

GROUND STATE ENERGY SIMULATIONS USING MONTE CARLO RANDOM WALK

ELLIOTT ASHBY
PHYSICS AND ASTRONOMY
UNIVERSITY OF SOUTHAMPTON

ABSTRACT. Placeholder for abstract.

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1. INTRODUCTION

Overview of the challenges in solving the Schrödinger equation numerically The connection between the imaginary-time Schrödinger equation and diffusion processes Historical development of Monte Carlo methods in quantum mechanics Brief comparison with alternative numerical approaches (matrix diagonalization, variational methods) Motivation: why random walks are particularly well-suited for ground state energy calculations

2. METHOD

2.1. THEORETICAL FOUNDATION. While the usage of Monte Carlo methods to simulate quantum mechanics may seem strange at first, looking at the time-dependent Schrödinger equation as a diffusion equation in imaginary time reveals the connection that makes it possible. Here is the time-dependent Schrödinger equation for a particle of mass m in a potential $V(x)$:

$$i\hbar \frac{\partial}{\partial t} \psi(x, t) = -\frac{\hbar^2}{2m} \frac{\partial^2}{\partial x^2} \psi(x, t) + V(x) \psi(x, t) = \hat{H} \psi(x, t) \quad (2.1)$$

By using $\tau = it$, it becomes:

$$\frac{\partial}{\partial \tau} \psi(x, \tau) = \frac{\hbar}{2m} \frac{\partial^2}{\partial x^2} \psi(x, \tau) - \frac{V(x)}{\hbar} \psi(x, \tau) = -\frac{\hat{H}}{\hbar} \psi(x, \tau) \quad (2.2)$$

This is a diffusion equation with a growth/decay term with a diffusion constant $D = \hbar/2m$ where the growth/decay term determines whether the population density of walkers at a given position increases or decreases.

The general solution to equation 2.2 can be written using the eigenstates and eigenvalues of the Hamiltonian:

$$\psi(x, \tau) = \sum_n c_n \phi_n(x) e^{-E_n \tau / \hbar} \quad (2.3)$$

where $\phi_n(x)$ are the eigenfunctions of the Hamiltonian with corresponding energies E_n , and c_n represents the projection of the initial wavefunction onto each eigenstate. If we consider the case where $\tau \rightarrow \infty$, all terms decay exponentially, but the ground state decays the slowest:

$$\lim_{\tau \rightarrow \infty} \psi(x, \tau) = c_0 \phi_0(x) e^{-E_0 \tau / \hbar} \quad (2.4)$$

If we then were able to simulate the diffusion process for a sufficiently long time, then the distribution of our random walkers would approach the ground state wavefunction $\phi_0(x)$, so the decay rate of the walker population would be the ground state energy E_0 .

2.2. IMPLEMENTATION DETAILS. In order to not have infinite computation time, we must discretize space and time. To do this we can use a lattice with spatial sites j and temporal sites n . The probability $p(j, n)$ for a walker to be at lattice site j after n time steps satisfies:

$$p(j, n+1) = \frac{1}{2} [1 - a(j)] [p(j-1, n) + p(j+1, n)] \quad (2.5)$$

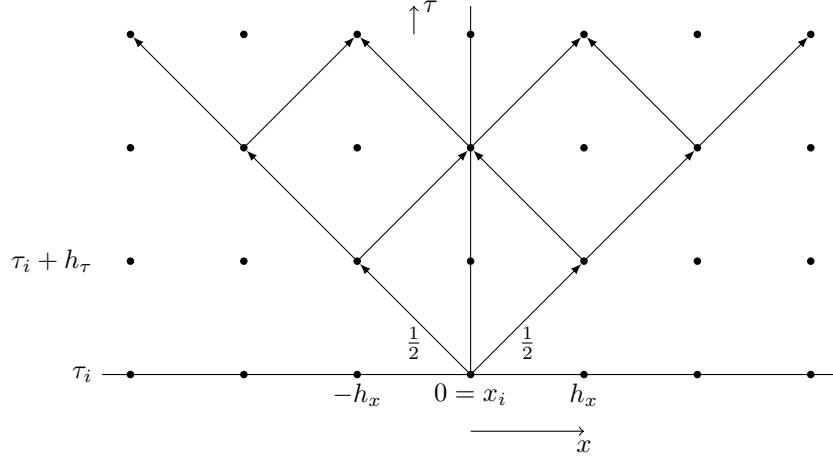


FIGURE 2.1. A lattice showing the possible moves of a walker at position x_i and time τ_i . The walker can move to any of the neighbouring sites with equal probability.

