Game of Finches: iQuHack documentation

Challenge: IonQ

Team: Entanglement5

1 Introduction

Almost exactly 100 years after Darwin developed his theory of evolution, Niels Bohr posed the question of whether quantum theory could be used to describe living systems. Since then, the fields of molecular biology and, more recently, quantum biology have grown exponentially yet much is still not understood. Existing quantum technologies are not yet capable of solving complex biological problems it is hoped they will one day do. In lieu of this, we wanted to use the IonQ computing platform to demonstrate the striking parallels between measured quantum state evolution and the theory of natural selection.

We encode the prototypical model of evolution, Darwin's finches, in the states of trapped ion qubits and impose evolutionary constraints by single qubit gate operations. Furthermore, we harness the all-to-all connectivity of the IonQ platform to simulate both correlations between the 4 characteristics of a single finch, and the genetic mixing of different finch populations. Our 'Game of Finches' allows the player to generate an evolutionary tree where each time-step is created by a programmable quantum circuit and the probabilistic nature of quantum measurement mimics the evolutionary process.

2 Approach

1. Encode finch characteristics in expectation value of each qubit.
2. Set initial characteristics of finches, interaction strengths, and natural selection pressure
3. Each evolutionary time-step is realised by averaging 20-50 repeats of a quantum circuit (QC) composed of:
   (a) Single qubit gates to impose island-specific environmental pressures.
   (b) Two qubit partial SWAP gates to simulate genetic mixing.
   (c) Two qubit CNOT gates to induce correlations between, e.g., finch body size and wingspan.
4. The output distribution of the QC, as well as natural selection pressure, sets a new set initial characteristics of finches and changes the QC implement for subsequent evolutionary steps accordingly.
5. Repeat 3-4

In our model, each finch is defined by four characteristics: body size, wingspan, colour, and beak shape.

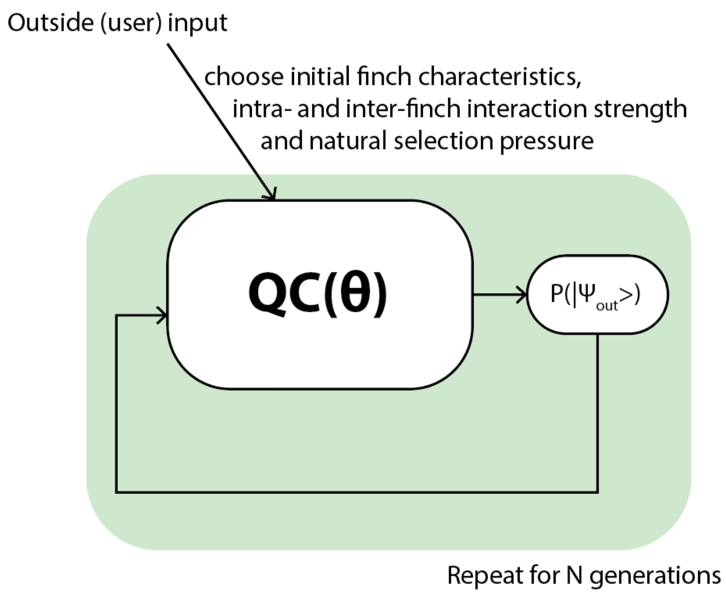


Figure 2: **Overview schematic of approach**

3 Implementation

Each evolutionary step consists of four stages: 1) initialization, 2) intra-finch evolution, 3) inter-finch evolution, and 4) a second step of intra-finch evolution 3.

