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Phases Unlocked: The Crucial Role of Qubit Phases in Quantum Computing

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Abstract: Quantum computing applies quantum physics ideas to problems that traditional computers cannot address. The qubit, or quantum equivalent of the classical bit, is fundamental to this paradigm shift. Unlike its classical equivalent, a qubit can exist in a superposition of states, representing both 0 and 1. This superposition is defined not only by magnitudes, but also by important phase variables. These phases have a significant impact on qubit behavior and quantum computation outputs. This work conducts a thorough investigation of qubit phases, exploring their tremendous impact on the efficacy and capabilities of quantum algorithms. We investigate how constructive and destructive interference caused by phase interactions provides the foundation of quantum algorithms. Furthermore, we look into the intricate role of phases in establishing and managing entanglement, a unique quantum phenomenon that allows tremendous interactions between qubits. Our investigation includes the effects of numerous quantum operations on qubit phases. We present a thorough mathematical framework for describing how typical quantum gates, such as Hadamard, Pauli, and phase-shift gates, change the phase and thus the overall state of a qubit. We show these concepts through actual implementations of the Qiskit library. Finally, we discuss the intrinsic difficulty of managing and monitoring qubit phases, particularly the negative impacts of decoherence, which disrupts the delicate phase relationships. We describe tactics for mitigating these obstacles and investigate techniques for extracting phase information indirectly, such as quantum state tomography and interferometry. This comprehensive study seeks to provide a better understanding of the critical role phases play in quantum computing, paving the way for advances in algorithm design, quantum control, and the development of fault-tolerant quantum computers.

Keywords: Qubit, Relative phase, Global phase, Quantum algorithm, Qiskit

Introduction

Quantum computing is a field interested in performing computational tasks using the principles of quantum mechanics. At its core, quantum computing seeks to solve complex problems significantly faster than possible on classical computers. Classical computers are engineered using electrical devices, which employ the principles of classical mechanics to perform calculations. Quantum computing, on the other hand, is based on quantum mechanics, where nature is described using completely different rules than those for macroscopic objects. The adoption of these quantum mechanics principles into computing enables performing calculations and operations that remain otherwise impossible using classical methods. Quantum computers store, process, and transfer information using quantum bits, also known as qubits. The states of qubits provide information about a system. In quantum computing, qubits are the minimal units of quantum information processing (Bravyi et al., 2022; Uehara et al., 2021).

One notable characteristic of qubits is their ability to exist in multiple states simultaneously, a phenomenon known as superposition. This occurs because qubits function on a scale that is far more fragile than that of classical bits, leading to behaviors that are not typically observed in the classical realm. Additionally, quantum computers leverage a fundamental connection between qubits known as entanglement, which enhances operational efficiency by distributing tasks among the states of multiple qubits. In practical applications, simulated qubits are represented as physical qubits positioned on computer chips. The potential applications of quantum computing are vast, encompassing fields such as cryptography and information security (Ajala et al., 2024). Drug development and medical diagnostics (Blunt et al., 2022). Traffic management, and financial risk assessment (Ajagekar et al., 2020; Harwood et al., 2021). However, significant challenges remain due to the complexities of quantum mechanics. For a quantum computer to be effective, it must manipulate each qubit with high precision and at rapid computational speeds (Mohamed et al., 2022, Deutsch, 2020).

The two main types of quantum computers currently being developed are gate-based quantum computers and adiabatic quantum computers (Hegade et al., 2021; Jaradat et al., 2023). Gate-based quantum computers- which are the most common type of quantum computers- work by using quantum gates to manipulate qubits, while adiabatic quantum computers find the lowest energy state of a quantum system through a process called adiabatic evolution.

Quantum computers utilize qubits, which can exist in superposition and entangled states, offering tenfold greater processing capacity than classical bits. A fundamental principle of quantum mechanics that differentiates quantum computing from classical computing is the notion of phase. In contrast to classical computing, which represents bits as binary values 0 and 1, quantum states employ complex amplitudes. The amplitudes possess both magnitude and phase, with the phase governing interference patterns and determining the evolution of qubits under transformations.

A qubit's state is represented as:

$$|\psi >= \alpha|0> +\beta|1> \tag{1}$$

where α and β are complex amplitudes, and satisfies the normalization condition $|\alpha|^2 + |\beta|^2 = 1$. While $|\alpha|^2$ and $|\beta|^2$ dictate the probabilities of measuring 0 or 1, the phase difference between α and β is critical for quantum computation.

