can be improved for other implementations, even in different contexts.

Furthermore, the activity showed its potential in reaching the objectives it was designed for, i.e. bridging the gap between quantum technologies and the future and opening up the students to lots of different scenarios. As a matter of fact, during a follow-up meeting with some of the students who accepted to be interviewed, several degrees of continuity between the two sides emerged. Someone explicitly said that they did not feel any gap between quantum technologies and the future, others said that they were able to grasp a connection between them. Here are some of the students' answers to the interview translated from Italian to English:

> *"I perceived both the parts [quantum technologies and the future, ed] as bound, especially connected by the idea of possibility, because the whole quantum logic, compared to the classical one, is rife with the idea of possibility and of… of interpretations… […] lots of alternatives, all preferable to a precise line going from A to B… from the present to the future… in a deterministic way. So, I saw the link, especially between the number of possibilities of quantum physics and the number of possible futures…"*

"I see them as something connected, but not necessarily in a tight way. I mean… quantum computers are a *future but not* the *future, rather, in my opinion, they are a little part of the whole situation…"*

Overall, this activity and its implementation show that quantum technologies are a proper example of advanced STEM topic, perfectly adapting to an integrated STEM approach, and they go even further: Quantum technologies properly unfold a future-oriented discourse and an analysis about the close relationship between science, technology, and society.

Conclusions

This thesis is the concluding work of a year-long experience within the I SEE Project and with the Research Group in Physics Education of the Department of Physics and Astronomy for designing and implementing a STEM module on quantum technologies and specifically an activity on their applications and implications in society.

In the academic path I followed so far, this thesis represents the conclusion of a Bachelor of Science in Physics, as well as a bridge between the Physics world and the world of Science and Technology Studies, which I hope to soon become part of. Moreover, the importance of this work for me lies in the fact that I, too, as a young person living in the society of acceleration, feel overwhelmed by the uncertainty that characterises the way my peers and I see the future. With this work, I, too, got in touch with all the ways one has to manage uncertainty. In this way, I was able to get a sense of the kind of tools STEM Education, combined with the science of complex systems and the futures studies, can provide.

In the design of the activity and in coping with its criticalities and its strengths, I could realise how much important it was, for the young generation and for me, to search for these tools, in STEM education, to grappling with the future. In particular I found very important the following point. When we selected the institutional documents for the activity and the content within, when we organised information for constructing connections, and when we tried to see how the various, non-STEM dimensions could emerge, we were not just aiming at increasing the students' knowledge of quantum technologies. We were looking for ways to make them reflect, reason, act critically, and bring the topic close to them in terms of values, beliefs, perspectives, desires, and actions.

Such an analysis is very far from the usual practice of managing knowledge as a pure provider of information, especially as far as science communication and science policy are concerned. Several approaches can help manage the increasing complexity of our world. This whole project successfully identified some such as: (1) To be able to build a big picture on the complexity of the problem; (2) To be aware of the multiple dimensions involved in every situation, especially when the latter involve science; and (3) To drive education in formal, non-formal and informal contexts towards fostering the activation of a critical reasoning.

Further research could be made on whether such an approach can be taken out of the context of science education and generalised in order to create guidelines for other areas that involve science and technology, such as communication, policy, and research. I hope to be able to contribute to this big project in my future.

Annex A

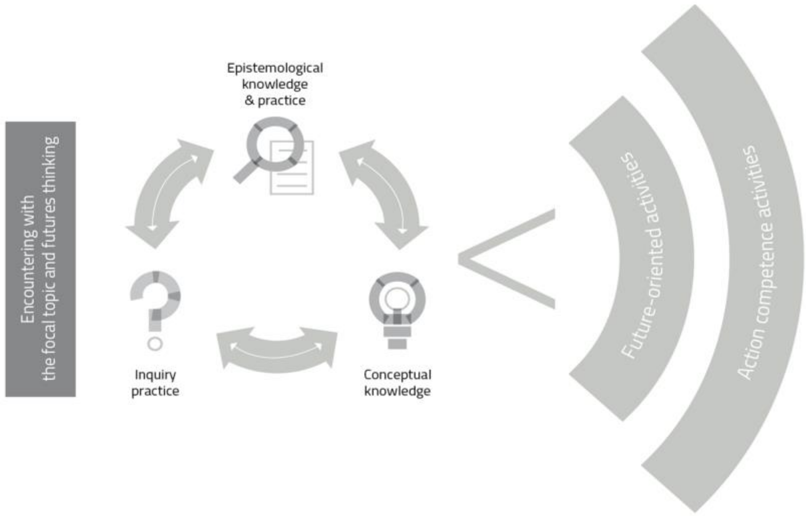
“I SEE Project” official sheet of the activity,
available on the website https://iseeproject.eu/ (Login required).