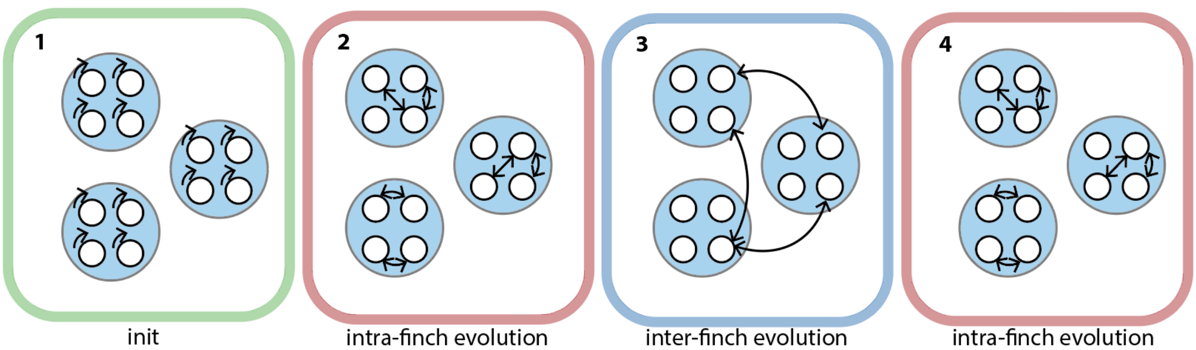


Figure 3: **Schematic of evolutionary step**

3.1 State preparation and single qubit rotations

All qubits are initialised into $|0\rangle$and the desired state, Eq. 1, is generated by single qubit $R_x(\theta)$ gates. The rotation angle is chosen so that $\langle Z\rangle$ maps onto the desired value for each characteristic, for example beak length $\propto (1 + \langle Z\rangle)/2$ and $\langle Z\rangle = \cos\theta$.

$$|\psi\rangle = \begin{pmatrix} \cos\frac{\theta}{2} \\ i\sin\frac{\theta}{2}\beta \end{pmatrix} \tag{1}$$

Single qubit rotations are then used to impose preferred characteristics on the finches as determined by the island they live on, for example favouring longer beaks, smaller bodies or muted colours.

Say the qubit state is $|\psi\rangle$, Eq. 1, and the environment favours an expectation value of $\langle Z\rangle_{env}$. We want