In quantum computing, two principal types of phases significantly influence the behavior of qubits and quantum computation and algorithms: global phase and relative phase. These phases stem from the intricate characteristics of quantum states and influence the interference and evolution of qubits during computation. The two types of phases are significant for the following reasons (Gill et al., 2022; Bhat et al., 2022):

- Global Phase: The overall phase of a qubit state that does not impact measurement probabilities but affects interference.
- Relative Phase: The phase difference between components of a superposition state, essential for algorithms such as Grover's and Shor's.

This work aims to examine and emphasize the significant importance of qubit phases, particularly global and relative phases, in quantum computing. This study seeks to deliver a comprehensive assessment of the impact of these phases on quantum state evolution, interference patterns, and the efficacy of quantum algorithms. This study aims to further our comprehension of phase manipulation as an essential tool in quantum computation by analyzing the impacts of different quantum gates on qubit phases. Moreover, through simulations of Qiskit, the study seeks to provide practical insights into how phase control might enhance the execution of quantum algorithms, thereby contributing to the development and deployment of more efficient quantum computing systems.

The rest of the paper is organized as follows. Section II provides an analysis of the quantum phases. Phase gates and their effect are provided in section III. Section IV provides simulation results of the role of relative phase in quantum interference and algorithms. Finally, section V concludes the paper.

Quantum Phase Analysis

Equation (1) represents a general formula for the representation of the quantum state, where α and β are complex amplitudes. Equation (1) can be re-written in vector form as:

$$|\psi>= \begin{bmatrix}\alpha \\ \beta\end{bmatrix} \tag{2}$$

The complex numbers α and β can be represented as:

- $\alpha = r_1 e^{j\theta_1}$
- $\beta = r_2 e^{j\theta_2}$

r_1,*r2* being the magnitudes of the coefficients, and θ_1, θ_2 being the phases associated with each state. Then equation (2) becomes:

$$|\psi>= \begin{bmatrix}r_1 e^{j\theta_1} \\ r_2 e^{j\theta_2}\end{bmatrix} \tag{3}$$

Global Phase

The global phase is a common phase factor applied uniformly to all components of a quantum state. This can be done by multiplying the entire state by a phase factor $e^{j\gamma}$ where γ is a real number, this gives:

$$|\psi' >= e^{j\gamma}\big|\psi > = e^{j\gamma}(\ \alpha\big|0 > +\beta|1 >) \tag{4}$$

This phase γ represents the global phase. Mathematically, it changes the phase of the entire state by the same amount. The global phase affects neither physical observables nor measurement probabilities because it is shared by both terms. Only the relative phases between the components of a superposition can be observed using quantum mechanics. The reason for this can be seen from the fact that measurement probabilities depend on the squared magnitudes of the state components, and for any complex number $z = re^{j\phi}$, $|z|^2 = r^2$, which is independent of the phase ϕ. Thus, the global phase γ drops out in measurement probabilities, leaving the physical state unaffected.

Relative Phase

In contrast to global phase, relative phase refers to the phase difference between the superposition state's components. The phase difference is important because it influences the interference patterns that can be measured. Utilizing quations (1) and (2), the relative phase can be given by:

$$\Delta\theta = \theta_1 - \theta_2 \tag{5}$$

To figure out what this relative phase means, let's rewrite the state in terms of the coefficients' magnitude and phase:

$$\big|\psi > = r_1 e^{j\theta_1}\big|0 > +r_2 e^{j\theta_2}|1 > \tag{6}$$

Factoring out a global phase $e^{j\theta_1}$ from both terms, we get:

$$\big|\psi > = e^{j\theta_1}(r_1\big|0 > +r_2 e^{j(\theta_2-\theta_2)}|1 >)\ = e^{j\theta_1}(r_1\big|0 > +r_2 e^{j\Delta\theta}\big|1 >) \tag{7}$$

Here θ_1, is the global phase (which can be ignored in terms of measurement outcomes), and Δθ=θ2−θ1 is the relative phase. The relative phase directly affects the interference between |0⟩ and |1⟩, as it controls how the superposition state evolves under quantum gates.