Quantum Computers and the Future of ICT

ACTIVITY No. 5

Applications and Implications of Quantum Computers in Society

<table>
<tr>
<td>Position in the module

Encountering with the focal issue</td>
<td>


The main aim of the activity is to contextualise quantum technologies within the present and future world in order to make students think about the possible implications and applications of quantum technologies. The implications and applications stressed in the activity range not only over scientific and technological research but also over fields that can initially appear less related to the issue, such as politics and society. The silver thread of the whole activity is the Quantum Manifesto, a 2016 document edited by a group of European researchers for calling on the European Union to launch initiatives in support of the research on quantum technologies.
</td>
</tr>
<tr>
<td>Goals</td>
<td>
Conceptual

To understand the concepts of “Second Quantum Revolution” and “Quantum Computational Supremacy”;
To understand the relevance of the Quantum Manifesto, its objectives and its hopes, within the European and the global contexts;
To understand the implications of quantum technologies within four areas: communication, politics, scientific and technological research, and society;
To grasp the future and present relevance of quantum technologies;
To identify the current stakeholders within the Second Quantum Revolution;

</td>
</tr>
</table>

	• To be introduced to the concepts of quantum optimisation, quantum simulators, quantum sensors, quantum Internet, and quantum programming. ***Epistemological (referred to the scientific epistemic practices of, e.g. modelling, explaining, argumentation…)*** • To understand the complexity of the tight relationship between science, technology, and society; • To recognise the different dimensions involved when contextualising science and technology in society; • To recognise the importance of the concept of "dimension" (political, social, economic, scientific, ethical, environmental, professional...) for unpacking the relationships among the different components of a complex context and among the stakeholders; • To get acquainted with the future-oriented nature of the scientific practices; • To be able to creatively grasp new connections between quantum technologies and various aspects of life. ***Social/Emotional*** • To become aware of the one's own ethical values implied in the emergence of new technologies; • To comprehend the relevance of one's own role within society and to aspire to actively take part in it (citizenship competences); • To get involved personally in group or collective discussions (teamwork skills); • To be able to explain one's own point of view to the others (public-speaking skills); • To learn to share different points of view and to cope rationally, emotionally, creatively and responsively with their future (future-scaffolding transversal skills); • To enlarge the imagination about possible future STEM careers.
Time required	**2 hours and a half**: 30 minutes for explaining the activity, one hour for working in teams on a chosen topic, one hour for having each team presenting its results.
Materials	**Slides** • The Quantum Manifesto: presentation of the document and its objectives; • Explanation of the activity and formation of the working teams on the basis of personal interest in a topic among the four of the worksheets. **Four Worksheets for Each Student** The worksheets present the topic both with some definitions and examples, and by posing some captivating questions about the topic in order to engage students in creative thinking about the present and the

	future. They also contain a list of hyperlinks to websites the students should use as a resource for their reflection. The topics are the following: • Quantum Computing & Communication; • Quantum Computing & Politics; • Quantum Computing & Scientific and Technological Research; • Quantum Computing & Society. **Map: "Quantum Computing &…" (one for each team)** The map contains several aspects onto which quantum technologies can/could impact and some blank spaces for finding new aspects. The team should read it carefully and discuss it together, in order to find some links between the team topic and the aspects. This map belongs only to the team and must explain to the other teams the work that has been done. **Instructions for the teams: A New Era of Technology—Which possible applications and implications? (one for each team)** The instructions for completing the activity are fully explained here. The activity is divided into two parts: • Activity 5a: reading the map and exploring the four worksheets, looking for possible applications and implications in the use of quantum computers, drawing arrows and potentially adding new aspects in the blank spaces; • Activity 5b: Confronting each other and discussing together the connections and the map, by paying close attentions to the different dimensions of impact on the applications/implications of quantum computers; highlighting the connections that the team finds more meaningful among the others. Later, speaking about the results of analyses in front of the whole class.
Teaching methods	The teacher presents the content and the objectives of the Quantum Manifesto and he/she contextualises it within the European Union and the scientific and technological research, by introducing the Second Quantum Revolution and by highlighting the stakeholders involved in it. Then he/she explains the activity and forms the teams, merging students on the basis of their interests upon the four topics of the worksheets. After writing the chosen topic on the map, each team has to explore and analyse the corresponding worksheet with different aims: • To recognise and highlight in the map the aspects "touched or involved" by their topic; • To find valuable connections between the topic and the various aspects selected in the map, by drawing arrows between their topic and the ovals; • To reason about the connections. Throughout the activity, the students are asked to reflect on the distinction between *applications* and *implications* of the technologies and,

	if their discussion leads them to recognise an aspect that does not appear in the map, they are asked to add it in the blank spaces. The arrows have to be clarified and discussed by paying close attention to the different dimensions of impact on the applications of quantum computers (scientific, environmental, social, ethical, economic, political, etc.). The team should also be able to say which connections are more meaningful among the others and why. Writing some keywords or sentences for the arrows could be useful for describing why the team considers something more important than something else. At the end of the teamwork session, each team has to present its findings and analyses to the others, by the means of slides, a short video, a poster, or simply a little speech.
Tips for teachers from previous classroom experiences	When explaining the Quantum Manifesto, it is important to highlight the connection between it and the activity. In particular, it is important to stress that the activity has been designed as a guide to navigate and analyse scientific and institutional texts and resources. In particular, it is important to foster an *analytic attitude* toward the activity where the "judgement in terms of good-bad" is suspended and postponed after an engagement with scientific texts and a process of analysis. The teacher should emphasise the fact that quantum technologies are still on their way to be implemented, but also that this fact did not stop institutions, scientists and stakeholders from thinking about implications and applications. Finally, it is very important to highlight the importance of creativity in the team activity, so as to create in students the right mindset for thinking creatively about the future of their topic.
Additional resources	Quantum Flagship website https://qt.eu/ de Wolf, R. (2017). *The Potential Impact of Quantum Computers on Society*. https://arxiv.org/abs/1712.05380v1 Harrow, A.W. & Montanaro, A. (2018). *Quantum Computational Supremacy*. https://arxiv.org/abs/1809.07442

Annex B

Activity instructions for the group project,
One to be given to each group.

