WIP: Teaching basic concepts of quantum computing using Scratch

Carlos Rosa-Remedios, Pino Caballero-Gil, Daniel Escanez-Exposito
Department of Computer Engineering and Systems
University of La Laguna. Tenerife, Spain
crosarem@ull.edu.es, pcaballe@ull.edu.es, jescanez@ull.edu.es

***Abstract*—This work-in-progress research paper presents an innovative learning methodology based on gamification and the concept of "building your own knowledge" to motivate and spark students' interest in quantum computing. Using the Scratch platform with younger high school students, basic quantum computing principles are taught through interactive mini-games, focusing on concepts like superposition and entanglement. For older students, a more formal methodology is proposed that uses the Bloch Sphere representation via the CreatiCode platform. This paper discusses an implementation of the proposal with high school groups, including statistical analysis and feedback collection to assess concept acquisition, strengths, weaknesses and student satisfaction. Data is gathered through questionnaires and interviews, enabling comparison with external test groups for comprehensive evaluation. This approach integrates computational thinking, gamification and visual knowledge construction, aligning with STEM education principles and fostering knowledge retention.**

***Keywords*—Computing, Educational software, High school.**

I. Introduction

Quantum computing represents a radical change in information technology, expected to transform industries dependent on computing. Preparing students early in this field will provide them with the skills to lead in these emerging fields. Besides, since this area is rooted in advanced principles of physics and mathematics, introducing these concepts at the pre-college level can enhance analytical, problem-solving, and abstract thinking skills, while increasing interest in STEM (Science, Technology, Engineering and Mathematics) careers.

The main issue of this work is to design a suitable methodology to introduce the basic concepts of quantum computing in the early stages of education, incorporating evaluation mechanisms that allow to generate a process of continuous improvement in each classroom performance. The proposed methodology introduces fundamental principles of quantum computing through the Scratch platform [1], organizing a comprehensive visual program into several stages to enable multilevel program assessment, taking advantage of the benefits of the inclusion of Scratch in education [2], [3].

To date, the bibliography includes various proposals to motivate undergraduate or graduate students in the study of quantum computing [4], [5]. However, very few of them introduce basic concepts at pre-university levels [6], [7], which is precisely the objective of this work.

For this reason, the proposed framework is designed for two pre-university educational stages.

The secondary school stage (14-16 years) is selected because, although it is assumed from the outset that the students have no prior knowledge of quantum computing, they do have a level of educational maturity that would allow them to assimilate it at a basic level. Hence the reason for using Scratch and setting up some previous questionnaires to validate this hypothesis about the starting knowledge.In addition, another reason for selecting this stage it is the time when students begin to define their future preferences. For younger high school students, a program has been designed to bypass the complex physical and mathematical foundations of quantum mechanics and focus on understanding basic concepts such as superposition, entanglement, and Heisenberg's indeterminacy principle. Accompanied by Scratch's reference graphic icon, now resembling Schrödinger's cat, students are able to construct programming blocks as mini-games to reflect various quantum computing concepts (see Fig. 1). This approach allows creating learning situations that blend computational thinking, gamification and concept assimilation through visual knowledge construction, aligning well with the STEM model and ensuring knowledge retention. In order to ensure that the underlying physical and mathematical concepts are correctly aligned with the level of the students, Scratch sessions will be coordinated with the physics and mathematics teachers so that they can support the more formal bases related to the concepts covered in each area.

The last year of high school (ages 17-18) is the stage prior to entering university, so the mathematical and physical concepts are more established, making it possible to delve deeper into the theoretical aspects and scientific context. In a second phase, as a future continuation of this work, aimed at older students with a stronger background in mathematics and physics, a methodology closer to the formal basics of quantum computing is envisaged, introducing the Bloch Sphere as a key piece for representing qubits, quantum gates, and quantum algorithms through their representation as circuits. In this case, an evolution of Scratch enabling 3D modeling, called CreatiCode platform [8], was chosen for this purpose, providing a more formal visualization of the concepts while maintaining the "knowledge construction" and "learning through play" methodology.