Bloch Sphere Representation

Bloch spheres are a way to show the qubit state in three dimensions using geometric shapes. We rewrite the amplitudes α and β in terms of spherical coordinates to show a qubit state on the Bloch sphere. Using equation (7) define new parameters θ and ϕ to describe the state on the Bloch sphere. These angles describe the state in spherical coordinates:

$$\left|\psi > = \cos(\frac{\theta}{2})\right| 0 > +e^{j\phi}\sin(\frac{\theta}{2})|1 > \quad (8)$$

Where θ is the polar angle (latitude) on the Bloch sphere and determines the ratio of |0⟩ to |1⟩, and ϕ is the azimuthal angle (longitude) and represents the relative phase between |0⟩ and |1⟩. Fig. (1) shows an example of the impact of the global phase on the state of a single qubit. In this example The global phase multiplies the entire quantum state by a constant phase factor $e^{j\phi}$. In our case, $\phi=\pi/2$. Global phase factors do not influence measurement results. In quantum physics, they remain unobservable since all physical probabilities rely on the modulus squared of the amplitudes, resulting in the cancellation of the global phase.

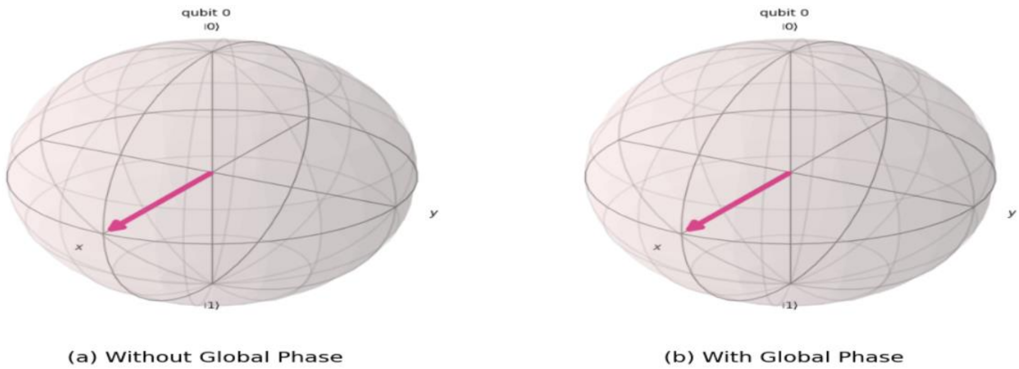


Figure 1. Global phase impact on the state vector of a single qubit

We show below how solve the above example numerically by showing the quantum state vector before and after applying the global phase.

- **No global phase**

$$|\psi_{no-global} >= \frac{1}{\sqrt{2}}(|0 > +|1 >) = \frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix} = \begin{bmatrix}0.7071 + 0j\\0.7071 + 0j\end{bmatrix}$$

- **With global phase**

A global phase of *π/2* is applied:

$$|\psi_{with-global} >= e^{j\frac{\pi}{2}}\frac{1}{\sqrt{2}}(|0 > +|1 >) = \frac{j}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix} = j\begin{bmatrix}0.7071 + 0j\\0.7071 + 0j\end{bmatrix} = \begin{bmatrix}0 + j0.7071\\0 + j0.7071\end{bmatrix}$$

From the above example we notice these essential Insights:

a. The experiment validates that global phases lack physical significance and do not modify the qubit's representation on the Bloch sphere.
b. The state vectors exhibit a numerical difference characterized by a phase factor $e^{j\frac{\pi}{2}}$, which is seen in the imaginary components of the amplitudes in the "With Global Phase" scenario.
c. Upon measuring these qubits, both would produce identical probability for |0⟩ and |1⟩.

Fig. 2 shows a demonstration of the impact of a relative phase on a qubit's state. We'll create two quantum circuits:

- **Without Relative Phase**: A qubit in a superposition state created by a Hadamard gate.

$$|\psi_{no-relative} >= \frac{1}{\sqrt{2}}(|0>+|1>) = \frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix} = \begin{bmatrix}0.7071+0j\\0.7071+0j\end{bmatrix}$$

- **With Relative Phase**: The same superposition state with an added relative phase using a phase gate.

