

Quantum error correction for kids

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Abstract—No one should wait until college to get acquainted with core concepts of quantum information. Given the human bias of favouring the familiar over the unknown, early exposure to concepts of quantum information helps learners build stronger appetite for the field, as well as allowing them to develop an intuitive approach to it. In this work, I present an intuitive gamified approach to one of the core concepts in quantum error correction: the stabiliser formalism.

Index Terms—education, primary education, STEM education, quantum education, quantum error correction, gamification

CONTEXT

Early exposure to scientific concepts is considered to impact positively future engagement of the audience with the subject matter. Given the recognised urgency of educating a wider audience to quantum technologies and the pivotal role quantum error correction (QEC) plays within quantum computing, targeting early outreach towards this branch of the field is key.

With quantum training having been recognised as a priority by authorities [12] and quantum technologies now having their own European competence framework [10], [11], a number of creative approaches to teaching and outreach has seen the day. On top of the traditional approach to curricula building, a number of alternatives have been suggested such as thought experiments [19], behaviourism-inspired processes [20] and games. This gamification [16] has been increasingly explored through video games [3], [5], [14], interactive story-telling [18], quantum games [4] and a variety of other playful approaches [16].

In terms of age range, however, most initiatives target the upper range of K12, leaving audiences below the age of 12 under-served. Yet exposing early K12 learners to general STEM [1], [6] or even physics [15] has been done successfully. Some initiatives exist to familiarise these younger audiences with quantum-related topics, but they remain limited [8].

QEC [17] is considered to be one of the major bottlenecks now faced by quantum computing [2]. The process of turning physical information into logical information to shield it from noise and potential errors isn't specific to quantum computing, however some specificities of quantum systems make it more challenging. Barriers such as the *no cloning theorem* or the collapse of the wave function due to measurement make it impossible for some of the primitives of classical error correction to hold. Moreover, even if continuous quantum errors are digitised, they are still of two kinds -bit flips and phase flips-, compared with classical errors which only affect bit flips.

Though not the most popular field of quantum computing for newcomers, QEC harbours core concepts which can in

some cases be presented in a straightforward way. Simple families of codes such as *stabiliser codes* -to which the popular *surface code* [7], [13] belong- relies on, among others, the concept of parity checks. This concept which comes from classical error correction [9], is central in a number of codes, both classical and quantum, and because of how intuitive it can be constitutes a fair candidate for early learning.

In this paper, I present a game which helps players build an intuitive grasp of the concept of parity checks used in the stabiliser formalism. A main game is presented with two extensions. The initial game mimics a situation of classical error correction while the last one reflects a quantum one. Each game can either be played stand-alone or in continuation from the other ones, complexifying the game play until reaching the quantum setup.

How to use

This paper is meant as a resources for people working in quantum education wishing to tackle the topic of QEC with young audiences. It provides the rules and mechanics of a game meant to convey intuitively basic element of classical and quantum error correction. I also provide a non-exhaustive list of *focus points* from which educators can pick and choose the aspects they are most interested in conveying in their game sessions. Note that this paper is not meant as an introduction or presentation of QEC to the reader, it assumes the reader is familiar with the aspects of QEC being modelled in the game and wishes to convey the intuitions behind it to a young audience.

GAME OVERVIEW

In this game of communication, Messengers try to deliver information to a Receiver while avoiding being caught by the Noise.

Teams and scoring

The game will see 2 teams compete against each other: the Communication and the Noise teams. Players of the Communication team are divided into two groups: the Messengers and the Receiver. The way the Communication team can score a point is by having the Messengers successfully deliver their message to the Receiver. To do so, Messengers must cross the space (hereafter called the Channel¹) while avoiding the Noise. The Noise team scores a point by preventing the Communication team to score.

Note that the winner at the end of all rounds will be either Communication or Noise based on their total scores across

¹Channel: in reference to a *communication channel*

all rounds. Players don't win individually, the team of either Communication or Noise does.

The game goes on for as many rounds as there are players, so that each player gets to be the Receiver once and the Noise at least once -depending on the number of Noise roles available-. Players should swap teams so they get to experience different roles in the game.

Teams: The minimal number of players for the Communication team is 3 Messengers + 1 Receiver = 4. The minimal number of players for the Noise team is 1. Below is a table with suggested team split for growing numbers (up to 10 players):

Communication	Noise	Total
4 (3 + 1)	1	5
5 (4 + 1)	1	6
6 (5 + 1)	1	7
6 (5 + 1)	2	8
7 (6 + 1)	2	9
8 (7 + 1)	2	10
8 (7 + 1)	3	11
9 (8 + 1)	3	10

TABLE I: Suggested player split

General setup

While the game can be adapted to suit various group sizes and age ranges, I detail the core setup for the target group size and age, leaving the readers (and future players!) room for adaptations.