To validate the proposed approach, it is being put into practice with several secondary school groups, conducting an extensive statistical study to assess concept acquisition,

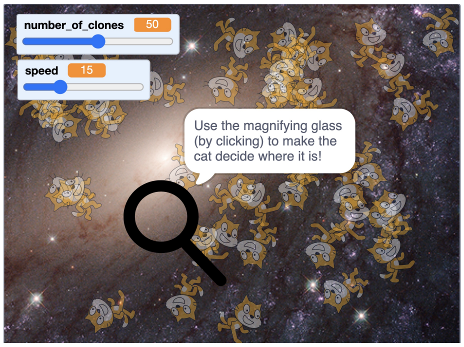


Fig. 1. Partial Scratch screenshot of superposition module.

project strengths and weaknesses, and student satisfaction level. Besides, from the feedback of both collaborating teaching staff and participating students, several improvement proposals are being considered. Data collection is being carried out through different choice questionnaires and interviews, whose results allow comparison between the participating students and a test group outside the project for external evaluation, providing a comprehensive diagnosis that covers both quantitative and qualitative data.

This work is structured as follows. In Section II, the used framework is detailed, highlighting the concepts introduced through the project and the modular methodology to cover them. Next, in Section III, the planned actions to put the proposed methodology into practice are described, detailing each of them. Section IV shows the techniques used to collect objective and subjective data, in order to evaluate, through the methodology described in Section V, both the aspects related to the acquisition of knowledge and those related to the degree of acceptance by students and teachers of the methodology used. Finally, Section VI discusses the main conclusions and open research lines of this work.

II. Preliminary research project

In line with the objectives set out in this study, the first part of the research involved identifying the fundamental concepts to be addressed, translating the associated mathematical and computational foundations into a context that is familiar to the students and easy to understand and assimilate.

For the phase aimed at students in the last years of high school, the following basic principles of quantum computing have been selected: Heisenberg indeterminacy principle [9], superposition [10], entanglement [11], [12], quantum measurement [13], and applications of quantum computing [14].

Using the Scratch mascot (the drawing of a cat) as a story-line and taking advantage of the paradox posed by Erwin Schrödinger in 1935 known as “Schrödinger’s cat” [15], a series of short stories and mini-games are constructed that turn the Scratch cat into the protagonist of the selected quantum principles. Thus, each concept becomes a gamification experience through which the student internalizes the meaning and consequences of each principle without the need to introduce mathematical or physical terms.

The methodological proposal consists of the following phases, ordered from the creation of prototypes in Scratch to the staging in the classroom:

1) Creation of the story-line.
2) Development of Scratch modules linked to the concepts.
3) Design of the methodological sequence to be followed in the classroom and creation of the session timetable.
4) Coordination with the educational center and selection of target groups.
5) Pre-assessment for further differential analysis.
6) Staging of the sessions.
7) Data collection.
8) Final assessment.
9) Conclusions and proposals for improvement.

Below are brief descriptions of the different modules developed in the proposal, including their objectives and operation.

A. Introductory Scratch Session

This module corresponds to an hour-long activity, covering the fundamentals of Scratch.

Since one of the objectives is for students to build their own knowledge, as a preliminary phase to the classroom work sessions, a session is planned to summarize the basics of Scratch, its main elements and some examples of simple programs. In this way, in the practical sessions, the student is directed towards the self-construction of the modules developed through pre-built blocks that avoid delaying the gamification phase excessively.

The story is also introduced here, which acts as a thread to introduce the concepts in the various mini-games.

B. Module of the Heisenberg Indeterminacy Principle

This module corresponds to a half-hour-long activity, where the concept to be covered can be defined as follows. In the quantum world it is impossible to determine with certainty, and simultaneously, certain pairs of physical properties of a particle. An example of this may be that the position and momentum (linear momentum) of a given particle is not determined at the same time. For the students, “momentum” is introduced as the amount of motion of an object, making some analogies with elements of everyday life.