A phase ϕ can be introduced utilizing the phase gate $P(\Phi)$.

$$P(\Phi) = \begin{bmatrix}1 & 0\\0 & e^{j\phi}\end{bmatrix} \tag{9}$$

$$|\psi_{with-relative} >= P(\frac{\pi}{2})\frac{1}{\sqrt{2}}(|0>+|1>) = \begin{bmatrix}1 & 0\\0 & j\end{bmatrix}\frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix} = \begin{bmatrix}0.7071+0j\\0+0.7071j\end{bmatrix}$$

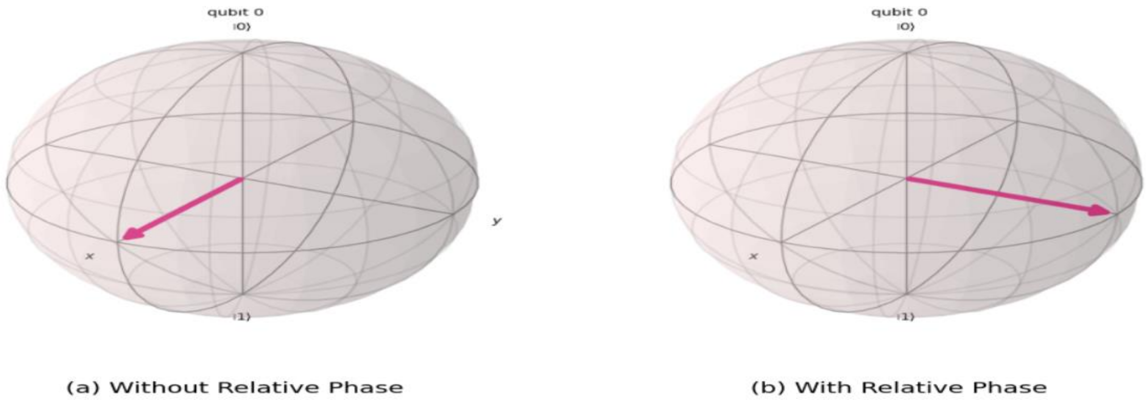


Figure 2. Relative phase impact on the state vector of a single qubit

It is clearly obvious that the relative phase has rotate the qubit's state vector around the Z-axis. The angle of rotation is equal to the relative phase ϕ which is π/2 in this example.

Phase Gates and Their Effect on the State Vector of a Qubit

In quantum computing, phase gates are single-qubit operations that apply a phase shift to the quantum state. They are vital for manipulating the relative phases among quantum states, which is critical for quantum interference and entanglement. This section examines the prevalent phase gates, their mathematical formulations, and their impact on qubit states (Hill et al.,2021 Feng et al., 2021). Phase gates induce a phase shift in the |1⟩ component of a qubit's state. The generic phase gate is represented as $P(\Phi)$ and is characterized by equation (9). When applied to a qubit in a superposition state, phase gates alter the relative phase between the |0⟩ and |1⟩ components, affecting how the qubit interferes with other qubits or itself.

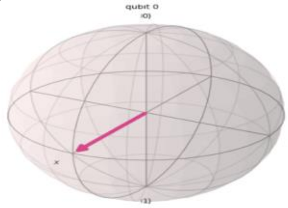
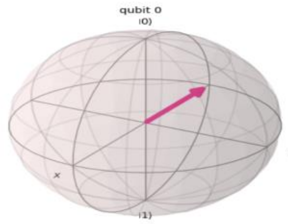
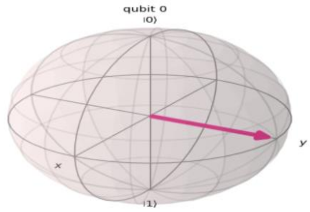
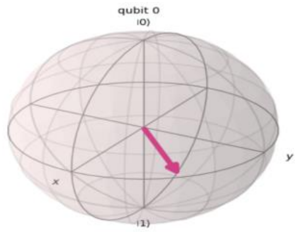
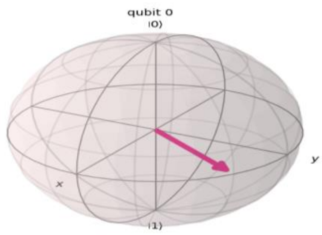
Table 1 shows the different types of relative phase gates applied to a qubit in superposition state after applying the Hadamard gate. When a qubit is in a superposition stateas shown in equation (1), applying a phase gate modifies the phase of the |1⟩ component while leaving the |0⟩ component unchanged.

- The Z gate introduces a phase shift of π, effectively multiplying the |1⟩ coefficient by −1. This reflects the state vector across the X-axis on the Bloch sphere, turning |+⟩ into |−⟩.
- The S gate, with a phase shift of π/2, multiplies the |1⟩ component by j. This rotates the state vector by 90∘ around the Z-axis, moving it from the positive X-axis to the positive Y-axis on the Bloch sphere.
- The T gate applies a phase shift of π/4, multiplying the |1⟩ component by $e^{j\frac{\pi}{4}}$. This results in a 45∘ rotation around the Z-axis, positioning the state vector between the positive X and Y axes.

