



**Universidade do Minho**  
Escola de Engenharia??  
Departamento de Informática??

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**Staggered Quantum Walks in Qiskit??**  
**Second Part of Title**

**First Part of Subtitle**  
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November 2020



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Master dissertation

Master Degree in Física da Informação

Dissertation supervised by

**Luís Barbosa**

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November 2020

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## ACKNOWLEDGEMENTS

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Write acknowledgements here

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## ABSTRACT

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Implementation of staggered quantum walks in qiskit.

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## RESUMO

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Pensar no que escrever aqui. Hello!

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## INTRODUCTION

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## QUANTUM COMPUTING

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### 2.1 GROVER'S ALGORITHM

Searching through an unstructured database is a task classically achieved by exhaustively evaluating every element in the database. Assume there exists a black box (oracle) that can be asked to find out if two elements are equal. Since we're looking for a specific element in a database of size  $N$ , we'd have to query the oracle on average  $\frac{N}{2}$  times, or in the worst case  $N$  times.

Grover's algorithm, presented in [1], comes as a quantum alternative to this type of problems, taking advantage of superposition by increasing desirable states' amplitudes through a process called *amplitude amplification*. This method has a quadratic gain over the classical counterpart [2], being able to find a target element with  $\mathcal{O}(\sqrt{N})$  oracle complexity.

Let us now expand on the inner workings of the black box. We start by focusing on searching indexes instead of directly evaluating the element and we assume  $N = 2^n$ ,  $n$  being a positive integer. We can now define a function  $f : \{0, 1, \dots, N - 1\}$  that returns 1 when evaluating the desired (marked) element and 0 otherwise. Since this function is to be applied to a quantum system, we must build a unitary operator  $\mathcal{F}$

$$\mathcal{F} |x\rangle |i\rangle = |x\rangle |i \oplus f(x)\rangle. \quad (1)$$

where  $|x\rangle$  is the index register,  $\oplus$  is the binary sum operation and  $|i\rangle$  is a qubit that is flipped if  $f(x) = 1$ .

The action of the oracle on state  $|0\rangle$  will be

$$\mathcal{F} |x\rangle |0\rangle = \begin{cases} |x_0\rangle |1\rangle, & \text{if } x = x_0 \\ |x\rangle |0\rangle, & \text{otherwise.} \end{cases} \quad (2)$$

where  $x_0$  is the marked element. More generically,  $\mathcal{F}$  can be written as

$$\mathcal{F} |x\rangle = (-1)^{f(x)} |x\rangle. \quad (3)$$

This offers a bit of insight into the oracle, it *marks* the solutions to the search problem by applying a phase shift to the solutions. As shown in ?, for an  $N$  item search with  $K$  solutions, we must only apply the oracle  $\mathcal{O}(\sqrt{N})$  times, which will be useful later when we describe the *single shot Grover*.

The question now is, what is the procedure that determines a solution  $x_0$  using  $\mathcal{F}$  the minimum number of times? The answer lies in the amplitude amplification section of Grover's search, starting with the creation of a uniform superposition

$$|\Psi\rangle = H^{\otimes n} |x\rangle = \frac{1}{\sqrt{N}} \sum_{x=0}^{N-1} |x\rangle. \quad (4)$$

where  $H^{\otimes n}$  is the *Hadamard* operator applied to an arbitrary number of states.

If we were to measure  $|x\rangle$  at this point, the superposition would collapse to any of the base states with the same probability  $\frac{1}{N} = \frac{1}{2^n}$ , which means that on average, we'd need to try  $N = 2^n$  times to guess the correct item. This is where amplitude amplification comes into effect, by means of a second unitary operator

$$\mathcal{D} = (2|\Psi\rangle\langle\Psi| - I) = H^{\otimes n}(2|0\rangle\langle 0| - I)H^{\otimes n} \quad (5)$$

This operator applies a conditional phase shift, with every computational basis state except  $|0\rangle$  receiving a phase shift. This can also be described as the *inversion about the mean*, for a state of arbitrary amplitudes

$$|\phi\rangle = \sum_{k=0}^{N-1} \alpha_k |k\rangle \quad (6)$$

the action of  $\mathcal{D}$  on state  $\phi$  will be

$$\mathcal{D}|\phi\rangle = \sum_{k=0}^{N-1} (-\alpha_k + 2\langle\alpha\rangle) |k\rangle \quad (7)$$

where  $\langle\alpha\rangle$  is the average of  $\alpha_k$

$$\langle\alpha\rangle = \frac{1}{N} \sum_{k=0}^{N-1} \alpha_k |k\rangle \quad (8)$$

The evolution operator that performs one step of the algorithm is then

$$\mathcal{U} = \mathcal{D}\mathcal{F} \quad (9)$$

and after  $t$  steps the state of the system is

$$|\Psi(t)\rangle = \mathcal{U}^t |\Psi\rangle. \quad (10)$$

The optimal number of steps is, as aforementioned,  $\sqrt{\frac{N}{K}}$  where  $K$  is the number of solutions to the problem.

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## QUANTUM WALKS

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Precisamos fazer uma introdução aqui, descrever o conteúdo do capítulo, algumas referências se necessário. Não precisa ser muito longo.

### 3.1 COINED QUANTUM WALK

Consider a one dimensional walker on top of a line, whose decision to go left or right depends on a coin toss. As expected, the outcome after many iterations of the coin toss is a binomial distribution centered in the starting position. It can be shown that the standard deviation is  $\sqrt{t}$ , where  $t$  is the number of time steps. The one dimensional walk can be abstracted to a graph of any dimension. This is known as the classical random walk and when the graph has its nodes weighted and it's edges directed, it is analogous to a discrete-time Markov chain <sup>1</sup>. *Você precisa esclarecer desde o início que está falando de uma caminhada clássica aqui, referenciar o livro do renato portugal, por exemplo, sobre o desvio padrão. Se quiser, pode fazer uma simulação clássica ou até mesmo abrir uma seção antes só para isso. Ah, precisa dizer que é uma linha infinita.*

In the quantum case, the walker is a quantum system whose position  $x$  on the line is described by a vector  $|x\rangle$  in Hilbert Space. The next position of the system is determined by a unitary operator, which can be viewed as a quantum coin. *O operador unitário não é somente da moeda, precisa falar do espaço do caminhante também* The analogy is, if the coin is tossed and rolls "heads", for example, the system transitions to position  $|x + 1\rangle$ , otherwise it advances to  $|x - 1\rangle$ . The Hilbert space of the system is  $\mathcal{H} = \mathcal{H}_C \otimes \mathcal{H}_P$ , where  $\mathcal{H}_C$  is the two-dimensional Hilbert space associated with the "coin" and  $\mathcal{H}_P$  is the one-dimensional lattice's Hilbert space. One of the most commonly used coins is the Hadamard operator, which is the one chosen for this example.

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<sup>1</sup> A Markov chain can be described as a sequence of stochastic events where the the probability of each event depends only on the state of the previous event.