In this mini-game, the player encounters a quantum search experience of the character, as if it were a particle. There is a slider that is initially in the center, which can go from the exact definition of the position to the complete determination of the momentum. At the beginning a highlighted surface is shown (in continuous random motion), which marks the possible positions in which the cat can be found. This point cloud is surrounded by arrows (also randomly varying in size), which represent the possible moments. By dragging the slider towards the end of the precision in the position, the surface becomes smaller and smaller, until it concentrates on a single point: where the cat is located. However, the number of arrows will grow considerably, until an inordinate number of arrows is reached, with the momentum of the cat being completely undetermined. Similarly, by sliding the controller to the opposite end, which indicates the definition of the momentum, the number of arrows and their oscillations are reduced until they are completely determined, resulting in a single arrow of fixed size: the momentum of the cat. In contrast, the position surface will have grown to fill the entire screen, making it completely indeterminate.

Through this module, students are able to familiarize themselves with the property of indeterminacy, playing with the slider and seeing the practical result on these two variables. In addition, they get a magnifying glass element, which allows them to measure the position and momentum of the cat, which are randomly defined at that instant, depending on the indeterminacy resulting from the slider.

C. Entanglement

In this half-hour-long module, the concept to be covered can be described as follows. When two particles are intertwined, a change of state in the first one can instantaneously generate the same state in the second one. This implies that when a measurement is made on the first particle, the states of both particles are identical.

In this case, the idea of entanglement of two particles is introduced through a mini-story where the main character and another pet go through a "quantum door" leaving them entwined from this moment on. The secondary character departs on a journey, moving away from the protagonist. The idea here is that the student can initially place the lead in different stances by placing the magnifying glass on him at any time. At that moment the image of the intertwined companion is revealed, showing the same stance as the main character. This action is repeated multiple times, varying the traveler's distance, thereby demonstrating that the effect is independent of distance, no matter how great.

D. Superposition

This half-hour-long module covers the concept of quantum superposition, which can de defined as follows. A particle can exist in multiple different states simultaneously and when measured it "collapses" to a single state of all possible states.

This module is focused on the introduction of the idea of superposition through a mini-game, where the protagonist starts to replicating through space depending on two input parameters: number of clones and speed. Once the process begins, the student is invited to place a magnifying glass that acts as an emulator of the "quantum measurement" process, forcing the system to collapse in a specific position, showing the mascot in a single place (see Fig. 2).

E. Quantum Measurement

In 30 minutes, an activity module covers the following concept. In contrast to classical physics, where observations do not affect the state of the system, measuring a quantum system can alter its state.

Quantum measurement is dealt transversely in the other experiments, since in all of them it is necessary to measure in order to appreciate their effects. Additionally, a mini-game

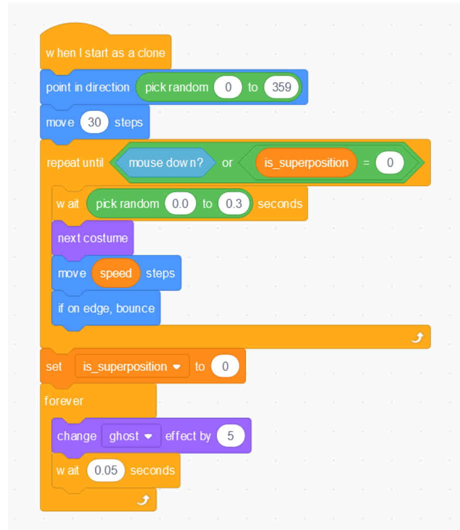


Fig. 2. Partial Scratch screenshot of superposition code.

is planned where a simulation of the cat exploring a maze is performed. With the superposition, it will unfold, increasing the probability of finding a hidden chest on the map. At any time, the student can press the magnifying glass and one of the copies of the cat will randomly become the real one. If the chest has not yet been found, the quantum search will fail, and a single cat is obtained in a random position. However, if one of the copies of the cat has already found the chest by then, clicking on the magnifying glass will leave the cat that found it. In this way, students can be made to reflect that superposition alone does not solve problems, but that it must be used intelligently to ensure the solution.

F. Applications of Quantum Computing

The last 30-minute slot is devoted to the application of quantum computing in cryptography, where superposition and entanglement are used to encrypt and decrypt information.