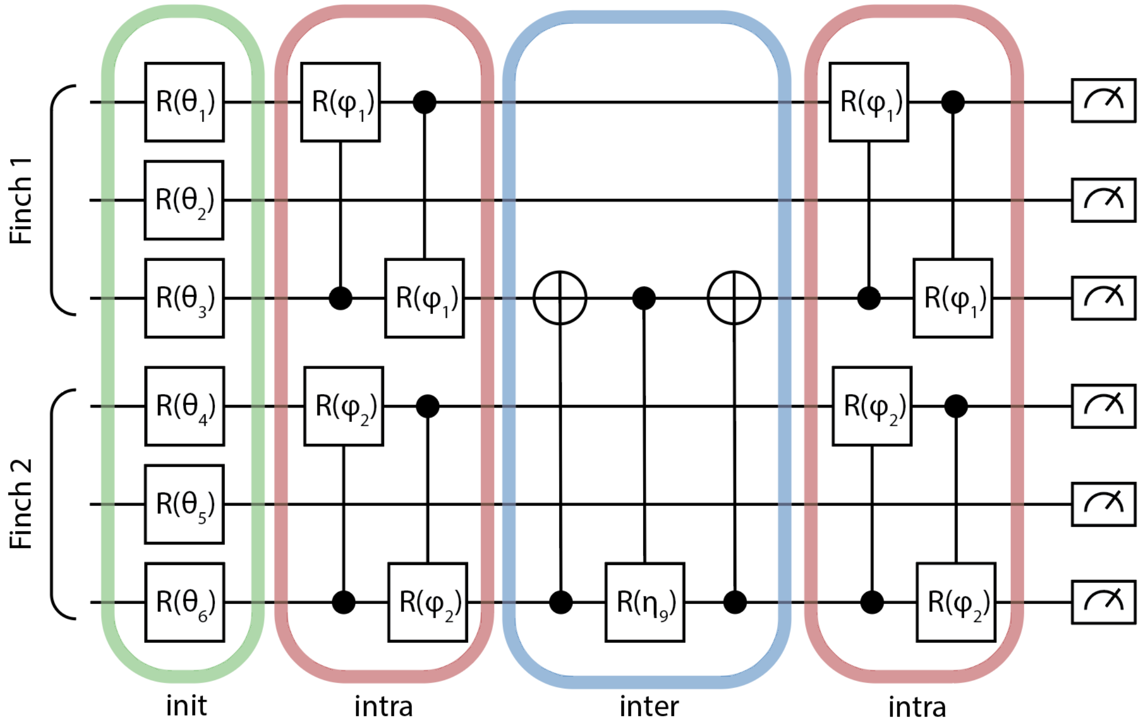


Figure 4: **Quantum circuit implementation of evolutionary evolution**

to perform a $R_x(\alpha)$ gate where the value of α is chosen to 'push' the qubit state towards $\langle Z \rangle_{env}$.

$$|\psi'\rangle = R_x(\alpha)\,|\psi\rangle = \begin{pmatrix} \cos(\alpha/2) & -i\sin(\alpha/2) \\ -i\sin(\alpha/2) & \cos(\alpha/2) \end{pmatrix} \begin{pmatrix} \cos(\theta/2) \\ i\sin(\theta/2) \end{pmatrix} = \begin{pmatrix} \cos((\theta-\alpha)/2) \\ i\sin((\theta-\alpha)/2) \end{pmatrix} \tag{2}$$

This means that $\langle \psi' | Z | \psi' \rangle = \cos(\theta - \alpha)$ so the appropriate value of α is given by

$$\alpha = \theta - \arccos(\langle Z \rangle_{env}) \tag{3}$$

In practice, the two rotations $R_x(\theta)$ and $R_x(\alpha)$ are consolidated into a single rotation gate $R_x(\theta + \alpha)$ as shown in the init of Fig. 4.

3.2 Intra-finch evolution

Some characteristics of a finch are more likely to be correlated with each other. For example, it might seem reasonable that the fatness of a finch is related to its wingspan or its beak size. We model these correlations as two $CR_x(\phi)$ gates that entangle the characteristic qubits with each other. The angle ϕ of the controlled rotations directs the strength of the interaction.

3.3 Inter-finch evolution

On the rare occasion that a finch pays a visit to another island, they can mix some of their characteristics with the finch population of that island before flying home again. This is implemented by partial SWAP gates, where the probability of a swap is determined by the user-defined island overlap (think how long a finch spends on the island, how friendly the native species is...).

This is implemented by a partial SWAP gate, Fig. 4, where the choice of rotation angle determines the "amount" of swapping. For examples, $\eta = 0$ corresponds to identity, or no interaction at all, and $\eta = \pi$ corresponds to a SWAP gate, a maximal swapping of characteristics. $\eta = \pi/2$ implements a $\sqrt{\text{SWAP}}$.

Fig. 5 shows an example of a 3 generation evolution outcome.

Figure 5: **Example of a finch evolution outcome**

4 Discussion

4.1 Finch evolution results

The finch evolution simulator allows for a large parameter space to be explored. Most notably we can tune the natural selection parameters. If, for example, we set finch 1 to have all desirable characteristics be in $|0\rangle$ and finch 2 to have all desirable characteristics be the $|0\rangle$, we find that in just 3 generations, the finches preferentially evolve in this manner in simulation. Figure 6 shows this simulated evolution graphically.