The transition from  $|x\rangle$  to either  $|x+1\rangle$  or  $|x-1\rangle$  must be described by a unitary operator, the *shift operator* precisa descrever a moeda também e como ela funciona no unitário e acredito que as equações estejam trocadas

$$\mathcal{S} |0\rangle |x\rangle = |0\rangle |x-1\rangle \quad (11)$$

$$\mathcal{S} |1\rangle |x\rangle = |1\rangle |x+1\rangle \quad (12)$$

that can also be described by

$$S = |0\rangle \langle 0| \otimes \sum_{x=-\infty}^{x=\infty} |x+1\rangle \langle x| + |1\rangle \langle 1| \otimes \sum_{x=-\infty}^{x=\infty} |x-1\rangle \langle x|. \quad (13)$$

It follows that the operator that describes the dynamics of the quantum walk will be given by Não necessariamente é o Hadamard, poderia ser uma coin qualquer. Você pode explicar também que a H é a sem viés.

$$U = S(H \otimes I). \quad (14)$$

Consider a quantum system located at  $|x=0\rangle$  with coin state  $|0\rangle$ , for  $t=0$ . It's state will be described by

$$|\Psi(0)\rangle = |0\rangle |x=0\rangle, \quad (15)$$

and after  $t$  steps the walker's state will be

$$|\Psi(t)\rangle = U^t |\Psi(0)\rangle, \quad (16)$$

more explicitly

$$|\Psi(0)\rangle \xrightarrow{U} |\Psi(1)\rangle \xrightarrow{U} |\Psi(2)\rangle \xrightarrow{U} \dots \xrightarrow{U} |\Psi(t)\rangle. \quad (17)$$

After applying the Hadamard operator followed by the shift operator twice the respective system states are seria bom especificar que é na moeda, ou até mesmo dizer que o quantum walk consiste da aplicação da moeda e logo em seguida o shift

$$|\Psi(1)\rangle = \frac{|0\rangle |x=-1\rangle + |1\rangle |x=1\rangle}{\sqrt{2}} \quad (18)$$

$$|\Psi(2)\rangle = \frac{|0\rangle |x=-2\rangle + |1\rangle |x=0\rangle + |0\rangle |x=0\rangle - |1\rangle |x=2\rangle}{2} \quad (19)$$

$$(20)$$

If one were //?// to measure the system after each application of  $\mathcal{U}$ , it would be expected to see the walker at  $x=1$  50% of the time and at  $x=-1$  for the remainder, after the first iteration (??). Measure the system  $t$  times and the result is a binomial probability distribution.

The conclusion is that repetitive measurement of a coined quantum walk system reduces to the classical case, which means that any desired quantum behaviour is lost.

It is possible, however, to make use of the quantum correlations between different positions to generate constructive or destructive interference, by applying the Hadamard and shift operators successively without intermediary measurements. The consequences of interference between states are very apparent in

$$|\Psi(3)\rangle = \frac{|1\rangle |x = -3\rangle - |0\rangle |x = -1\rangle + 2(|0\rangle + |1\rangle) |x = 1\rangle + |0\rangle |x = 3\rangle}{2\sqrt{2}}. \quad (21)$$

Even though an unbiased coin was used, this state is not symmetric to the origin and the probability distributions will not be centered in the origin. Moreover, the standard deviation will not be  $\sqrt{t}$ . Bom, faltou dizer qual o desvio padrão da quantum walk que é  $t$  e esse  $\sqrt{t}$  é da clássica. Precisa justificar com alguma referência também

The quantum walk is said to be *ballistic* since its standard deviation is proportional to  $t$  ? meaning exponentially faster hitting times in certain graphs ?? which can be advantageous in problems that involve visiting certain vertices in a graph. There are also studies that show that a quantum walk may have advantages in element distinctness ? and spatial search ? problems. talvez esse parágrafo deva subir, porque você fala de desvio padrão muito antes

In order to study this distribution, a simulation of the coined quantum walk was coded in *Python*. Using the Hadamard coin and the aforementioned initial condition, the resulting probability distribution is:

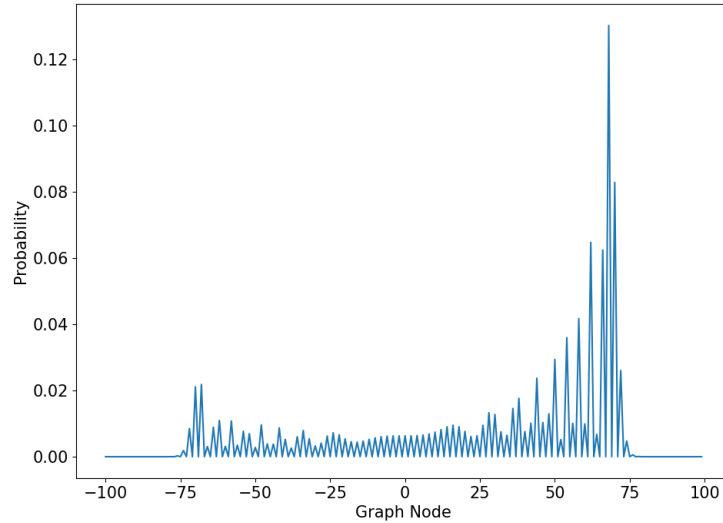


Figure 1: Probability distribution for the coined quantum walk on a line, after 100 steps, with initial condition  $|\Psi(0)\rangle = |0\rangle |x = 0\rangle$  and the Hadamard coin.

Analyzing the plot, it is noticeable that the distribution is asymmetric, the probability amplitude of finding the walker at the right-hand side is much larger than at the left, with a peak around  $x = \frac{100}{\sqrt{2}}$ . Regardless of number of steps, this peak is always present (albeit in varying positions), which is to say that the walker can always be found moving in a uniform fashion away from the origin, further confirming the quantum walk's ballistic behaviour. agora penso que um grafo sobre desvio padrão seria bom para ilustrar, porque o desvio padrão foi muito comentado ao longo do texto

Another interesting case study is to find if this behaviour is preserved for a symmetric distribution around the origin. For this purpose, one must first understand where the asymmetry comes from. The Hadamard operator induces a sign flip [in OU on ?] não entendi state  $|1\rangle$ , hence more terms are cancelled when the coin state is  $|1\rangle$ . Since  $|0\rangle$  was defined to induce movement to the right, the result is as shown in ??. It then follows that the initial condition cuidado com a notação embaixo dos kets, e esse sinal negativo é necessário? acredito que não.

$$|\Psi(0)\rangle = -|1\rangle |x=0\rangle \quad (22)$$

Will return a mirror image of ??:

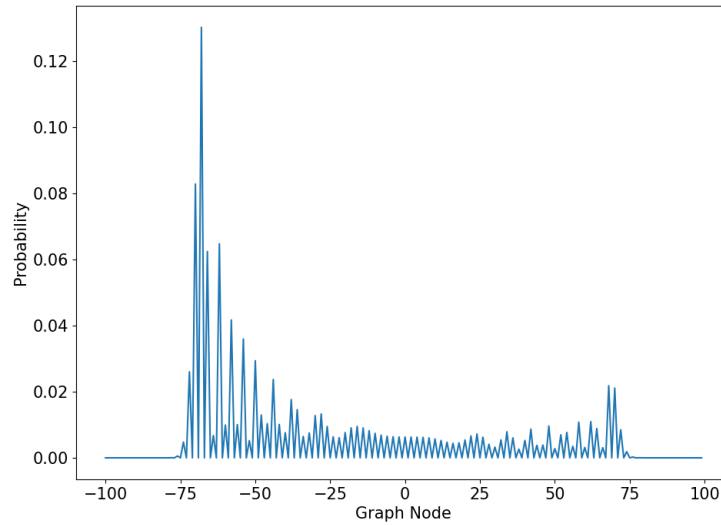


Figure 2: Probability distribution for the coined quantum walk on a line, after 100 steps, with initial condition  $|\Psi(0)\rangle = -|1\rangle |x=0\rangle$  and the Hadamard coin.