It's your time to imagine the futures

Activity No. 5: **A New Era of Technology… Which possible applications and implications?**

Team No.:
Members:

Activity 5a:

- Read the map and explore the four worksheets, looking for possible applications and implications in the use of quantum computers. Use the map to represent the found connections between quantum computers and the aspects written in the ovals:
  - ⇒ By drawing arrows, if need be in both directions.
  - ⇒ If necessary, by adding new aspects in the blank spaces.

Activity 5b:

- Confront each other and discuss together the arrows and the map, especially by paying close attentions to the different dimensions of impact on the applications of quantum computers (scientific, environmental, social, ethical, economic, political, etc.). During the discussion, highlight and make more explicit the connections that the team finds more meaningful among the others, by writing some keywords that can describe the reason why the team considers those applications/implications important.
- Choose the way you prefer for speaking about the results of your own analyses (a poster, some slides, a short video, or simply a little speech) and prepare for expressing your ideas and opinions in front of the whole class during the third day.

Annex C

Worksheets,
Four to be given to each student.

QC & Communication

Some definitions:

- ***Quantum cryptography:*** a branch of cryptography that uses quantum physics laws and properties for developing new cryptographic protocols for the exchange of information.
- ***Quantum internet:*** a kind of quantum network that allows communication between quantum computers on networks that are protected by quantum teleportation, which is the transmission of quantum information both through entanglement and classical channels.
- ***Quantum programming:*** a branch of computer science that develops algorithms for quantum computers in a programming language that is comprehensible to the user. While a classical computer works through classical logic gates (AND, OR, NOT), a quantum computer works through quantum logic gates (Hadamard, Pauli-X, Pauli-Y, Pauli-Z, Identity, Quantum-NOT, etc.).

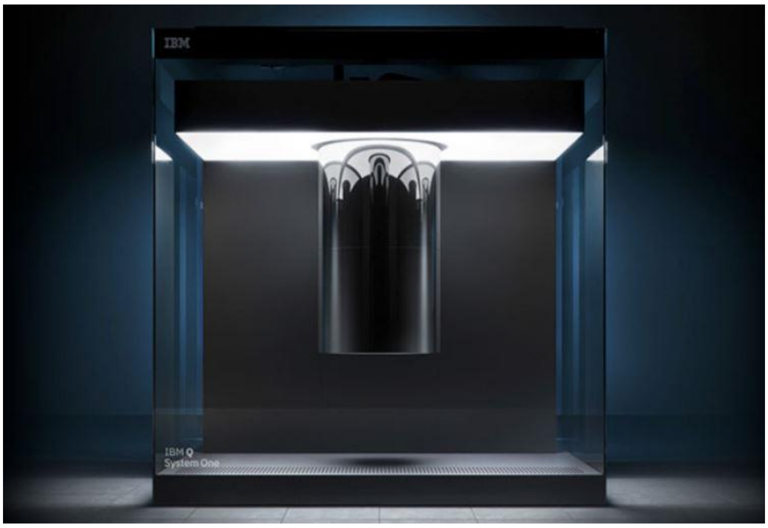
Nowadays, communications via internet are essentially based on three elements: computers, networks between computers and cryptography. Classical cryptography is unbreakable by classical computer because it would take too much time for them to factorise huge numbers. The break of classical cryptography could be possible by the means of quantum algorithms and quantum computers, which are potentially enough powerful to do that. This would have an enormous impact on economic, political, military and social contexts, especially when it comes to privacy, surveillance and security of communications, and money and data transfer.
Game is on, not only in labs but also on a geopolitical level. It is not by chance that the US National Security Agency is one of the most involved institutions in this kind of research. Furthermore, the development of a secure quantum network would imply that whichever kind of cryptography would be “eavesdroppers-free”: that would also lead to hiding illegal activities, maybe strengthening the so-called *deep* and *dark web*.

Some examples:

- **BB84**: it is a quantum cryptographic protocol developed by Charles H. Bennet and Gilles Brassard in 1984;
- **Quantum Internet Alliance:** it is an alliance between some European research groups with the aim of developing a quantum network for internet purposes.
- **IBM Q Experience:** within its research area on quantum technologies, IBM has developed a *software development kit* called "Qiskit" which contains tools for developing programmes with a real QC, localised in the IBM laboratories. The user programmes the quantum logic gates with packages for some classical programming languages (Python, Swift o Java), launches them on a designated provider and the latter translates classical instructions in quantum instructions for the QC, giving back the results.

Links	Descriptions
https://www.youtube.com/watch?v=UiJiXNEm-Go	Educational video by the YT channel "Physics Girl" on the differences between classical and quantum cryptography.
https://www.wired.it/scienza/lab/2018/03/09/internet-quantistica-punto-siamo/	[ITA] *Wired Italia* article on quantum internet
http://quantum-internet.team/	Quantum Internet Alliance website
https://www.scientificamerican.com/article/china-shatters-ldquo-spooky-action-at-a-distance-rdquo-record-preps-for-quantum-internet/	*Scientific American* article on the current record for quantum teleportation, made by China
https://www.accenture.com/us-en/insights/technology/quantum-cryptography	Report made by Accenture on how cryptography will change with the arrival of. Accenture is a multinational company of strategic consultancy.
https://quantumexperience.ng.bluemix.net/qx/experience	IBM Q Experience platform. It allows to create circuits made of quantum gates and to send them to a QC for analising.
https://qt.eu/app/uploads/2018/04/93056_Quantum-Manifesto_WEB.pdf	Quantum Manifesto

QC & Politics



Some definitions:

- ***Quantum Computational Supremacy:*** the situation of technological progress where a universal quantum computer (a theoretical model of a hardware and software that can simulate the operations of a quantum computer) is capable of performing calculations that are beyond the capability of any other classical computer.