- **Age range:** 7+
- **Number of players:** 5+
- **Materials**
 - Two non-translucent bags.
 - Marbles of 2 colours in sufficient numbers (if there are n players, there should be $2(n - 2)$ marbles of each colour).
 - One or more dice (depending on variations).
- **Environment:** large space for movement, either outdoors or indoors with alterations or a lot of free space. Especially in the version where they run, participants should be given enough room.
- **Game-play:** competitive, by team.



Fig. 1: Player setup
The Messengers (green) will have to cross the channel (rectangle) and reach the Receiver (purple). All this while avoiding to get caught by the Noise (red).

REPETITION CODE

In this basic version of the game, the Communication team carries information across the channel, avoiding being caught by the Noise, and delivers it to the Receiver. The Receiver then decodes the message and must guess what message was sent.

Round setup

Before the game starts, players prepare and are then asked to stand in position.

- The Receiver stands on one side of the Channel, holding an empty bag.
- The Noise stands in the middle of the Channel with a die in their pocket.
- The Messengers stand on the side of the Channel that is across from the Receiver with a bag containing marbles of each of the 2 colours.
- Messengers agree on a colour for the round. Once agreed, each of them takes a marble of the round's colour with them.
- All players agree on a number called the **Noise Value**. When the Noise throws the die, any value equal or greater than the Noise Value means the Noise gets to act. Any value below means they don't.

Game phases

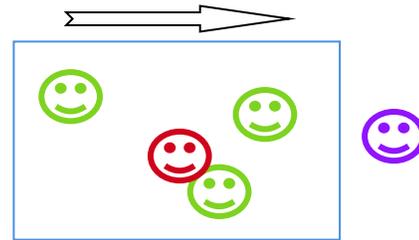


Fig. 2: Crossing the channel phase
Messengers (green) start crossing the channel trying to avoid the Noise (red). Here one of the Messenger was caught by the noise

Crossing the Channel: A member of the Noise gives the GO signal. As soon as the signal is given, Messengers can start crossing the Channel. The goal of the Noise is to catch as many Messengers as they can before they reach the Receiver. The goal of the Messengers is to reach the Receiver before getting caught by the Noise. If a Messenger gets caught by the Noise, they must freeze in place and wait for the crossing to be over. If a Messenger manages to reach the Receiver, they put their marble in the Receiver's bag. It's crucial at this stage that the Receiver does **not** look at the marble or inside the bag. Once all Messengers have either reached the Receiver or are have been frozen in place by the Noise, this phase is over.

Noise acts: In the case where the Noise failed to catch any Messenger, this phase is skipped. In the event that the Noise did catch some Messengers, their turn now begins. Noise collects the marble bag from the Messenger's side of the Channel and approaches each Messenger one by one. For each Messenger, the interaction goes as follows:

The game unfolds in a similar way to the previous *Parity checks* ones, with some modifications.

Noise phase

Instead of only being able to exchange marble colours, the Noise can now either exchange either the colour or the shape of the marble, or both. The Noise first throws to see if they affect the colour of the marble. Here the same rule applies as before when checking the Noise Value. Then they throw the die a second time for the shape.

Decoding phase

Now instead of having to figure out only which colours have been switched, the receiver also has to figure out which shapes have been. The actions allowed to figure that out are the same as in the *Parity check* version except that the Receiver can now either ask whether players share the same shape or share the same colours.

GAME MODIFICATIONS

Simplifications

If the Noise has difficulty catching Messengers, you can either change the ratio and add more Noise players to the team (though it is not recommended for less than 6 players) or increase the probability that the Noise can act if it catches a player by lowering the Noise Value or changing the die.

Complexifications

Exploring different Messengers/Noise proportions: The proportion of players being the Messengers or the Noise can be varied.

Exploration of noise levels: Players can experiment by changing the Noise Value to different numbers and/or by using different dice.

Adversarial noise levels: Instead of all players agreeing on a Noise Value, this choice could be left to the Noise alone. Instead of being publicly shared, it would also be possible for the Noise to keep that choice secret from the Receiver.

Measurement noise: On top of the initial Noise phase which happens when Messengers cross the Channel, an additional phase for a different kind of Noise (measurement noise) can be accommodated. In this case, once all Messengers have put their marbles into the Receiver's bag, there is a last phase before the decoding one where the Noise can take swap some number of marbles for others from outside the bag. Whether they are swapped for the opposite colour or whether they are swapped for a random colour is left to the players to decide.