In order to obtain a symmetrical distribution, one must superpose ?? and ?? carefully, as to not cancel terms before the calculation of the probability distribution, by multiplying ?? by the imaginary unit. This works because the entries of the Hadamard operator are real numbers; terms with the imaginary unit will not cancel out with terms without it, thus



the walk can proceed to both left and right. The initial condition is then: **o sinal pode ser justificado apenas aqui**

$$|\Psi(0)\rangle = \frac{|0\rangle - i|1\rangle}{\sqrt{2}} |x=0\rangle \quad (23)$$

With a corresponding plot:

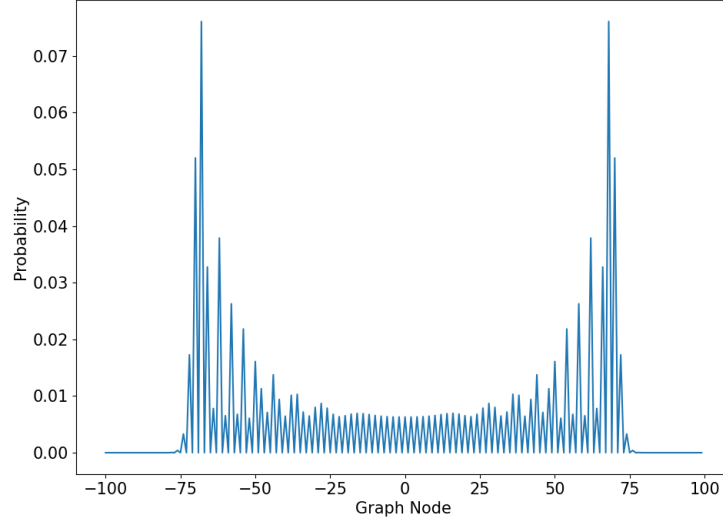


Figure 3: Probability distribution for the coined quantum walk on a line, after 100 steps, with initial condition  $|\Psi(0)\rangle = \frac{|0\rangle - i|1\rangle}{\sqrt{2}} |x=0\rangle$  and the Hadamard coin.

**precisa de um fechamento para esta parte, algo que sumarie os resultados, o que veremos nas próximas partes, etc**

### 3.2 CONTINUOUS-TIME QUANTUM WALK

The continuous-time random walk model on a graph is a Markov process where transitions have a fixed probability per unit time  $\gamma$  of moving to adjacent vertices, firstly introduced by ?. Consider a graph  $G$  with  $N$  vertices and no self-loops, this walk can be defined by the linear differential equation that describes the probability of jumping to a connected vertex in any given time **pode colocar  $G(V,E)$  e depois especificar que  $(i,j)$  é uma aresta**

$$\frac{dp_i(t)}{dt} = \gamma \sum_j L_{ij} p_j(t), \quad (24)$$

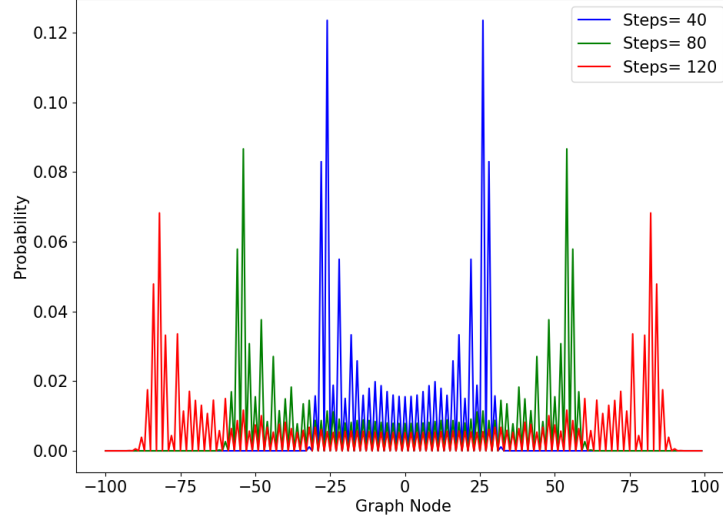


Figure 4: Multiple walks temp

where  $L$  is the Laplacian defined as  $L = A - D$ .  $A$  is the adjacency matrix that represents each vertex connection, given by

$$A_{ij} = \begin{cases} 1, & \text{if } (i, j) \in G \\ 0, & \text{otherwise,} \end{cases} \quad (25)$$

and  $D$  is the diagonal matrix  $D_{jj} = \deg(j)$  corresponding to the degree<sup>2</sup> of a vertex  $j$ .

In the quantum case, the nodes are quantum states that form the basis for the Hilbert space. The continuous-time quantum walk model will also be described by a differential equation, the Schrödinger equation

$$i\hbar \frac{d|\Psi(t)\rangle}{dt} = \hat{H} |\Psi(t)\rangle, \quad (26)$$

where  $\hat{H} = -\gamma L$  is the Hamiltonian of the system. More explicitly,

$$\hat{H}_{ij} = \begin{cases} \deg(j)\gamma, & \text{if } i = j; \\ -\gamma, & \text{if } i \neq j \text{ and adjacent;} \\ 0, & \text{if } i \neq j \text{ and not adjacent.} \end{cases} \quad (27)$$

<sup>2</sup> The degree of a vertex refers to the number of edges that it is connected to.

A general state of a system  $|\Psi(t)\rangle$  can be written as a function of it's complex amplitudes  $q_i = \langle i | \Psi(t) \rangle$ , as credited in equation 28

$$q_i = \langle i | \Psi(t) \rangle, \quad (28)$$

which means ?? can be rewritten as

$$i\hbar \frac{dq_i(t)}{dt} = \sum_j \hat{H}_{ij} q_j(t). \quad (29)$$

This highlights the similarities between the Schrödinger equation and ?. One of the main differences is the complex phase  $i$ , which will result in a very different behaviour. you can say that 29 is a quantization of 24