and converting to continuous space and time with intervals h_x and h_τ :

$$p(x, \tau + h_\tau) = \frac{1}{2} [1 - a(x)] [p(x - h_x, \tau) + p(x + h_x, \tau)] \quad (2.6)$$

Here, $a(x) = h_\tau V(x)$ and represents the probability of a walker being absorbed at position x .

So for $\tau \rightarrow \infty$, swapping $\psi(x, \tau)$ for $p(x, \tau)$ and defining $h_\tau = h_x^2$ we get the final form of the diffusion equation:

$$\frac{\partial p}{\partial \tau} = \frac{1}{2} \frac{\partial^2 p}{\partial x^2} - V(x)p \quad (2.7)$$

2.3. ALGORITHM VARIANTS. Using the diffusion equation 2.7 we can derive a couple different ways to simulate the ground state energy of a quantum system.

The simplest method is the simple absorption method, where walkers are absorbed at the boundaries of the lattice. This method is simple to implement but can be computationally expensive for large systems.

A more efficient method is the diffusion Monte Carlo method, which uses branching to kill and birth new walkers. This method is much more efficient but can be more difficult to implement due to the branching process.

2.3.1. *Simple Absorption Method.* In the case for the simple absorption method, our potential is implemented as a infinite square well potential. The probability of a walker being absorbed at a given position is given by:

$$a(x) = \begin{cases} 0 & \text{if } x \in [-L/2, L/2] \\ 1 & \text{otherwise} \end{cases} \quad (2.8)$$

where L is the width of the well.

Using this potential, we can implement the diffusion equation as a random walk on a lattice where:

$$P_{survival}(\tau) = \int_{-L/2}^{L/2} p(x, \tau)^2 dx \approx e^{-\lambda\tau} \quad (2.9)$$

where λ is the decay rate of the population.

The algorithm is then as follows:

Simple Absorption Method

- (1) Initialize the walker population at the centre of the lattice.
- (2) For each walker, move it to a neighbouring lattice site with equal probability to move to any of the neighbouring sites.
- (3) If the walker is at the boundary of the lattice ($x \geq L/2$), kill it and record the number of steps it took to reach the boundary.
- (4) Repeat steps 2-3 for a maximum number of steps. If any of the walkers survive, mark them as surviving.
- (5) Find the number of walkers that survive at each step and using a linear regression calculate the decay rate of the population λ .
- (6) The ground state energy can then be approximated as $E_0 = \lambda(L/2)^2$.

2.3.2. Diffusion Monte Carlo with Branching. The diffusion Monte Carlo with branching method is more complex than the simple absorption method and requires some additional theory.

One of the problems with the simple absorption method is that to get reasonable accuracy, a very large number of initial walkers is required. This can be a problem for large systems since the run time will be $O(N)$ where N is the number of walkers since every walker must be simulated individually.

While we cannot lower the run time, we can lower the number of initial walkers and also greater our chances of finding the ground state. If we were to kill walkers that have a high probability of being absorbed and birth new walkers at positions with a low probability of being absorbed, we can attempt to maintain a more constant number of walkers throughout the simulation.