- The general phase gate $P(\Phi)$ allows for an arbitrary phase shift , offering precise control over the qubit's relative phase. Applying $P(\Phi)$ rotates the state vector by Φ around the Z-axis on the Bloch sphere.

By altering the relative phases, these gates change how qubit states interfere with each other, which is crucial for quantum algorithms and operations that rely on quantum interference and entanglement.

Table 1. Relative phase gates

	Gate name	Gate relative phase	Gate matrix	Gate Bloch sphere
1.	Hadamard	None	$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\ 01 & -1\end{bmatrix}$	
2.	Z	$\phi = \pi$	$\begin{bmatrix}1 & 0\\ 0 & -1\end{bmatrix}$	
3.	S	$\phi = \pi/2$	$\begin{bmatrix}1 & 0\\ 0 & j\end{bmatrix}$	
4.	T	$\phi = \pi/4$	$\begin{bmatrix}1 & 0\\ 0 & e^{j\frac{\pi}{4}}\end{bmatrix}$	
5.	P	ϕ any other phase Choose $\phi = \pi/3$	$\begin{bmatrix}1 & 0\\ 0 & e^{j\frac{\pi}{3}}\end{bmatrix}$	

Relative Phase Role in Quantum Interference and Algorithms

Quantum interference arises when the probability amplitudes of distinct quantum states combine, resulting in a cumulative probability that may exceed (constructive interference) or diminish (destructive interference) the sum of the individual probabilities. In contrast to classical probabilities, quantum probability amplitudes are complex numbers, and their phases are essential for interference phenomena.

Consider a quantum system that can be in states $|\psi 1\rangle$ and $|\psi 2\rangle$. The system's state can be a superposition:

$$|\Psi> = \alpha|\psi_1> + \beta|\psi_2> \tag{10}$$

where α and β are complex probability amplitudes. The probability of measuring a particular outcome is given by the modulus squared of the total amplitude:

$$P = |\alpha + \beta|^2 = |\alpha|^2 + |\beta|^2 + 2Re(\alpha^*\beta) = |\alpha|^2 + |\beta|^2 + 2\,|\alpha||\beta|\cos(\phi_\beta - \phi_\alpha) \tag{11}$$

The cross term $2Re(\alpha^*\beta)$ represents the interference effect, which depends on the relative phase between α and β. A constructive Interference, ($\cos(\phi_\beta - \phi_\alpha) = 1$), occurs when the relative phase between amplitudes leads to an increased probability of an outcome. On the other hand, a destructive Interference, ($\cos(\phi_\beta - \phi_\alpha) = -1$) , occurs when the relative phase causes the amplitudes to cancel out, decreasing the probability. This shows the importance and the necessity of having relative phase as quantum interference inherently depends on relative phases between quantum states. Without relative phases, the interference terms vanish, and quantum systems behave classically in terms of probability distributions.

Quantum interference and relative phase are an essential assets in quantum computing, allowing quantum algorithms to surpass classical algorithms. They permit:

- Parallelism: Quantum superposition facilitates concurrent computation across various states.
- Algorithmic Speedup: Algorithms such as Shor's factoring algorithm and Grover's search algorithm utilize interference to achieve solutions more rapidly than conventional algorithms.
- Quantum Simulations: Interference is crucial for simulating quantum systems, as phase relationships dictate physical features.

Some examples of quantum algorithms that utilize relative phase and quantum interference include: Grover's algorithm which uses interference to amplify the probability amplitude of the desired solution while suppressing others; Quantum phase estimation (QPE) which relies on interference patterns to estimate eigenvalues of unitary operators; and quantum Fourier transform (QFT) which transforms quantum states into a superposition where interference encodes frequency components.

Figure 3. shows a quantum circuit that is comprised of a single qubit initiated in the state $|0\rangle$. Initially, it employs a Hadamard gate to establish an equal superposition of the states $|0\rangle$ and $|1\rangle$. Subsequently, it creates a relative phase shift by employing a phase gate, which adds a certain phase angle Φ to the $|1\rangle$ component of the superposition. Subsequently, a second Hadamard gate is applied, resulting in the interference of the probability amplitudes of the qubit's states. The relative phase Φ dictates the combination of these amplitudes, resulting in constructive or destructive interference, which directly influences the probability of measuring the qubit in either state $|0\rangle$ or $|1\rangle$. The qubit is ultimately measured. This circuit illustrates the essential function of relative phase in quantum interference and how its manipulation can influence the results of quantum measurements.