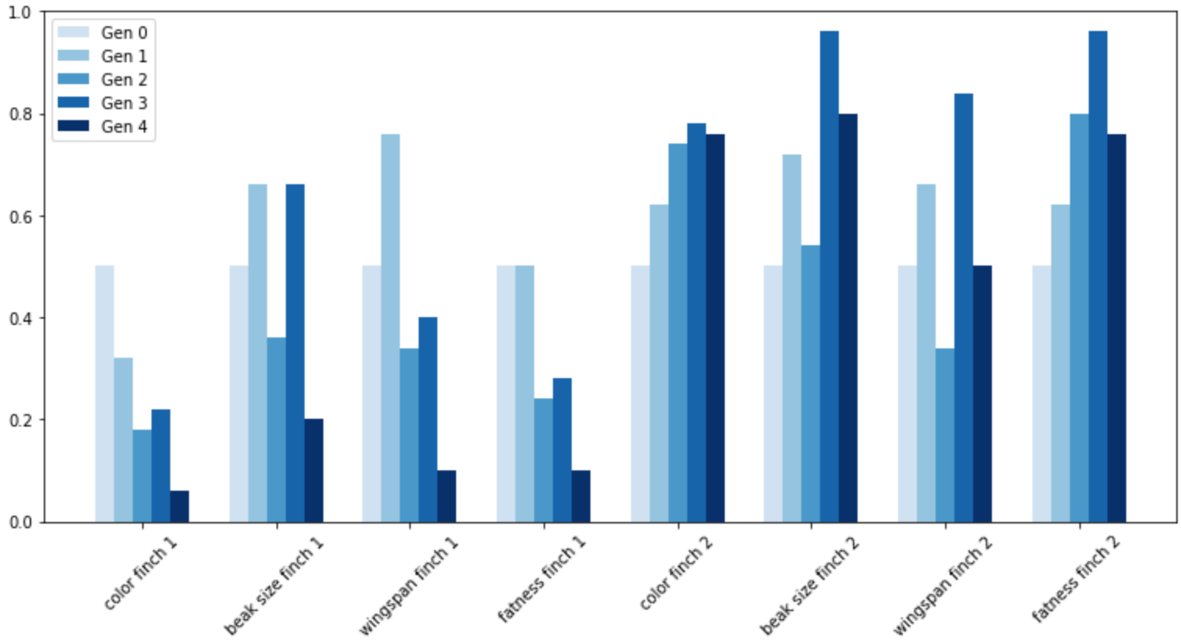
4.2 Finch evolution on harmony

We initialized 2 finches with 4 characteristics in an initial state of 0.5 for all characteristics and then let the finches evolve for 2 generations on the Harmony IonQ QPU. The intra-finch interaction angles were set to $\phi = \pi/10$ (fairly weak correlation) and the inter-finch interaction angles were set to $\pi/4$ (moderate mixing). Each generation was 50 shots. The results are shown in Fig. 7. Due to the probabilistic nature of the evolution, it is difficult to say if the quantum algorithm was a "success". We can however see that the intra-finch correlations are somewhat random, in line with the low interaction angle $\phi = \pi/10$. The inter-finch interactions were larger however, but not all characteristics participated in the mixing. Color and beak size participated in mixing, and both finches seem to converge to similar color and beak size, but wing span and body size did not, hence the discrepancy between the two finches.

4.3 Finch evolution in the NISQ era

One of key principles of Darwin's theory of evolution is the premise that variation exists within a population. However, it was only after the discovery of DNA structure that the idea of genetic mutations was further understood. In biology, mutations occur due to high energy events or spontaneously during replication. Mutations are essential to evolution and every genetic feature in every organism was, initially, the result of a mutation.

Noisy Intermediate-Scale Quantum (NISQ) technology, which is well represented by the IonQ computer, is able to produce exciting results, however noise in quantum gates still limits the size and depth of quantum circuits that can be executed reliably. In our application, we attempted to make use of the