In this module we work on the concept of quantum cryptography through a mini-game where the protagonist is in a spaceship that is protected by a secret password. First, the student is asked to try to guess it by trying different options. Obviously, this is a really tedious task, as the learner could try, one by one, all the existing words in the dictionary. However, after a couple of attempts, the cat invites the student to use quantum computing to "hack" the password. To do this, a quantum computer appears on the scene, and visually simulates a quantum cryptography algorithm that, through superposition and entanglement, allows "hacking" the secret key (as it tries all possible words at once), accessing the controls of the spacecraft. In this way, the student recognizes in a practical way one of the most important utilities of quantum computing: its hot use in cryptography.

III. Practical Implementation in the Classroom

To implement the methodology, two types of classroom interventions were planned: online and face-to-face sessions.

Online sessions were designed to facilitate access from any geographical location, allowing for a greater diversity of students and geographical areas. In this case, the intervention was programmed in the form of workshops that include, on the one hand, introductory sessions to Scratch and the dynamics that are intended to be transferred with the mini-games and, on the other hand, the mini-game sessions. This modality, scheduled at the beginning of the academic course, allows a wide range of educational stages and modalities to be covered, including secondary school and vocational training students. In a later phase, the baccalaureate stage is covered, using in this case the Creaticode tool, since it allows visualization of the more mathematical concepts of the principles of quantum computation. The objective is to design a methodology for areas that are geographically more distant from the main population centers and that, consequently, have less possibility of accessing face-to-face sessions.

Face-to-face sessions were developed with specific centers. In particular, they were focused on two different centers in the metropolitan area, at the secondary school stage. The classroom sessions were proposed following the same pattern as the online workshops but, in this case, group participation was sought in such a way that in each “mini-game” a team leader is rotated who must then transfer the conclusions in a brief presentation to the rest of the teammates.

The deployment of the proposed dynamics through face-to-face and online sessions with geographic diversity greatly enriches data collection and subsequent analysis, which allows the search for an optimal strategy to introduce new concepts.

IV. Data collection and assessment

For data collection, different strategies were designed to ensure the collection of both objective and subjective data, allowing a much more in-depth analysis to be carried out.

Firstly, an initial diagnosis was conducted using a battery of questions for both teachers and students to establish a baseline of knowledge Including teachers in this step aims to design specific training for them, ensuring long-term continuity of the project through the ‘trainer of trainers’ principle.

The initial questionnaires are not intended to rule out any student profile, but are used only as a baseline to carry out, after the classroom actions, a subsequent assessment of the effect obtained in the assimilation of concepts. Based on the measurable results obtained, different training itineraries will be proposed as a future line of work.

Stratified sampling was chosen to ensure a balanced sample in terms of sex, age and level of education.

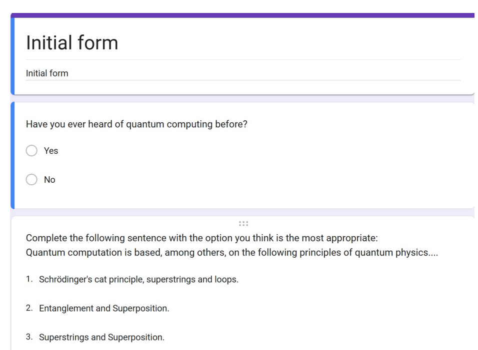
Some questions of the initial form for students are:

1) Have you heard of quantum computing before?
2) Complete the following sentence with the option you think is the most appropriate: Quantum computing is based, among others, on the following principles of quantum physics...
    a) Schrödinger’s cat principle, superstrings and loops.
    b) Entanglement and Superposition.
    c) Superstrings and Superposition.
3) The equivalent to a bit in classical computing is the...
    a) Cube.
    b) Qubit.
    c) Bit-q.

Some questions of the initial form for teachers are:

1) Do any of the subjects you teach introduce concepts related to quantum physics or quantum computing?
2) Are you knowledgeable about the fundamentals of quantum computing?
3) What relevance do you think quantum computing may have in society in the short to medium term?
    a) Very little. No impact in the short or medium term.
    b) Few. This is a field still without applications in the short and medium term.
    c) A lot. It has major implications for the information society.
4) Choose the option that best reflects the concept of quantum computing:
    a) It consists of replacing traditional chips with photon-based chips.
    b) It represents a new paradigm that uses the principles of quantum physics to create computers that are more powerful than current ones in all fields of computing.
    c) Quantum computing leverages quantum physics principles like superposition and entanglement to process information differently from classical computing.