What would happen if a world superpower, economic or political, obtained the quantum supremacy before the others? What would the implications be, if one nation or company had more computing power than another nation or competitor? Which would the consequences of possible inequalities be, as far as society, the military, economy, and science are concerned?

Which kinds of professions would the world of the **second quantum revolution** need? Maybe a quantum advisor? A quantum engineer? Instead, which professions would disappear? A cooperation between the public and the private sector is undoubtedly necessary, in order to reinvent competences and create new job profiles.

Some examples:

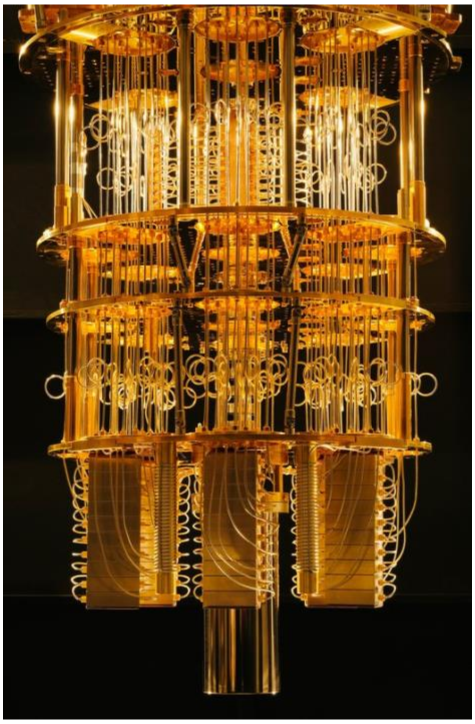
- **IBM Q System One:** At the CES (Consumer Electronics Show) in Las Vegas between 9 and 10 January 2019, IBM presented the System One, said by the company to be the first universal quantum computer ready to exit a laboratory. It has a 20-qubit processor and will serve scientific and commercial purposes. It will not be sold but will be accessible via Internet. According to the experts, it does not exceed the power of some supercomputers.

- **AcceleraItalia IBM:** it is a collaboration between IBM and 48 Italian universities. They united for creating a common pathway for education and research which has the aim of creating new job roles that can tackle the future technological innovation and the digital transformation.

- **FET Flagship in Quantum Technologies:** ten-year research programme that has been launched by the European Commission with an investment of one billion euros thanks to the requests of scientists, entrepreneurs and institutions representatives collected in the ***Quantum Manifesto***—a document written in 2016 for showing the urgency of developing the field of quantum technologies in Europe and make it able to compete on a global level in the new technological challenges.

Links	Descriptions
https://www.youtube.com/watch?v=LAA0-vjTaNY	IBM Q System One Advertisement
https://www.research.ibm.com/ibm-q/system-one/	IBM Q System One website
https://www-01.ibm.com/easytools/runtime/hspx/prod/public/X0027/PortalX/page/pageTemplate?s=78c374df5c884363b46454a5ffefb5d9&c=4917f54dfcd0484b91880482d28f8a85	[ITA] AcceleraItalia project for the new fields of knowledge: launched projects in Italian universities
https://qt.eu/app/uploads/2018/04/93056_Quantum-Manifesto_WEB.pdf	Quantum Manifesto
http://www.qtflagship.cnr.it/	[ITA] CNR (Italian National Research Council) website on Quantum Technology Flagship.
https://www.wired.it/attualita/tech/2019/01/08/ces-2019-ibm-svela-suo-primo-computer-quantistico-commerciale/	[ITA] *Wired Italia* article on Q System One
https://ai.google/research/teams/applied-science/quantum-ai/	Google research area on QC
https://www.microsoft.com/en-us/research/research-area/quantum/	Microsoft research area on QC
https://www.dwavesys.com/home	D-Wave Systems research area on QC
http://www.research.ibm.com/ibm-q/	IBM research area on QC

QC & Research in Science and Technology



Some definitions:

- ***Quantum simulator***: a controllable quantum system used for the simulation of other quantum systems, as it is possible to control some parameters.
- ***DQS (digital quantum simulator)***: a system that can reproduce a quantum algorithm for simulating another system. Quantum computers are an example: they are universal simulators, as they can *potentially* reproduce any kind of quantum system.
- ***AQS (analogue quantum simulator)***: tangible quantum systems that can replicate other ones. They can simulate a limited class of systems or phenomena. Because they are tangible, one can directly make measurements on them, contrary to DQSs, where states are manipulated through algorithms for obtaining results. In the recent years, different types of AQS models were implemented, and the development of some of them is based on the principles of physics of condensed matter—neutral atoms in optical lattices, cooled and trapped ions, superconducting circuits, et cetera.
- ***Quantum sensors:*** devices that use the superposition principle and/or entanglement in order to obtain higher sensibility and resolution for measurements of gravitational and magnetic fields, time intervals, and fundamental physical constants.

Quantum simulation applies to various scientific and technological fields, from atomic physics and solid-state physics, to high-energy physics and cosmology, and beyond.
Moreover, as it will allow to analyse the properties of certain systems, to select systems with desired properties, and to realise new compounds with desired properties, it will also allow to design new drugs or materials with important features

(such as superconductors at high temperatures) that could be used in different fields, such as the energy or the transport ones.
As far as the environment is concerned, one of the so-called *world's critical problems* is the design of an efficient system for capturing carbon in the atmosphere.
A wide accessibility to quantum computers on one hand and to scientific knowledge on the other is necessary to avoid the creation of monopoles within pharmaceuticals companies, multinational corporations and governmental institutions. It is for tackling these new challenges that we need to educate new generations of technicians and scientists.