Limited resources: In the *Parity check* and *Quantum code* versions, this modification encourages the Receiver to optimise information gain. This system requires the setting up of a points budget, and here asking one question to a pair would cost a negative point. In this scenario, the player is prompted to limit the number of checks being performed.

Stabiliser size: With enough players, it is possible to allow the Receiver to experiment with different parity checks. For instance, instead of allowing only to ask questions to pairs of Messengers, the Receiver could be given the choice between asking a group of two or a group of four Messengers (or a group of six in larger settings). In this version, it will be important to emphasise to Messengers that they should count the *parity* of their pieces of information and not whether or not they all agree. This confusion can arise when going from two to four players since a parity check for a two-player group is effectively the same as asking whether or not all elements are the same. Which is not the case for larger groups.

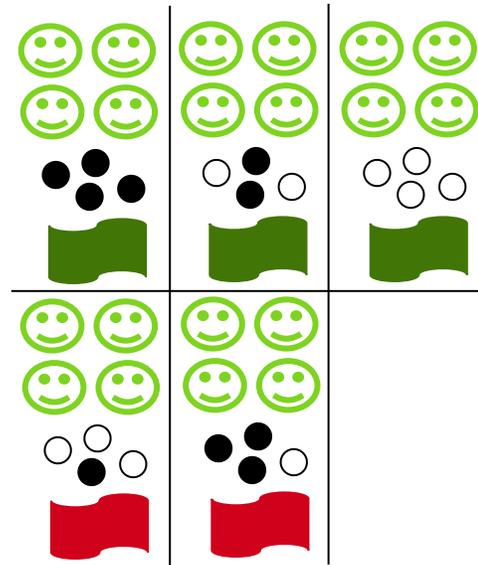


Fig. 6: Even parities for the size four parity checks groups with green cards, odd parities with red ones.

Inclusivity and accessibility

In order to accommodate for a wide range of players, here are a few non-exhaustive guidelines to adapt the game to your specific audience. It must be emphasised that each player being unique, modifications must be tailored to their specific needs.

Mobility adaptation: Different mobilities can easily be accommodated in this game, either by adapting the roles given to children with limited mobility (the needs for high-performing motor skills is less apparent in the Receiver role than it is for the Messengers of Noise ones for instance). Other options include giving time bonus/penalties to Noise versus Messengers in their crossing of the Channel.

Stimuli sensitivity adaptation: Bearing in mind that some children might be more sensitive to loud noises, abrupt movements or physical contact, the game can easily be adapted to accommodate a wide range of sensitivities. For loud noises, children can be asked to speak words instead of shouting them, potentially making the game happen in discrete sequences. Abrupt movements could be averted by setting the rule that the Messengers and Noise can only walk across the channel.

Sensory perception and processing adaptation: Accommodating the game for differences in sensory perception can easily be achieved with mindful planning. Examples of accommodation could include more visual communication for children who might be hearing impaired. For children with vision impairment, relying more on verbalisation can be considered, different marble textures could also be considered as an alternative to colours. For players who might be colour-blind, the choice of the two marble colours should be made considering the accessibility of the colour spectrum.

FOCUS POINTS

This section proposes a short non-exhaustive list of items which could be paid attention to when playing. Focusing player's attention on the following question should help build an intuitive sense of the stakes of error correction in communication channels and the interplay between information redundancy and noise levels.

- Why should the Noise throw a dice to decide whether they swap marble colours and not just automatically swap them? Try to allow the Receiver to observe whether the marbles are exchanged by the Noise or not. Does that change anything? If so, in which situations? Which team gets an advantage from this (if any)? Do they gain an advantage irrelevant of the Noise Level, or does the Noise Level have an impact on whether or not they do gain advantage?
- Does it make a difference when the ratio of Messengers versus Noise changes? What kind of difference? Does it become easier/harder for some team? Which one? Why?
- Does it make a difference when the Noise Value changes? What kind of difference? Does it become easier/harder for some team? Which one? Why?
- When **varying proportions of Messengers versus Noise**, players should be encouraged to observe how much easier/harder things get for each team.
- For the **adversarial noise levels** only: interesting things to observe here is whether higher Noise Values are always good, whether keeping the Noise Values secret is an advantage for the Noise and whether changing Noise values instead of sticking to a fixed value makes it easier or harder.
- For the *Quantum codes* version where the Receiver is left to choose the **stabiliser size**, does it become harder or easier to figure out where the error-s is/are with bigger or smaller parity check groups? Does it have anything to do with the Noise Value?

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