Setting  $\hbar = 1$  and solving the differential equation results in the evolution operator of this walk  $U(t) = e^{-iHt} = e^{i(-\gamma L)t} = e^{-i\gamma(A+D)t}$ , as we can adjust, maybe equation 32 should be there, because it is the solution of the differential equation

$$U(t) = e^{-iHt} = e^{i(-\gamma L)t} = e^{-i\gamma(A+D)t} \quad (30)$$

In the regular graph case, where  $D$  is simply the degree of the whole graph multiplied by the identity matrix,  $A$  and  $D$  will commute, meaning that the evolution operator can be written in terms of the adjacency matrix  $U(t) = e^{-i\gamma A t + i\gamma D t} = e^{-i\gamma A t} e^{i\gamma D t} = \phi(t) e^{-i\gamma A t}$  as it was very good here

$$U(t) = e^{-i\gamma A t + i\gamma D t} = e^{-i\gamma A t} e^{i\gamma D t} = \phi(t) e^{-i\gamma A t} \quad (31)$$

since the degree matrix becomes a global phase. Applying this operator to an initial condition  $|\Psi(0)\rangle$ , will give the state of the system at a time  $t$

$$|\Psi(t)\rangle = U(t) |\Psi(0)\rangle. \quad (32)$$

Considering a uni-dimensional quantum system, each vertex will have at most 2 other neighboring vertices, reducing equation ?? to

$$\hat{H}_{ij} = \begin{cases} 2\gamma, & \text{if } i = j; \\ -\gamma, & \text{if } i \neq j \text{ and adjacent;} \\ 0, & \text{if } i \neq j \text{ and not adjacent.} \end{cases} \quad (33)$$

For a more detailed visualization, this quantum walk model was coded in python and figure ?? was obtained setting the transition rate to  $\gamma = \frac{1}{2\sqrt{2}}$  the initial condition to  $|\Psi(0)\rangle = |0\rangle$  as shown in figure

A brief look at figure ?? reveals several similarities to the coined quantum walk model of figure ?. Both have two peaks away from the origin and low probability near the origin.

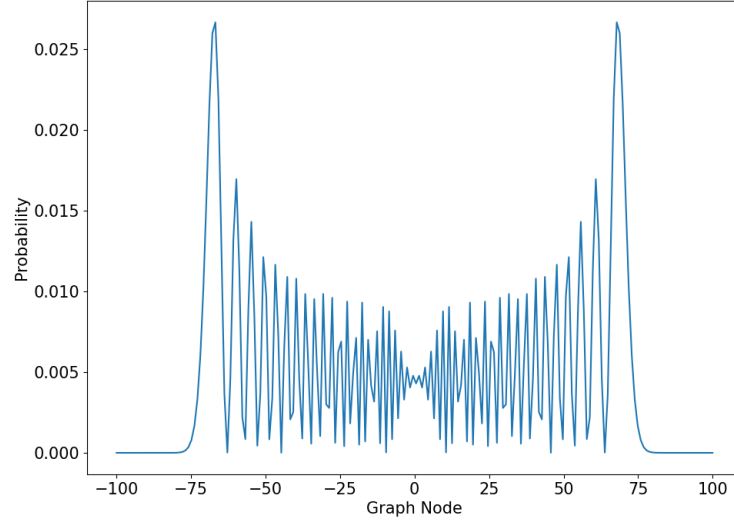


Figure 5: Probability distribution for the continuous-time quantum walk on a line, at  $t = 100$ , with initial condition  $|\Psi(0)\rangle = |0\rangle$  and  $\gamma = \frac{1}{2\sqrt{2}}$ .

However, in the previous quantum walk, these characteristics were altered as a function of the chosen coin and initial condition, whereas in this case different values of  $\gamma$  will influence the probability distribution. For example, a lower value of  $\gamma$  will limit the spread of the probability distribution, as is shown in figure ??.

**você pode dizer que o desvio padrão é proporcional ao  $\gamma$  também**

Moreover, the effects of altering the initial condition will also differ in the continuous-time example. For example, setting the initial condition to the balanced superposition of states  $|0\rangle$  and  $|1\rangle$  has no effect on the overall pattern of the probability distribution as can be seen in figure ??. Both peaks still are still present and at the same distance from the origin, with intermediate amplitudes being attenuated relative to figure ??. This behaviour is in contrast with the discrete-time case, where a change in the initial condition would dictate the number of peaks and where they would appear.

**precisa de um fechamento aqui também, alguns resultados e referências mais talvez**

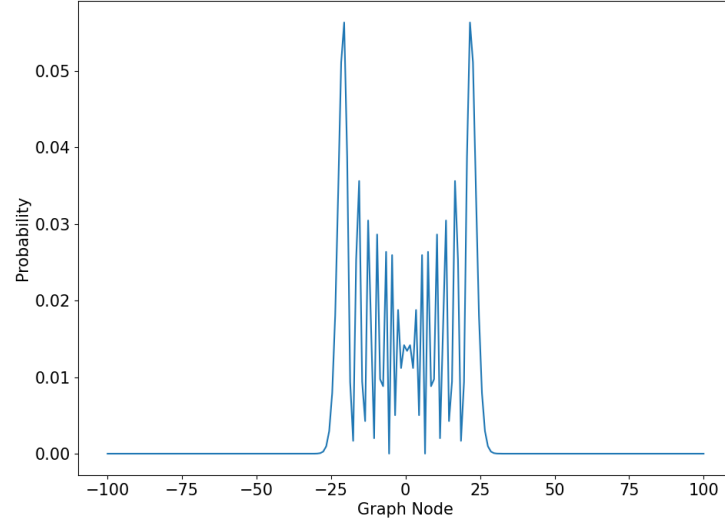


Figure 6: Probability distribution for the continuous-time quantum walk on a line, after 100 steps, with initial condition  $|\Psi(0)\rangle = |0\rangle$  and  $\gamma = \frac{1}{6\sqrt{2}}$ .

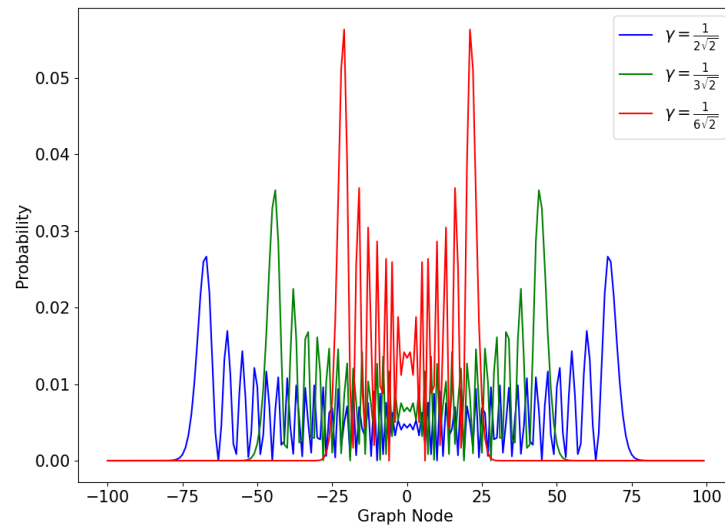


Figure 7: Temporary

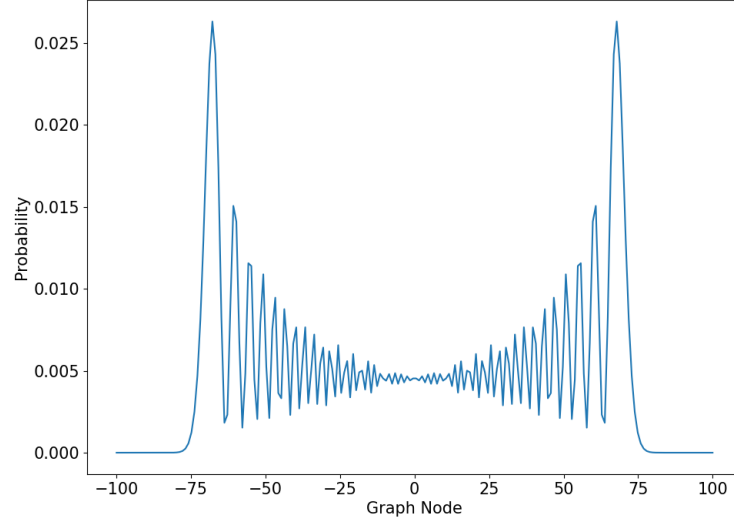


Figure 8: Probability distribution for the continuous-time quantum walk on a line, after 100 steps, with initial condition  $|\Psi(0)\rangle = \frac{|0\rangle+|1\rangle}{\sqrt{2}}$  and  $\gamma = \frac{1}{2\sqrt{2}}$ .