Links	Descriptions
https://www.youtube.com/watch?v=qarc7AA4-wM	Short introductive video on the challenges of quantum simulation
https://www.microsoft.com/en-us/research/blog/problems-will-solve-quantum-computer/	Article showing that a QC can be used to reveal the reaction dynamics within a complex chemical system. For example, the analysis of the nitrogenase (an enzyme), which is beyond the capacity of any supercomputer today, will have important consequences on the production of fertilisers
https://qt.eu/discover/applications-of-qt/fertilizer-and-other-quantum-computer-chemistry/	Website showing the objectives of computational chemistry in the development of mathematical models that simulate the behaviour and the properties of complex chemical systems
https://home.cern/news/news/computing/exploring-quantum-computing-high-energy-physics	QC for the challenges in high-energy physics
https://www.cnr.it/it/news/8292/sensori-quantistici-superconduttivi-per-comprendere-la-progressione-della-sla	Use of quantum superconductive sensors in the functional study of the brain
https://qt.eu/app/uploads/2018/04/93056_Quantum-Manifesto_WEB.pdf	Quantum Manifesto

QC & Society

Some definitions:

- ***Quantum optimisation:*** a branch of quantum technologies that tries to improve already existing machine-learning algorithms for obtaining new solutions, not only thanks to the fastest computational speed of QCs but also thanks to the qubit-like, substantially different from the classical bit-like one. The techniques for optimising machine-learning algorithms are called "quantum annealing techniques".

Optimisation has various applications in different fields, not only in the scientific and engineering ones. It is predicted that the massive use of such algorithms, robotics and machine learning will radically modify the way the intend jobs and industry today.
The mechanical, manual and computing professions could be given to machines, leaving creative and coordinating jobs to humans. It is the so-called "Industry 4.0": will the quantum computer accelerate its arrival?

Some examples:

- **Traffic optimisation:** Volkswagen, in collaboration with D-Wave Systems—a company specialised in quantum technology— is studying a way to predict the places of a city where traffic congestions are more probable, in order to direct cars to other free streets. This requires the analysis of a dataset that is so huge no supercomputer can actually handle it.
- **Optimisation for medicine:** a clinic in the US made a collaboration with D-Wave for developing algorithm that can optimise the current techniques that determine the optimal dosage of radiations for a patient in radiotherapy. This

depends on the kind of cancer, its stadium, and the clinical characteristics of the patient.

- **Optimisation of online advertisements:** Recruit Communications, a human resources company, has developed an optimisation algorithm that matches consumers with proper advertisements and allows companies using online ads to increase their CTR (Click-through-rate), which is the ratio between the number of times a consumer clicks on the ad and the number of times the ad appears on a website. This is one of the rates that most influences how much the provider of a website is paid by the company that wants its advertisements to be published online.

Links	Descriptions
https://ai.google/research/teams/applied-science/quantum-ai/	Google AI website with research areas in Quantum AI and short-term applications
https://qz.com/1323987/quantum-computing-could-put-a-stop-to-traffic-jams/	Article explaining the principle behind the traffic optimisation
https://media.vw.com/en-us/releases/1098	Press release by Volkswagen
https://www.dwavesys.com/sites/default/files/VW.pdf	Slides explaining in detail the algorithm for traffic optimisation
https://www.dwavesys.com/sites/default/files/Radiotheraphy-Optimization-Roswell-Park_0.pdf	Slides on the optimisation in the field of radiotherapy
https://www.dwavesys.com/press-releases/recruit-communications-and-d-wave-collaborate-apply-quantum-computing-marketing	Press release by D-Wave on the Recruit Communications algorithm for optimisation of online ads
https://www.dwavesys.com/sites/default/files/RCO_0_0.pdf	Slides on the algorithm for advertising
https://qt.eu/app/uploads/2018/04/93056_Quantum-Manifesto_WEB.pdf	Quantum Manifesto

Annex D

Map for the group project,
One to be given to each group.

Team No.:
Members:

Aerospace vehicules

STEM Careers (Science, Technology, Engineering and Maths)

DNA and cells

Privacy

Energy

New materials

Lack of food

Science Fiction

Optimisation

Unemployment

____

Economy

____

____

Quantum Computing
&
____

____

Security

Finance

Scientific education

New drugs and therapies

Art

New "Silicon Valleys"

Artificial Intelligence

Nanotechnology

Creativity

Global Warming

Driver-less vehicules

Sensors

Cryptography

Inequalities

ACKNOWLEDGEMENTS

"Oh, I've finally decided my future lies
beyond the Yellow Brick Road!".

The pathway of my Bachelor has been for me a little bit like *The Wizard of Oz*'s yellow brick road; the road that Dorothy and her friends follow to get to the Emerald City and meet the Wizard, trusting they would find the key to solve all their problems. Well, in the end, they discovered that everything they needed, they had conquered it on the way. Yet, Dorothy in her red shoes could have never done it without the help of all the people she met halfway, and maybe, without that tornado, she would have never grown up.

First things first, I thank professor Olivia Levrini, who, since the first day of her lectures, has been for me a role model and an unlimited source of new thoughts and perspectives. Thank you for believing in me, for all the smiles and for all the words that gave me back trust in my abilities.

Thanks to every member of the Research Group in Physics Education of the Department of Physics and Astronomy. Thanks to Giulia Tasquier, Eleonora, Giovanni and Michael, to Michela Clementi and to Paola Fantini. A thousand times "Thank you" to Sara, for spreading all her optimism even in the toughest moments I went through.