These forms were implemented using Google Forms. An example of this type of questionnaires is shown in Fig. 3.


Initial form

Initial form

Have you ever heard of quantum computing before?

- Yes
- No

Complete the following sentence with the option you think is the most appropriate:
Quantum computation is based, among others, on the following principles of quantum physics....

1. Schrödinger's cat principle, superstrings and loops.
2. Entanglement and Superposition.
3. Superstrings and Superposition.

Fig. 3. Initial form for students.

In addition to a series of short interviews with teachers to learn about their perception of the project’s evolution, during the development of the sessions, a subjective data collection is done, covering information about the following aspects:

- Has it been necessary to answer more than 2 questions per team?
- Has the session stayed within the planned timing?
- Have the students correctly followed the indications given for the execution of the session?

- Have students made improvement proposals?
- Have any proposals for improvement been made by the teaching staff?

Once the sessions are over, the initial questionnaires are repeated to establish the variation on the baseline but, in addition, a questionnaire based on Quizizz has been designed to collect data from the students in a more competitive way facilitating motivation (see Fig. 4). In this way, some conclusions can be drawn about the different answers to the same question expressed with different strategies.

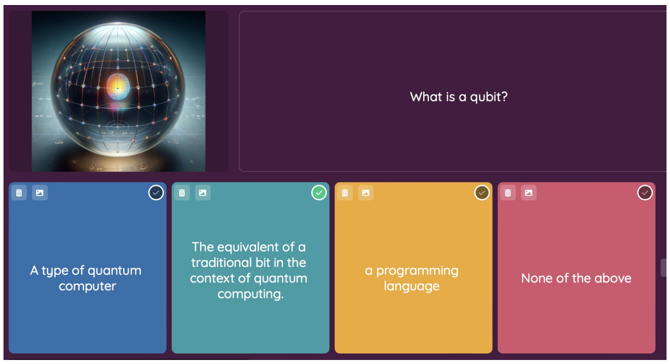


Fig. 4. Questions using Quizizz.

V. Methodology for Analysis

The process for the analysis of the collected data follows the steps outlined below.

To prepare and clean the data, ensure there are no incomplete questionnaires, and all data are legible and expressed in quantitative, standardized values for homogeneous scales. The only exception is qualitative data for subjective assessment in the final report. Frequently unanswered responses will be analyzed, as they highlight confusing concepts.

Secondly, as a rough approximation to statistical study, the elements of descriptive statistics are used, obtaining the following data according to each analyzed group:

- Statistical parameters: mean, mode, ranges and standard deviation of the responses to the questionnaires.
- Graphical representation through histograms to visualize response distribution and identify possible anomalies.

Thirdly, the correlation between objective and subjective data is analyzed, allowing us to know the relationship between both types of data and to detect possible inconsistencies in the responses. In addition, taking advantage of the geographical dispersion obtained in the online version of the workshops, a regression analysis is performed to determine how demographic or economic variables (from the educational environment) may influence learning outcomes.

Finally, depending on the number of groups that have been covered, ANOVA analyses are performed to establish whether the differences between groups are statistically significant. After this statistical process, a second phase of analysis is carried out with the aim of establishing corrective and improvement measures for the following editions, thus allowing a cycle of continuous improvement to be established.

VI. Conclusions and Future Work

This work presents a gamification-based methodology to introduce quantum computing at the secondary level, using Scratch for younger students and CreatiCode for older ones.

In the initial implementation phase, challenges arose from the complex concepts and the need for coordination across different centers and educational levels. Thus, efforts were made to simplify the concepts and integrate them into gamified experiences. Due to the overlap with the end of the school year, workshops were rescheduled to the next year, with a focus on online sessions to reach more centers and levels.

Future work includes developing a set of activities with the Creaticode tool for the pre-university stage, allowing deeper exploration of scientific concepts. The program will also include the design of different training itineraries according to the levels that are reached after the sessions.

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