Since this approach requires us to find the probability of a walker being absorbed at some position, it is reasonable to use a potential that is continuous rather than the infinite square well potential. I have chosen to use the harmonic oscillator potential with $m = \omega = 1$:

$$V(x) = \frac{1}{2}x^2 \quad (2.10)$$

The probability of a walker being absorbed at a given position is then:

$$a(x) = h_\tau V(x) = \frac{1}{2}h_\tau x^2 \quad (2.11)$$

The algorithm is then as follows:

Diffusion Monte Carlo with Branching

- (1) (a) Initialize N_0 walkers in a Gaussian distribution around the centre of the lattice and record their positions x_i .
 (b) Compute initial reference potential energy $V_{ref} = \sum_i V(x_i)/N_0$.
- (2) For each walker:
 (a) Move it to a neighbouring lattice site with equal probability to move to any of the neighbouring sites.
 (b) Compute the potential energy at the new position $V(x)$ and compute the change in potential energy $\Delta V = V(x) - V_{ref}$.
 (c) If $\Delta V > 0$, kill the walker with probability $|\Delta V \times h_\tau|$. Otherwise, birth a new walker at the new position with the same probability.
- (3) Re-calculate $V_{ref} \leftarrow \sum_i \frac{V(x_i)}{N_a} - k \left(\frac{N_a - N_b}{N_b \cdot h_\tau} \right)$ where N_a is the number of walkers after step 2 and N_b is the number of walkers before step 2 and k is a constant to tune.
- (4) Repeat steps 2-3 for a maximum number of steps or until the number of walkers reaches zero.
- (5) The ground state energy can then be approximated as $E_0 = V_{ref}$.

3. RESULTS

3.1. SIMPLE ABSORPTION METHOD.
 $params = \{N_0 : 50, maxsteps : 10000, L : 20\}$

Simulation Statistics:

Theoretical Value ($\pi^2/8$): 1.233701
 Average $\lambda(L/2)^2$: 1.228909 (residual: 0.004791)
 Median $\lambda(L/2)^2$: 1.199329 (residual: 0.034371)
 Mode $\lambda(L/2)^2$: 1.067469 (residual: 0.166232)
 Standard Deviation: 0.337445
 Range: [0.489469, 3.941426]

Error Analysis:

Standard Error of Mean (SEM): 0.015091
 Residual: 0.004791 ± 0.015091
 Relative Error: 0.3995% Confidence Interval: [1.199260, 1.258559]
 Theoretical value is within the 95% confidence interval

Bootstrap 95% CI: [1.199885, 1.259244]

Theoretical value is within the bootstrap confidence interval

3.2. DIFFUSION MONTE CARLO WITH BRANCHING. $params = \{N_0 : 50, h_x : 0.1, maxsteps : 50000, w0 : 1.0, k : 0.5, equilibration : 1000\}$

ENERGY STATISTICS

Number of samples: 16705
 Steps discarded: 1000

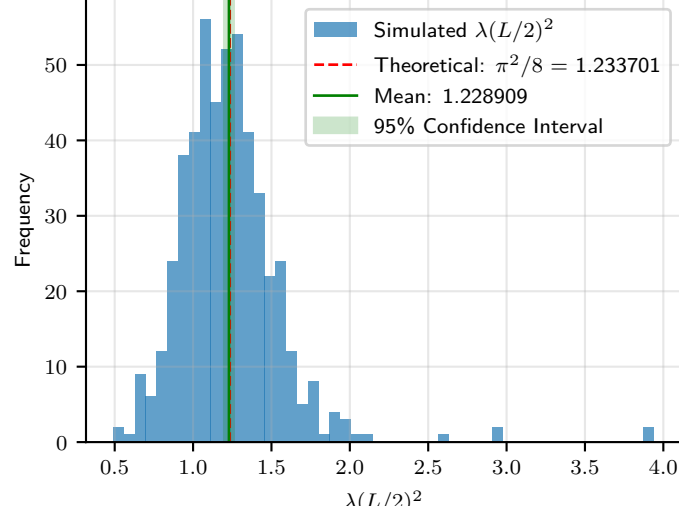


FIGURE 3.1. For the Simple Absorption Method, a histogram showing the distribution of walkers with their energy values compared vs the theoretical value. A 95% confidence interval is shown.