Thanks to my parents, Cinzia and Mario, for always supporting me and for knowing when to alternate the moments of silence with the moments for talking. Thanks to Alberto, who fills me with pride each and every day and who will always be the most special person I know, my favourite person of all.

Thanks to Federico L. for the patience and for the affection, being close or far away (and for all the corrections on the telephone at 1 A.M.!). Thanks to all my dear friends, for the joy, for backing each other, for the discussions, the memes, the *plpling* and all the rest. Thanks to Martina, Federico P., Gabriele, Federica, Cecilia, Giada, Matteo, Elena, Gaetano and to all the friends of the "Acquario". Thanks to Giulio, with whom I shared many moments since the earliest days of university.

Thanks to Riccardo Guidetti, the head of the hall of residence "Camplus Alma Mater", where I have lived for four wonderful years, for giving me so many occasions that have all been an opportunity to grow up and to learn.

I thank anyone who came close to me in this path. And (why not?), I also thank all the people I have come close to and whose words and actions were a constant inspiration and opportunity to reflect. After all, "We are like dwarves perched on the shoulders of giants". Thank you, then, to Immanuel Kant, Piero Angela, Michelle e Barack Obama, Isaac Newton, The Beatles, Stanley Kubrick, Marie Skłodowska Curie, Carl Sagan, Malala Yousafzai…

RINGRAZIAMENTI

"Oh, I've finally decided my future lies
beyond the Yellow Brick Road!".

Questo percorso di laurea triennale è stato per me un po' come la strada di mattoni gialli nel film *Il Mago di Oz*, quella che Dorothy e i suoi amici percorrono per arrivare nella Città di Smeraldo e incontrare il Mago, convinti di poter risolvere i propri problemi, per poi scoprire che tutto quello di cui avevano bisogno l'avevano conquistato proprio strada facendo. Ma Dorothy, con le sue scarpette rosse, non ce l'avrebbe mai fatta a tornare in Kansas senza l'aiuto di tutti i personaggi della storia che ha incontrato nella via, e forse senza quel tornado non sarebbe mai cresciuta.

Per prima cosa, ringrazio la professoressa Olivia Levrini, che, fin dal primo giorno del corso di "Insegnamento della Fisica", è stata per me un modello e una fonte inesauribile di pensieri e prospettive nuovi. Grazie per aver creduto in me, per i sorrisi e per tutte le parole che mi hanno restituito fiducia nelle mie capacità.

Grazie a tutte le persone del Gruppo di Ricerca in "Didattica della Fisica" del Dipartimento di Fisica e Astronomia. Grazie a Giulia Tasquier, a Eleonora, Giovanni e Michael, e alle professoresse Michela Clementi e Paola Fantini. Mille volte grazie a Sara, per avermi trasmesso tutta il suo ottimismo anche nei momenti più faticosi.

Grazie anche ai miei genitori, Cinzia e Mario, per avermi sostenuta in tutto e per aver saputo alternare i momenti di silenzio ai momenti in cui parlare. Grazie ad Alberto, che ogni giorno che passa mi riempie più di orgoglio e che sarà sempre la persona più speciale che conosco, la mia persona preferita.

Grazie a Federico L. per la pazienza e per l'affetto, da vicino e da lontano (e per le correzioni all'una di notte al telefono!). Grazie a tutti i miei cari amici, per le gioie, il sostenersi a vicenda, le discussioni, i memi, il *plplare* e tutto il resto. Grazie a Martina, Federico P., Gabriele, Federica, Cecilia, Giada, Matteo, Elena, Gaetano e a tutti gli amici dell'Acquario. Grazie a Giulio con cui ho condiviso tanti momenti fin dai primi giorni del primo anno di università.

Grazie a Riccardo Guidetti, il direttore del Camplus Alma Mater, in cui ho vissuto quattro anni meravigliosi, per avermi dato tante opportunità che sono state per me occasione di crescita e di formazione.

Ringrazio chiunque si sia avvicinato a me in questo percorso. E (perché no?) ringrazio anche le persone a cui io mi sono avvicinata e le cui parole e azioni mi hanno dato tanto di bello su cui riflettere. D'altronde, "Siamo come nani sulle spalle di giganti". Grazie, allora, Immanuel Kant, Piero Angela, Michelle e Barack Obama, Isaac Newton, i Beatles, Stanley Kubrick, Marie Skłodowska Curie, Carl Sagan, Malala Yousafzai…

References

Barelli, E. (2017). *Science of complex systems and future-scaffolding skills: a pilot study with secondary school students*. (Master's thesis). Alma Mater Studiorum – University of Bologna, Italy. Retrieved from https://amslaurea.unibo.it/id/eprint/13644.

Benasayag, M., & Schmit, G. (2004). *L'epoca delle passioni tristi.* (E. Missana, Italian Trans.). Milano: Giangiacomo Feltrinelli Editore. ISBN: 88-07-10367-2. [Original French version (2003): *Les passions tristes. Souffrance psychique et crise sociale.* Paris: Édition La Découverte.]

Bergmann, W. (1992). The Problem of Time in Sociology: An Overview of the Literature on the State of Theory and Research on the `Sociology of Time', 1900-82. *Time & Society, 1*(1), 81-134. doi: https://doi.org/10.1177/0961463X92001001007.

Branchetti, L., Cutler, M., Laherto, A., Levrini, O. Palmgren, E.K., Tasquier, G., & Wilson, C. (2018). The I SEE project: An approach to *futurize* STEM education. *Visions for Sustainability, 9*, 10-26.