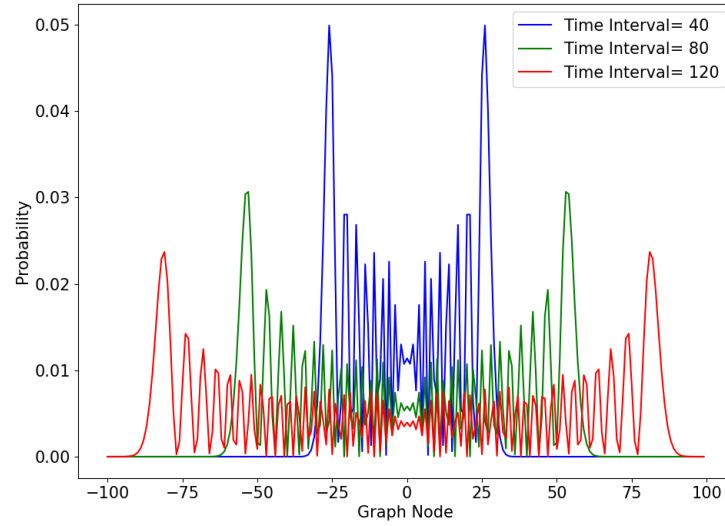


Figure 9: Temporary

## 3.3 STAGGERED QUANTUM WALK

Similarly to the continuous-time quantum walk, the staggered case aims to spread a transition probability to neighboring vertices but with discrete time steps. The notion of adjacency now comes from cliques<sup>3</sup>, and the initial stage of this walk consists in partitioning the graph in several different cliques. This is called tessellation, and it is defined as the division of the set of vertices into disjoint cliques. An element of a tessellation  $\mathcal{T}$  is called a polygon, and it's only valid if all of its vertices belong to the clique in  $\mathcal{T}$ . The set of polygons of each tessellation must cover all vertices of the graph, and the set of tessellations  $(\mathcal{T}_1, \mathcal{T}_2, \dots, \mathcal{T}_k)$  must cover all edges.

These definitions allow the construction of operators  $H_1, H_2, \dots, H_k$  that will be used to propagate the probability amplitude locally, in each polygon. The state associated to each polygon is

$$|u_j^k\rangle = \frac{1}{\sqrt{|\alpha_j^k|}} \sum_{l \in \alpha_j^k} |l\rangle \quad (34)$$

where  $\alpha_j^k$  is the  $j$ -th polygon in the  $k$ -th tessellation.

The unitary and Hermitian operator  $H_k$ , associated to each tessellation is defined in ? as

$$H_k = 2 \sum_{j=1}^p |u_j^k\rangle \langle u_j^k| - I \quad (35)$$

Solving the time-independent Schrodinger equation for this Hamiltonian gives the evolution operator

$$U = e^{i\theta_k H_k} \dots e^{i\theta_2 H_2} e^{i\theta_1 H_1} \quad (36)$$

where

$$e^{i\theta_k H_k} = \cos(\theta_k)I + i \sin(\theta_k)H_k \quad (37)$$

since  $H_k^2 = I$ . **trocar and por since. Posso referir livro do nielsen**

The simplest use case of this quantum walk model is the one-dimensional lattice, where the minimum tessalations are

$$\mathcal{T}_\alpha = \{\{2x, 2x+1\} : x \in \mathbb{Z}\} \quad (38)$$

$$\mathcal{T}_\beta = \{\{2x+1, 2x+2\} : x \in \mathbb{Z}\} \quad (39)$$

<sup>3</sup> A clique is defined as the subset of vertices of an undirected graph such that every two distinct vertices in each clique are adjacent.

Each element of the tessellation has a corresponding state, and the uniform superposition of these states is

$$|\alpha_x\rangle = \frac{|2x\rangle + |2x+1\rangle}{\sqrt{2}} \quad (40)$$

$$|\beta_x\rangle = \frac{|2x+1\rangle + |2x+2\rangle}{\sqrt{2}} \quad (41)$$

One can now define Hamiltonians  $H_\alpha$  and  $H_\beta$  as **trocar operators por hamiltonians, talvez**

$$H_\alpha = 2 \sum_{x=-\infty}^{+\infty} |\alpha_x\rangle \langle \alpha_x| - I \quad (42)$$

$$H_\beta = 2 \sum_{x=-\infty}^{+\infty} |\beta_x\rangle \langle \beta_x| - I \quad (43)$$

The Hamiltonian evolution operator reduces to

$$U = e^{i\theta H_\beta} e^{i\theta H_\alpha} \quad (44)$$

and applying it to an initial condition  $|\Psi(0)\rangle$  results in the time evolution operator

$$U |\Psi(t)\rangle = U^t |\Psi(0)\rangle \quad (45)$$

Having defined the time evolution operator, the walk is ready to be coded with a certain initial condition and  $\theta$  value, to better understand how the probability distribution spreads through time. **voçê pode acrescentar que o  $\theta$  terá um papel similar ao  $\gamma$  no controle do desvio-padrão**

For the first case study, the initial condition will be a uniform superposition of states  $|0\rangle$  and  $|1\rangle$  and the  $\theta$  value will be varied in order to understand how this parameter impacts the walk

The overall structure of the probability distribution remains the same, the difference is that the walker is more likely to be found further away from the origin as the angle increases.

Another interesting case study is to see how the initial condition affects the dynamics of the system

Similarly to the coined case, each initial condition results in asymmetric probability distributions,  $|\Psi(0)\rangle = |0\rangle$  leads to a peak in the left-hand side while condition  $|\Psi(0)\rangle = |1\rangle$  results in a peak in the right-hand side. As was shown in ??, the uniform superposition of both these conditions results in a symmetric probability distribution. **acho que você pode explicar um pouco mais o papel de  $\theta$  através dos gráficos e podemos pensar se fazemos gráficos do desvio-padrão para este e o contínuo**



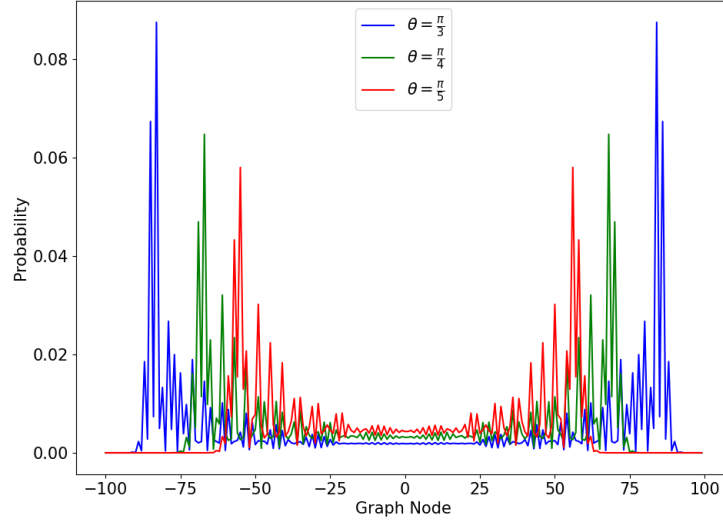


Figure 10: Probability distribution for the staggered quantum walk on a line after 50 steps, with initial condition  $|\Psi(0)\rangle = \frac{|0\rangle + |1\rangle}{\sqrt{2}}$ , for multiple angles.