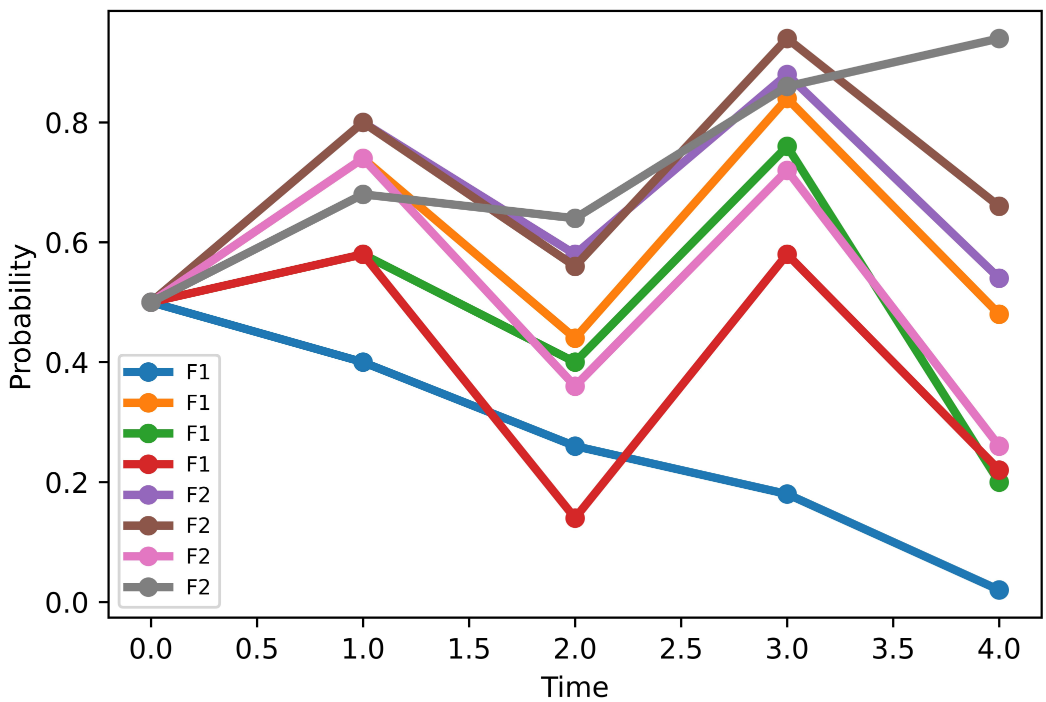


Figure 6: **Evolution of finch characteristics over the course of 3 generations. The characteristics of finch 1 where "naturally selected" towards $|0\rangle$while the characteristics of finch 2 where selected towards $|0\rangle$**

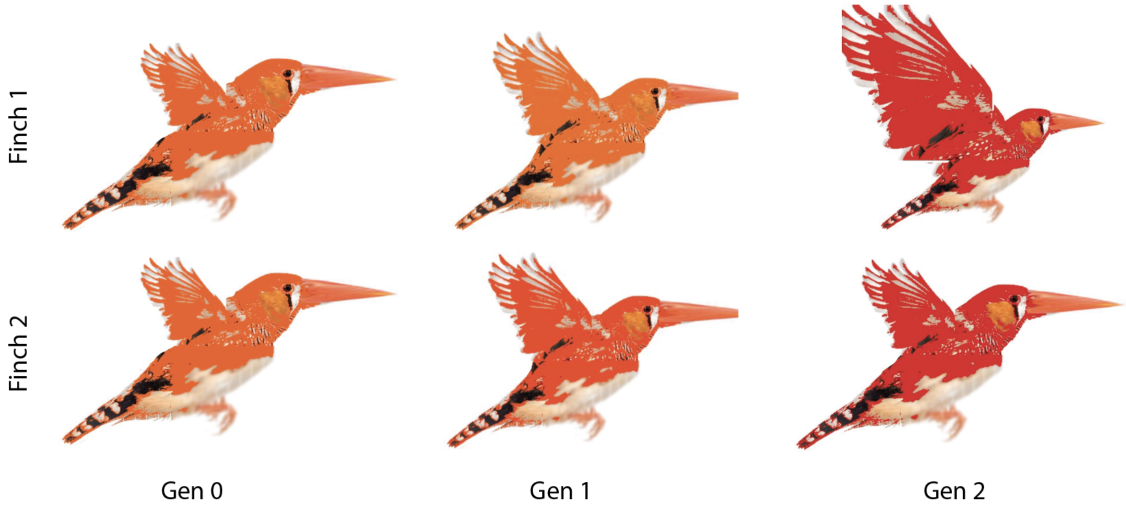


Figure 7: **Example of 2-finch evolution on Harmony QPU**

error rates of NISQ technology to broadly mirror the spontaneous mutations which occur in biological evolution.