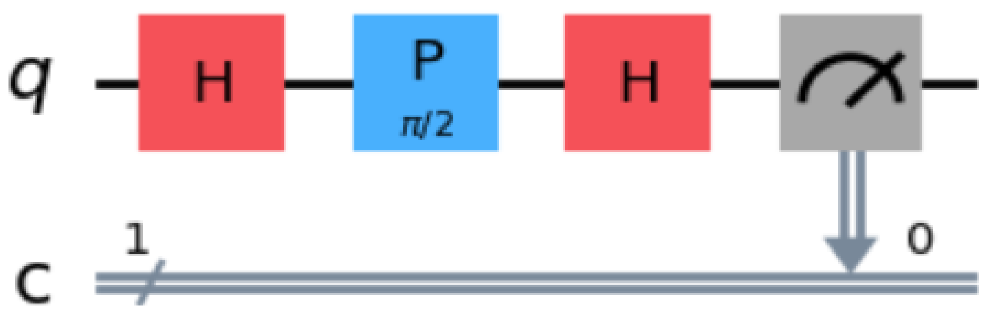


Figure 3. Quantum circuit to demonstrate the effect of relative phase on interference

Fig. 4 depicts how the probabilities of measuring the qubit in states $|0\rangle$ and $|1\rangle$ fluctuate when the relative phase Φ alters. It demonstrates that when Φ varies from 0 to 2π, the probabilities P(0) and P(1) fluctuate sinusoidally between 0 and 1. This oscillation illustrates the constructive and destructive interference effects resulting from the relative phase introduced by the phase gate. At specific phase values (e.g., Φ =0 or 2π), the probability P(0) attains its maximum, signifying constructive interference for the $|0\rangle$ state. Conversely, for Φ =π, P(1) attains its maximum due to constructive interference for the $|1\rangle$ state. The figure clearly illustrates the significant influence of relative phase on quantum interference and emphasizes that manipulating this phase can govern the results of quantum experiments.

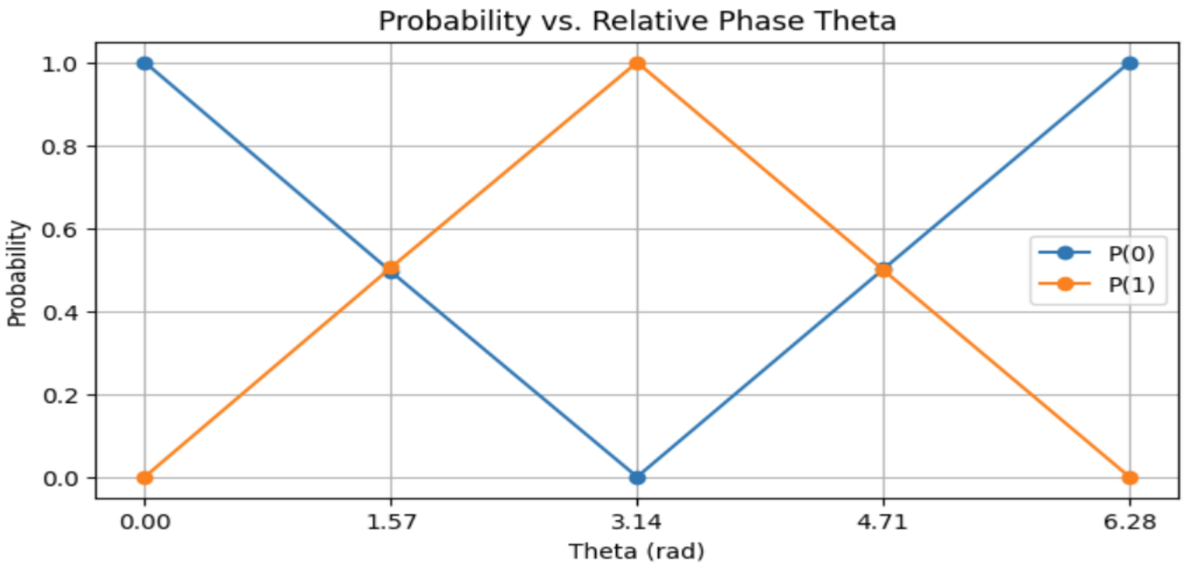


Figure 4. Probability vs relative phase (rad)