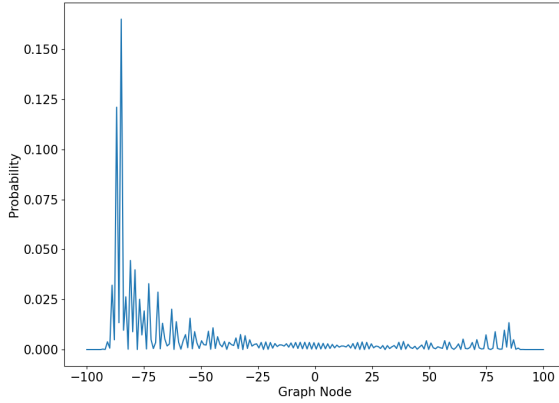


Figure 11:  $|\Psi(0)\rangle = |0\rangle$

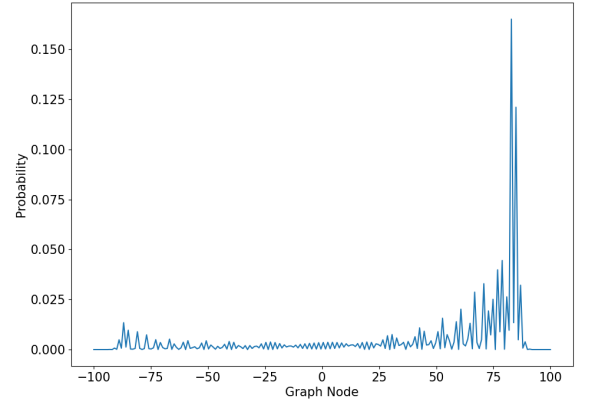


Figure 12:  $|\Psi(0)\rangle = |1\rangle$

### 3.4 SEARCH PROBLEMS WITH QUANTUM WALKS

In classical computation, a *spatial search problem* focuses on finding marked points in a finite region of space. Defining this region with graphs is fairly straightforward, the vertices of the graph are the search space, and the edges define what transitions are possible through the search space. As was previously mentioned in ??, exhaustively searching through an unstructured space, by means of a classical random walk for example, would mean that in the worst case, one would have to take as many steps to find the marked points as there

are vertices in the graph. Quantum computing provides an alternative to this complexity through Grover's algorithm, and applying some of his ideas to the coined quantum walk not only allows a quantum counterpart to the random walk search, but also further insight into the algorithm itself.

acho que você precisa delimitar o que fará ao longo desta seção, dizer que tratará os três modelos e a busca

#### 3.4.1 Coined

Following ?'s definition, a good first step is to borrow the diffusion from Grover's algorithm and invert the sign of the state corresponding to the marked vertex while leaving unmarked vertices unchanged. This is done through the following operator eu trocaria a notação de  $\mathcal{F}$  por  $\mathcal{O}$  e dizer que é um oráculo

$$\mathcal{F}' = I - 2 \sum_{x \in M} |x\rangle \langle x| \quad (46)$$

where  $M$  is the set of marked vertices and  $\mathcal{F}'$  is an analogue to Grover's oracle. For one marked vertex, this oracle can be written as você pode até dizer que  $M = \{0\}$

$$\mathcal{F}' = I - 2 |0\rangle \langle 0| \quad (47)$$

Notice that there is no loss of generality by choosing the marked vertex as 0, since the labelling of the vertices is arbitrary.

The next step is to combine the evolution operator from the coined quantum walk model with the oracle

$$U' = U\mathcal{F}' \quad (48)$$

Similarly to the simple coined case, the walker starts at  $|\Psi(0)\rangle$  and evolves following the rules of an unitary operator  $U$  followed by the sign inversion of marked vertices. The walker's state after an arbitrary number of steps will be

$$\Psi(t) = (U')^t |\Psi(0)\rangle. \quad (49)$$

For a better understanding of the search problem in the coined quantum walk model, consider a graph where all the vertices are connected and each vertex has a loop that allows transitions to itself, as shown in figure ??.

não precisa dizer que são arcos também acho que não há necessidade das figuras e dizer que é com grafo direcionado

Grover's algorithm is equivalent to a coined quantum walk on a directed complete graph with loops such as the one in figure ??.

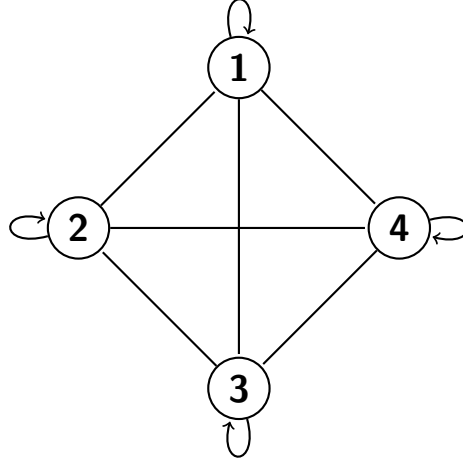
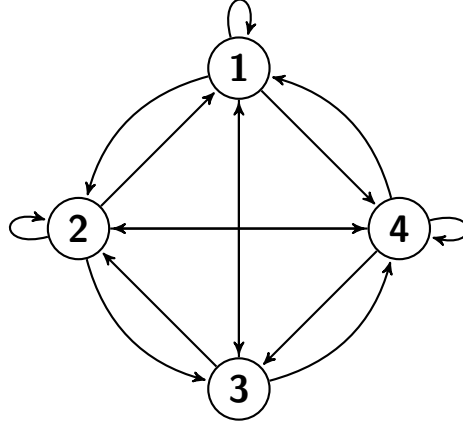


Figure 13: Undirected Complete Graph

Figure 14: Directed complete graph with  $N=4$  nodes.

The next step is to label the arcs using notation  $\{(v, v'), v \geq 0 \wedge v' \leq N - 1\}$  where  $N$  is the total number of vertices and  $(v, v')$  are the position and coin value, respectively, in the coined model. The shift operator, now called flip-flop shift operator, is

$$S |v1\rangle |v2\rangle = |v2\rangle |v1\rangle. \quad (50)$$

The coin operator is defined as

$$C = I_N \otimes G \quad (51)$$

where  $G$  is a  $D$

$$G = 2 |D\rangle \langle D| - I \quad (52)$$

is the Grover coin with  $|D\rangle$  being the diagonal state of the coin space. Given both of these operators, the evolution is defined for the unmarked case similarly to ??

$$U = S(I \otimes G). \quad (53)$$

Marking an element in a complete graph is done through the following oracle

$$\mathcal{F}'' = \mathcal{F}' \otimes I = (I_N - 2|0\rangle\langle 0|) \otimes I_N = I_{N^2} - 2 \sum_v |0\rangle|v\rangle\langle 0|\langle v|, \quad (54)$$

that can be seen, in the arc notation, as an operator that marks all arcs leaving 0.