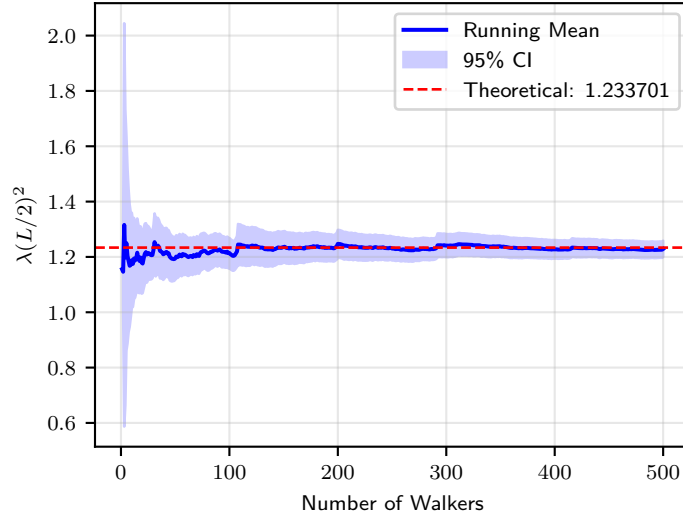


FIGURE 3.2. For the Simple Absorption Method, a running mean of the walkers energy values compared vs the theoretical value as a function of walkers. A 95% confidence interval is shown.

Theoretical ground state energy: 0.500000

Mean energy: 0.507812
 Standard deviation: 0.016660
 Standard error of the mean: 0.000129
 95% confidence interval: [0.507560, 0.508065]

Absolute error: 0.007812
 Relative error: 1.56%

Autocorrelation time: 971 Steps
 Effective number of independent samples: 8.6
 Corrected standard error: 0.005680
 Corrected 95% confidence interval: [0.494381, 0.521244]

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Theoretical value (0.5) is within the 95% confidence interval

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Final ground state energy estimate: 0.500528
 Theoretical ground state energy: 0.500000

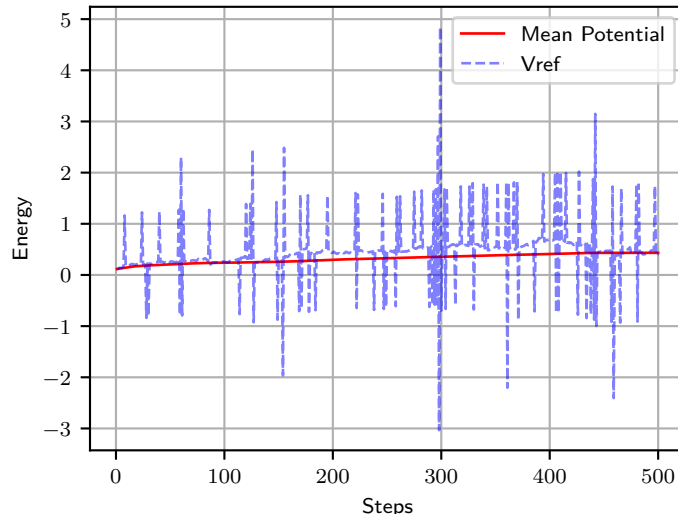


FIGURE 3.3. Time average mean potential energy of all walkers plotted with the estimate of the potential energy, V_{ref} as a function of steps.

4. DISCUSSION

While extension to higher dimensions is straightforward, focusing on one-dimensional cases allows for easier visualization and comparison with analytical solutions. I opted to spend more time on the one-dimensional case since it allowed for easier debugging, testing and iteration of the code.