An example of a noisy computer playing the role of random genetic mutation can be illustrated by considering the situation in which all finch characteristics are initialized to $|0\rangle$. The expected outcome of this initialization for the 1st generation is that each of the finch's remains in state zero. If no noise is considered, this is indeed what we see. Although we were not able to get the chance to run a sequence on the quantum computer that would show these noise properties, the inherent noise of the system can be something that is understood and factored into the simulation, and can even be seen to better the simulations adherence to the natural world.

4.4 Many-finch evolution

The aria-1 simulator is capable of hosting 23 qubits and therefore we could in principle run a simulation of up to five finches successfully. Unfortunately, prohibitively many gates would need to be applied in succession if we desired the full degree of connectivity. In figure 8 we show the results of a 3 finch simulation.

5 Conclusion and outlook

The random yet correlated processes of biological evolution seem like a natural subject for simulation using quantum computers. This project explored this idea using a simple model with a restrained number of qubits with a goal to be thought-provoking. It is unclear whether there is any advantage to simulation of the finch evolution with a quantum computer over a classical computer, even with a large population and characteristics dimensional space. It was however a great learning project to create, design, and implement. With access to more qubits and longer run times, we could imagine a quite complex evolution tree, where quantum effects might show up in interesting ways and could be studied more carefully. We hope that whoever reads this project documentation gets inspired to create their own quantum algorithm.

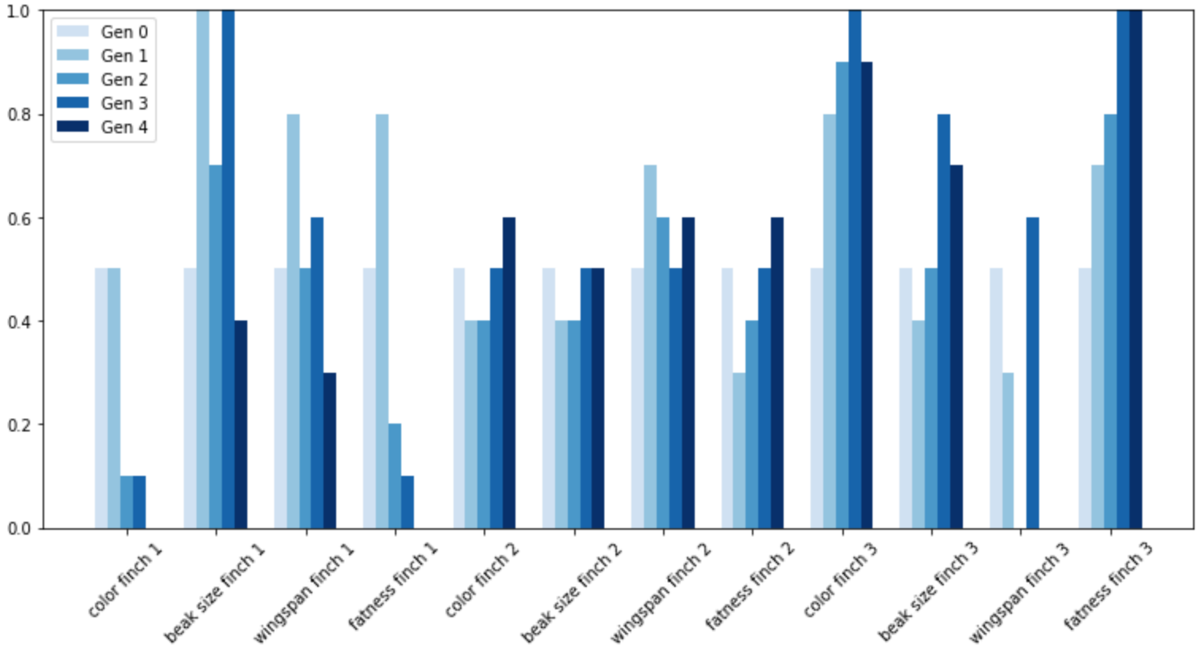


Figure 8: **Example of 3-finch evolution with the Harmony error model. The lower shot rate compared 6, to keep the simulation length tractable, leads to greater fluctuations in the outcomes of the quantum circuit.**