Recalling ??, the modified evolution operator can be written as

$$U' = S(I \otimes G)\mathcal{F}'' = S(I \otimes G)\mathcal{F}' \otimes I = S(\mathcal{F}' \otimes G), \quad (55)$$

and the state of the system will evolve according to equation ??.

As was shown in ?, maximum probability of the marked vertex is achieved after  $\frac{\pi}{2}\sqrt{N}$  steps. Figure ?? is the result of coding and plotting the evolution of this probability distribution, for graphs of varying sizes. It shows that the probability is close to one at *approximately* the predicted ideal steps, because of the discrete nature of the walk. The probability distributions have a stair-like shape, because transitions in this model only occur on even numbered time steps, because of how the unmodified evolution operator was constructed.

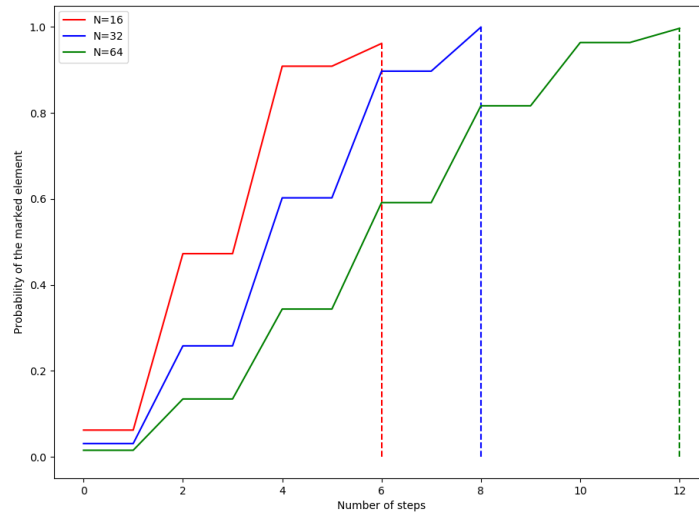


Figure 15: Discrete-time coined quantum walk search for a complete graph with 16, 32 and 64 nodes.

### 3.4.2 Staggered

The process for defining the search problem in this model is similar to the coined quantum walk case. The oracle still inverts the sign of a certain state and amplifies it, and the system's state will still be described by equation ???. However, instead of using a coin, the staggered model takes advantage of the notions of cliques and tessellations, as was shown in chapter ??, which means the unmodified evolution operator has to be defined for an undirected complete graph.

As was shown in figure ??, the vertices in a complete graph are all neighbors. This is a special case because this is the only connected graph where the tessellation cover can be done by one tessellation, since the graph is its own clique. The minimum tessellations required to cover this structures are defined by the one clique that encompasses all  $N$  nodes of the graph

$$\mathcal{T}_\alpha = \{\{0, 1, 2, \dots, N - 1\}\}. \quad (56)$$

The associated polygon can then be described as the balanced superposition of all the nodes in the graph

$$|\alpha\rangle = \frac{1}{\sqrt{N}} \sum_{v=0}^{N-1} |v\rangle. \quad (57)$$

The Hamiltonian, as defined in ??, is **falta índice no somatório**

$$H_\alpha = 2 \sum_0^1 |\alpha\rangle \langle \alpha| - I = 2 |\alpha_0\rangle \langle \alpha_0| - I \quad (58)$$

The unmodified evolution operator from equation ??

$$U = e^{i\theta_k H_k} \dots e^{i\theta_2 H_2} e^{i\theta_1 H_1} \quad (59)$$

reduces to the single Hamiltonian case

$$U = e^{i\theta H_\alpha}. \quad (60)$$

The choice of the  $\theta$  value is an important one, since maximum probability is achieved at  $\theta = \frac{\pi}{2}$ , as shown in figure ??. Since  $H_\alpha^2 = I$ , equation ?? can be rewritten as

$$U = e^{-i\frac{\pi}{2} H_\alpha} = \cos \frac{\pi}{2} I + i \sin \frac{\pi}{2} H_\alpha = i H_\alpha = i(2 |\alpha_0\rangle \langle \alpha_0| - I). \quad (61)$$

Having defined the the evolution operator associated with the complete graph, the next step is to use the oracle

$$\mathcal{F}' = I_N - 2 |0\rangle \langle 0|, \quad (62)$$

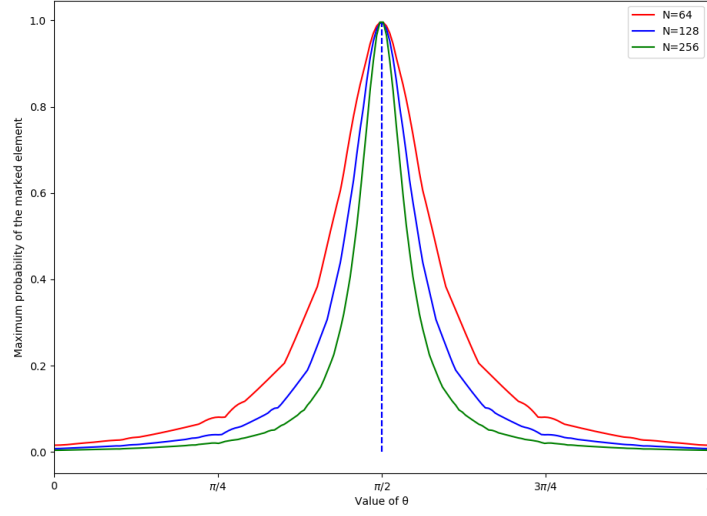


Figure 16: Maximum probability of the marked element as a function of the  $\theta$  value plotted from 0 to  $\pi$  for number of nodes  $N = 64, 128$  and  $256$ .

to create the modified evolution operator associated with the search

$$U' = U\mathcal{F}'. \quad (63)$$

The walk achieves the same result as Grover's algorithm after  $\frac{\pi}{4}\sqrt{N}$  steps, as shown in figure ?? . This plot also shows that the probabilities converge to 1 as  $N$  increases, this is because time is discretized and deviations to the ideal steps will matter less for bigger values of  $N$ .