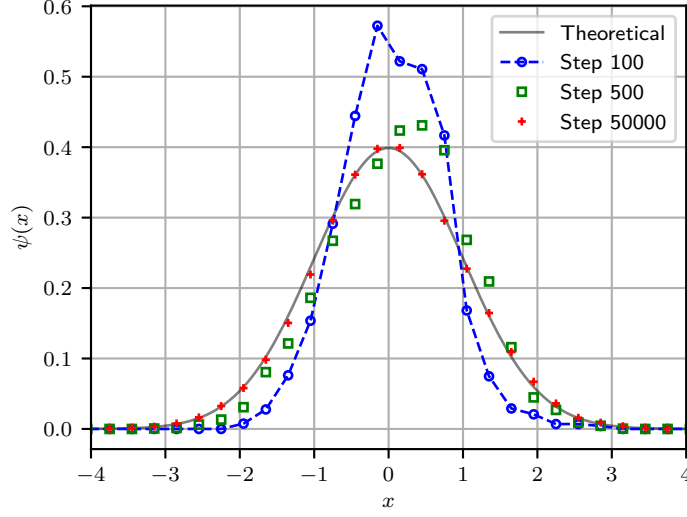


FIGURE 3.4. For the Diffusion Monte Carlo with Branching method, Ground state wavefunction of potential $V(x) = \frac{1}{2}x^2$ at step 100, 500 and 50000 with the theoretical wavefunction as a function of position.

4.1. PARAMETER OPTIMIZATION.

4.2. METHOD STRENGTHS AND LIMITATIONS.

5. CONCLUSION

Summary of key findings and method effectiveness Practical recommendations for implementation Future directions for method improvement Potential applications to more complex quantum systems

APPENDIX

APPENDIX A. ADDITIONAL CITATIONS

18 Examples

6 for each: random walk, Monte Carlo, random numbers

3 in academia, 3 outside academia

REFERENCES

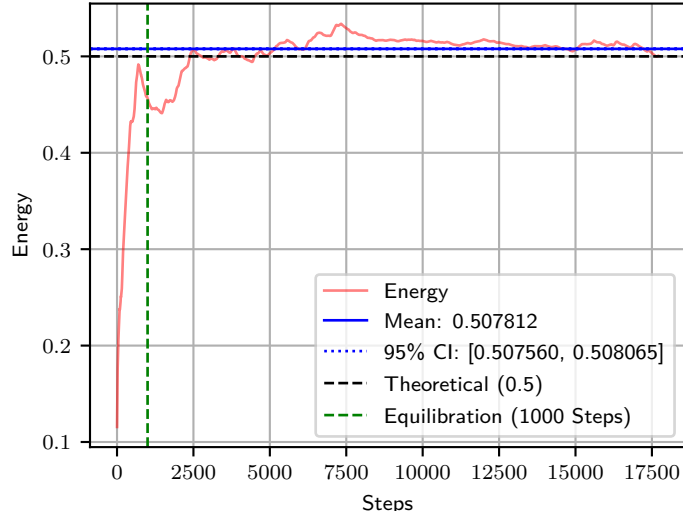


FIGURE 3.5. For the Diffusion Monte Carlo with Branching method, the walkers energy and a mean of the walkers energy compared vs the theoretical value as a function of steps. A 95% confidence interval is shown.

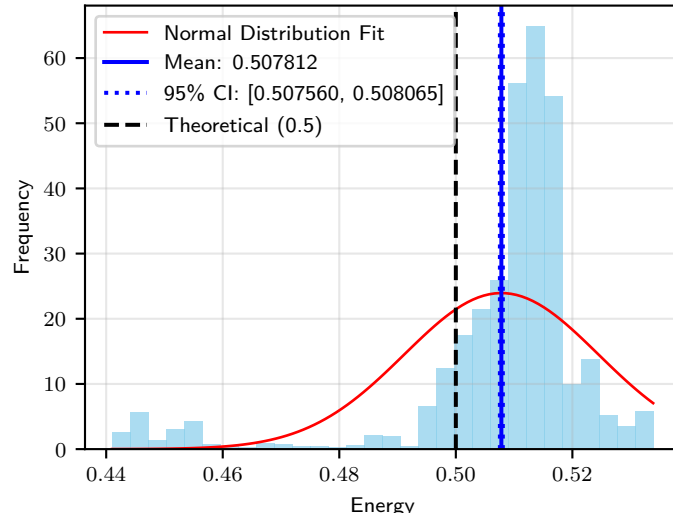


FIGURE 3.6. For the Diffusion Monte Carlo with Branching method, a histogram showing the distribution of walkers with their energy values compared vs the theoretical value. A Normal distribution is fitted to the data and a 95% confidence interval to the mean is shown.