Fig. 5 shows a quantum circuit introduces with Hadamard gates applied to both qubits immediately before the measurement step. These additional Hadamard gates effectively change the measurement basis from the standard computational basis to the Hadamard (or X) basis. The circuit begins by creating an entangled Bell state between the two qubits, and a relative phase shift is introduced to one qubit using a phase gate. By applying the Hadamard gates before measurement, the circuit allows the relative phase to influence the measurement outcomes. This modification makes the impact of the phase shift observable, as it causes the probability amplitudes of the qubit states to interfere differently, depending on the value of the phase. The circuit demonstrates how changing the measurement basis can reveal subtle effects of quantum phases on entangled states.

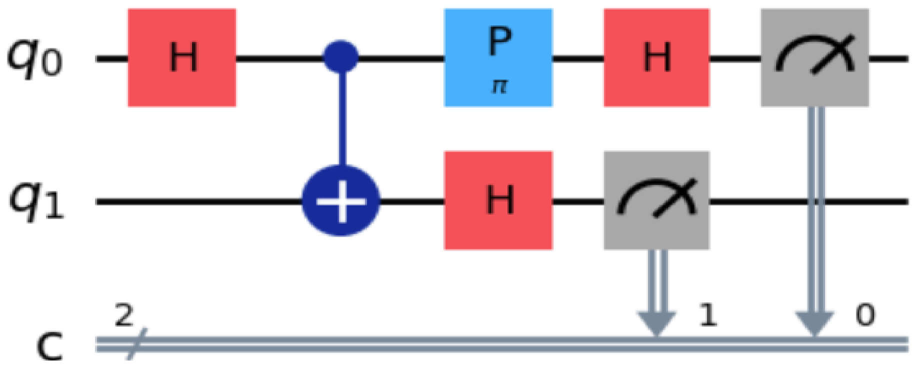


Figure 5. Entangled circuit with relative phase

Figure 6. shows the resulting histograms of the probability for each potential two-qubit outcome assessed in the computational basis following the use of Hadamard gates. The data indicate that the probability of detecting particular outcomes fluctuate considerably with varying values of the phase angle Φ. For example, when the relative phase (Φ is 0, π or 2π) the computational basis ‘00’ and ‘11’ are only have non-zero probabilities. While when the relative phase (Φ is $\pi/2$ or $3\pi/2$) all of the computational bases have non-zero probabilities. This variant demonstrates that the previously introduced relative phase in the circuit influences the interference patterns when the measurement basis is modified. The histograms demonstrate how constructive and destructive interference, affected by the phase shift, result in varying probabilities for each scenario. This demonstrates the crucial role of relative phases and measurement bases in quantum mechanics, as they directly impact the observable properties of quantum systems.

One final note to point out that drastically affects the relative phase and quantum interference is the decoherence problem. Decoherence, which can be defined as the loss of quantum coherence due to interactions with the environment, disrupts the delicate phase relationships between qubits. This interference can cause errors in computations and loss of information, posing a significant challenge to building reliable quantum computers. To overcome these obstacles, researchers are developing solutions such as quantum error correction codes, which can detect and fix errors without directly measuring the qubits. Other approaches include isolating qubits from environmental noise using sophisticated shielding techniques, employing decoherence-free subspaces where qubits are less susceptible to interference, and implementing dynamic decoupling methods to counteract decoherence effects. These strategies aim to preserve the integrity of qubit phases, allowing quantum computers to perform complex calculations accurately (Abdelmagid et al., 2023; Salmanogli & Sirat, 2024).