Branchetti, L. & Levrini, O. (February 2019). *Disciplines and interdisciplinarity in STEM education to foster scientific authenticity and develop epistemic skills*. Unpublished paper accepted at the ESERA Conference (26th-30th August 2019) in Bologna, Italy.

Chinn, C.A. (2018). Modelling, explanation, argumentation, and conceptual chance. In: Amin, T.G., Levrini, O. (Eds.), *Converging Perspectives on Conceptual Change: Mapping an Emerging Paradigm in the Learning Sciences* (pp. 206-226). London: Routledge.

Costa, P., & Araújo, L. (2018). *Quality of Teaching and Learning in Science* (EUR 28865 EN). Luxembourg: Publications Office of the European Union. ISBN 978-92-79-76294-9. doi:10.2760/860512, JRC109064.

CoSTEM (2013). *Federal Science, Technology, Engineering, and Mathematics (STEM) Education. 5-year Strategic Plan: A Report from the Committee on STEM Education.* Retrieved from https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/stem_stratplan_2013.pdf on 02 April 2019.

Council of the European Union. (2018). *Council Recommendation on Key Competences for Lifelong Learning (Text with EEA Relevance)*. ST/9009/2018/INIT. OJ C 189, 4.6.2018, p. 1–13 (BG, ES, CS, DA, DE, ET, EL, EN, FR, HR, IT, LV, LT, HU, MT, NL, PL, PT, RO, SK, SL, FI, SV). Council Recommendation of 22 May 2018. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.C_.2018.189.01.0001.01.ENG&toc=OJ:C:2018:189:TOC on 04 April 2019.

de Touzalin, A., Marcus, C., Heijman F., Cirac, I., Murray, R., & Calarco T. (2016). *Quantum Manifesto*. Retrieved from http://qurope.eu/manifesto#fn1 on 21 June 2019.

de Wolf, R. (2017). The Potential Impact of Quantum Computers on Society. *Ethics and Information Technology*, *19*(4), 271-276. doi: https://doi.org/10.1007/s10676-017-9439-z.

Dowling, J.P. & Milburn, G.J. (2003). Quantum Technology: The Second Quantum Revolution. *Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences 361*(1809). doi: https://doi.org/10.1098/rsta.2003.1227. Retrieved from ArXiv (arXiv:quant-ph/0206091v1) on 09 June 2019.

English, L.D. (2016). STEM education K-12: perspectives on integration. *International Journal of STEM Education 3*(3). doi:10.1186/s40594-016-0036-1.

European Commission. (nd*a*). *Science with and for Society (SWAFS)*. Retrieved from http://ec.europa.eu/research/swafs/index.cfm?pg=about# on 15 March 2019.

European Commission. (nd*b*). *Responsible Research and Innovation (RRI)*. Retrieved from https://ec.europa.eu/programmes/horizon2020/en/h2020-section/responsible-research-innovation on 18 March 2019.

European Commission. (nd*c*). *Quantum Technologies Flagship*. Retrieved from https://ec.europa.eu/digital-single-market/en/quantum-technologies on 21 June 2019.

European Commission. (2014). *Responsible Research and Innovation. Europe's ability to respond to societal challenges.* doi:10.2777/95935. Retrieved from http://ec.europa.eu/research/swafs/index.cfm?pg=library&lib=rri on 06 April 2019.

European Commission. (2015). *Science Education for Responsible Citizenship* (EUR 26893 EN). Luxembourg: Publications Office of the European Union. doi:10.2777/12626. ISBN 978-92-79-43636-9.

European Commission. (2016). *Developing future skills in higher education. ET2020 – Peer Learning Activity (PLA)*. Brussels, 25-26 February 2016.

European Commission. (2018). *Education and Training MONITOR 2018*. Luxembourg: Publications Office of the European Union. doi:10.2766/28521.

EU Skills Panorama (2014). *STEM Skills Analytical Highlight*. Prepared by ICF and Cedefop for the European Commission. Retrieved from https://skillspanorama.cedefop.europa.eu/en/analytical_highlights/focus-science-technology-engineering-and-mathematics-stem-skills on 04 April 2019.

Feynman, R.P. (1982). Simulating Physics with Computers. *International Journal of Theoretical Physics, 21*(6/7), 467-488. doi: https://doi.org/10.1007/BF02650179.

Gagliardi, M., & Giordano, E. (2014). *Metodi e strumenti per l'insegnamento e l'apprendimento della fisica*. Napoli, Italy: SES.

Gammaitoni, L., Vulpiani, A. (2019). *Perché è difficile prevedere il futuro. Il sogno più sfuggente dell'uomo sotto la lente della fisica.* Bari: Edizioni Dedalo.

Gonzalez, H. B., & Kuenzi, J. J. (2012). *Science, technology, engineering, and mathematics (STEM) education: A primer*. Library of Congress. Congressional Research Service. Retrieved from http://digital.library.unt.edu/ark:/67531/metadc122233/.

Hallinen, J. (2017). STEM. In *Encyclopædia Britannica*. Retrieved from https://www.britannica.com/topic/STEM-education on 15 March 2019.

Harrow, A.W. & Montanaro, A. (2017). Quantum Computational Supremacy. *Nature 549*, 203-209. doi: https://doi.org/10.1038/nature23458. Retrieved from https://arxiv.org/abs/1809.07442 on 05 May 2019.

Honey, M., Pearson, G., & Schweingruber, A. (2014). *STEM integration in K-12 education: status, prospects, and an agenda for research.* Washington: National Academies Press.