precisa de um fechamento também aqui

### 3.4.3 Continuous

As was previously seen, the continuous-time quantum walk model is defined by an evolution operator obtained by solving Schrödinger's equation

$$U(t) = e^{-iHt}. \quad (64)$$

The search problem requires introducing an oracle to the Hamiltonian, that will mark an arbitrary vertex  $m$

$$H' = -\gamma L - |m\rangle \langle m|. \quad (65)$$

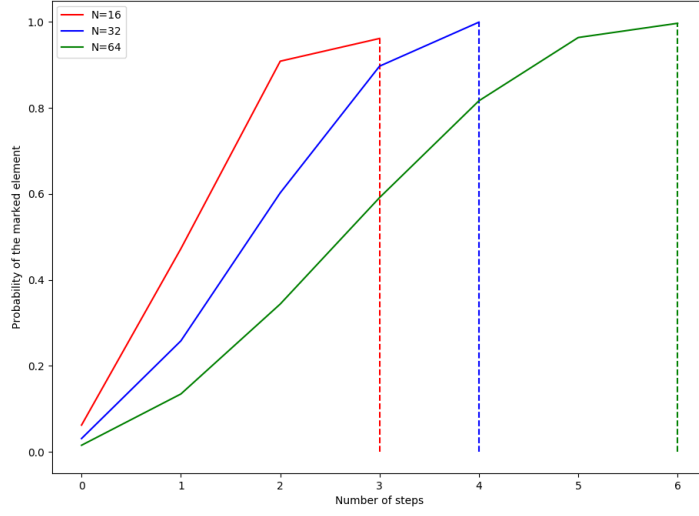


Figure 17: Staggered quantum walk search for a complete graph with 16, 32 and 64 nodes.

Since the complete graph is a regular graph, the operator can be rewritten in terms of the adjacency matrix plus the marked element. Considering  $|0\rangle$  is marked,

$$U'(t) = e^{iH't} = e^{i(-\gamma L - |0\rangle\langle 0|)t} = e^{i(-\gamma A + \gamma D - |0\rangle\langle 0|)t} = e^{-i\gamma(A + |0\rangle\langle 0|)t + i\gamma Dt}. \quad (66)$$

The degree matrix is again  $D = dI$ , which means it will commute with  $A + |0\rangle\langle 0|$  and become a global phase

$$U'(t) = e^{-i\gamma(A + |0\rangle\langle 0|)t} e^{i\gamma Dt} = \phi(t) e^{-i\gamma(A + |0\rangle\langle 0|)t}. \quad (67)$$

As was show by ?, the value of  $\gamma$  is crucial for the success of the search. As  $\gamma$  increases, the contribution of the marked element in the Hamiltonian decreases, and as  $\gamma$  approaches 0 the contribution of the adjacency matrix decreases. To find the optimum value, the Hamiltonian can be rewritten by adding multiples of the identity matrix to the adjacency matrix **H' é uma notação ruim, confunde com derivada e acredito não ser necessário aqui**

$$H' = -\gamma(A + NI) - |0\rangle\langle 0| = -\gamma N |s\rangle\langle s| - |0\rangle\langle 0| \quad (68)$$

where  $|s\rangle = \frac{1}{\sqrt{N}} \sum_i |i\rangle$ . Now it is obvious that, for  $\gamma = \frac{1}{N}$ , the Hamiltonian is  $H = -|s\rangle\langle s| - |0\rangle\langle 0|$ . It's eigenstates are proportional to  $|s\rangle \pm |w\rangle$  and eigenvalues are  $-1 - \frac{1}{\sqrt{N}}$  and  $-1 + \frac{1}{\sqrt{N}}$ , respectively. This means that the evolution rotates from the state of balanced superposition to the marked vertex state in time  $\frac{\pi}{\Delta E} = \frac{\pi}{2} \sqrt{N}$  which is, as was shown by ?, optimal and equivalent to Grover's algorithm. Plotting  $\Delta E$  as a function of  $\gamma N$ , as can be

seen in figure ??, has a minimum at  $\gamma N = 1$ . The difference between the largest eigenvalue and second largest, plotted in the y-axis, is the smallest for a value of  $\gamma N = 1 \implies \gamma = \frac{1}{N}$ , which will correspond to the maximum probability for the marked vertex, in optimal steps.

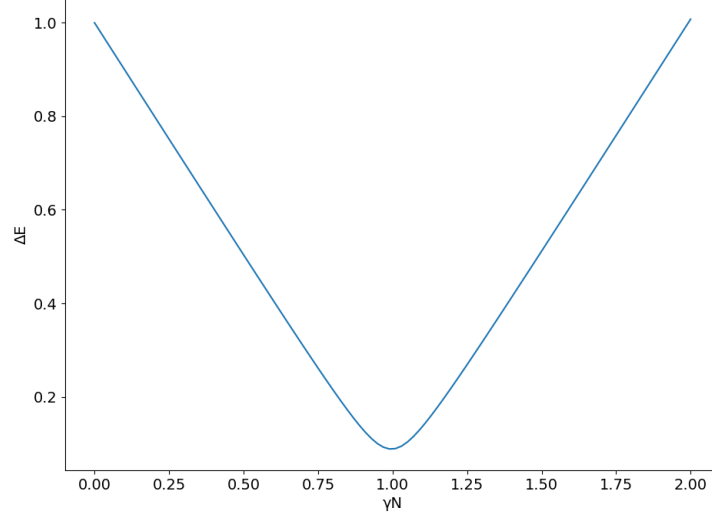


Figure 18: Value of the difference between the largest eigenvalue and the second largest, plotted as a function of  $\gamma N$ , for  $N = 512$ .

Figure ?? shows the evolution of the probability of the marked vertex in time, which is continuous in this model. In contrast with previous models, the distributions are smooth and reach exactly one, since the walk is allowed to evolve to exactly the ideal time steps.



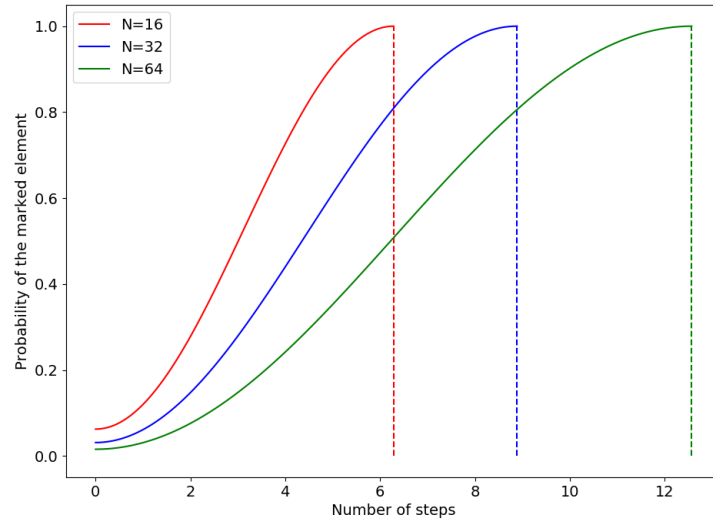


Figure 19: Continuous quantum walk search for a complete graph with 16, 32 and 64 vertices.

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## IMPLEMENTATIONS AND APPLICATIONS

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meter aqui os circuitos.

Pagerank? paparo2012 tem coisas

Simulações em python?

mencionar PC IBMQ

### 4.0.1 *Coined*

Test to see how many characters it takes to have a linebreak 1 2 3 4 5 6 7 8 9

### 4.0.2 *Continuous*

### 4.0.3 *Staggered*

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## DISCUSSIONS AND CONCLUSION

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discutir os resultados encontrados, o future work, o que falta fazer etc.

### 5.1 CONCLUSIONS

### 5.2 PROSPECT FOR FUTURE WORK

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## SUPPORT MATERIAL

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