I SEE. (2019). https://iseeproject.eu/ Retrieved on 05 May 2019.

Joyce, A. (2014). *Stimulating interest in STEM careers among students in Europe: Supporting career choice and giving a more realistic view of STEM at work*. Brussels: European Schoolnet.

Kelley, T.R., & Knowles J.G. (2016). A conceptual framework for integrated STEM education. *International Journal of STEM Education 3*(11). doi:10.1186/s40594-016-0046-z

Kennedy, T.J., & Odell, M. R.L. (2014). Engaging Students in STEM Education. *Science Education International*, *25*(3), 246-258.

Leccardi, C. (2009). *Sociologie del tempo. Soggetti e tempo nella società dell'accelerazione*. Roma-Bari: Editori Laterza.

Levrini, O., Tasquier, G., Branchetti, L., & Barelli, E. (under review). Developing Future-Scaffolding Skills through Science Education. Submitted to *International Journal of Science Education*.

Li, Y., Schoenfeld, A.H., diSessa, A.A. et al. (2019). On Thinking and STEM Eduation. *Journal for STEM Education Research*. Retrieved from https://doi.org/10.1007/s41979-019-00014-x on 02 April 2019.

Miller, R. (2006). Futures Studies, Scenarios, and the "Possibility-space" Approach. In: OECD (2006). *Think Scenarios, Rethink Education*. (pp. 93-105) Paris: OECD Publishing. doi: https://doi.org/10.1787/9789264023642-7-en.

Möller, M., & Vuik, C. (2017). On the Impact of Quantum Computing Technology on Future Developments in High-Performance Scientific Computing. *Ethics of Information Technology 19*(4), 253-269. doi: https://doi.org/10.1007/s10676-017-9438-0.

OECD. (2016a). *PISA 2015 Results (Volume I): Policies and Practices for Successful Schools*. Paris: OECD Publishing. doi:10.1787/9789264266490-en. Retrieved from https://www.oecd-ilibrary.org/content/publication/9789264266490-en.

OECD. (2016b). *PISA 2015 Results (Volume II): Excellence and quality in education*. Paris: OECD Publishing. doi:10.1787/9789264267510-en. Retrieved from http://www.oecd.org/pisa/pisa-2015-results-volume-ii-9789264267510-en.htm.

OECD (2016c). *Assessment and Analytical Framework: Science, reading, mathematic, financial literacy and collaborative problem solving. Revised edition.* Paris: OECD Publishing. doi: http://dx.doi.org/10.1787/9789264281820-en

PISA. (2018). About PISA. Accessed on 15 March 2019, retrieved from http://www.oecd.org/pisa/aboutpisa/.

Rosa, H. (2010). *Alienation and Acceleration. Towards a Critical Theory of Late-Modern Temporality*. Malmö, Sweden: NSU Press.

Sadler, T. D., Foulk, J. A., & Friedriechsen, P. J. (2017). Evolution of a Model for Socio-Scientific Issue Teaching and Learning. *International Journal of Education in Mathematics, Science and Technology*, *5*(2), 75-87. doi:10.18404/ijemst.55999

Sanders, M.E. (2009). STEM, STEM Education, STEMmania. *The Technology Teacher*, *68*(4), 20–26. Retrieved from https://vtechworks.lib.vt.edu/handle/10919/51616 on 26 March 2019.

Satanassi, S. (2019). *Quantum Computers for High School: Design of Activities for an I SEE Teaching Module*. (Master's thesis). Alma Mater Studiorum – University of Bologna, Italy. Retrieved from: https://amslaurea.unibo.it/id/eprint/18157.

SiS.net. (2016). *Science education policies in the European Commission: towards responsible citizenship.* Accessed on 14 March 2019, retrieved from http://www.sisnetwork.eu/media/sisnet/Policy_Brief_Science_Education.pdf.

STEM Task Force Report. (2014). *Innovate: a blueprint for science, technology, engineering, and mathematics in California public education*. Dublin, California: Californians Dedicated to Education Foundation.

Tasquier, G., Levrini, O., & Dillon, J. (2016). Exploring students' epistemological knowledge of models and modelling in science: Results from a teaching/learning experience on climate change. *International Journal of Science Education, 38*(4), 539-563. doi: https://doi.org/10.1080/09500693.2016.1148828.

UNESCO (2017). *Science Education Programme*. Retrieved in http://www.unesco.org/new/en/natural-sciences/special-themes/science-education/about-the-programme/.

Vasquez, J.A., Sneider, C., & Comer, M. (2013). *STEM lessons essentials, Grades 3-8: Integrating science, technology, engineering, and mathematics.* New York: Heinemann.

Vasquez, J.A. (2014/2015). STEM: Beyond the Acronym. *Educational Leadership*, Dec 2014/Jan 2015, *72*(4).

Wheeler, J.A. (1986). How Come the Quantum? *New Techniques and Ideas in Quantum Measurement Theory, 480*(1), 304-316. doi: https://doi.org/10.1111/j.1749-6632.1986.tb12434.x.

White House. (nd). *Educate to Innovate.* Retrieved from https://obamawhitehouse.archives.gov/issues/education/k-12/educate-innovate on 06 April 2019.

White House. (2018). *President Donald J. Trump is Working to Ensure All Americans Have Access to STEM Education*. 04 December 2019. Retrieved from https://www.whitehouse.gov/briefings-statements/president-donald-j-trump-is-working-to-ensure-all-americans-have-access-to-stem-education/ on 04 April 2019.