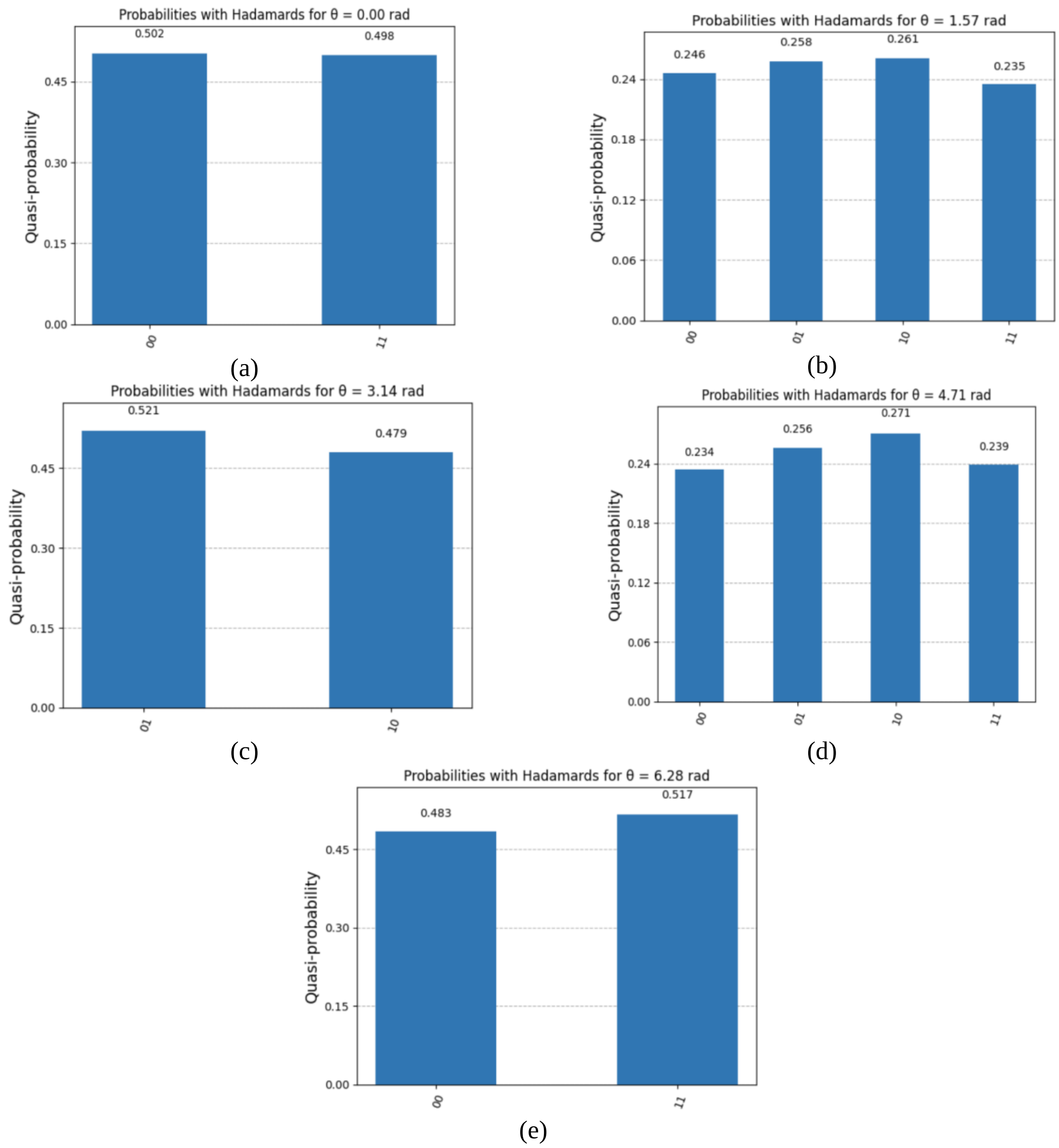


Figure 6. Probabilities for Entangled state with different relative phases

Conclusion

This paper explores the essential value of relative phases and quantum interference in quantum computing. We examined the impact of quantum gates, including the Z, S, T, and general phase gates, on the relative phases of qubits in superposition through comprehensive explanations and realistic Qiskit simulation. These gates alter the phase of quantum states, resulting in constructive or destructive interference patterns crucial for the operation of quantum algorithms. Through the analysis of particular quantum circuits, we illustrated how modifications to the relative phase affect measurement results. In the interference circuit with a single qubit, we demonstrated that altering the relative phase θ directly influences the probabilities of measuring the qubit in either the $|0\rangle$ or $|1\rangle$ state. This highlights how quantum interference, influenced by relative phases, can be utilized to manipulate quantum systems. We also examined the influence of relative phases in entangled systems. The application of phase gates to a single qubit inside an entangled pair demonstrated that the relative phase can affect the joint state and measurement probabilities, particularly when measurements are conducted in different bases. This underscores the complex interplay of entanglement, relative phases, and measurement results.

Moreover, the research examined the significance of relative phases in other quantum algorithms, including the Quantum Fourier Transform (QFT), Quantum Phase Estimation (QPE), Grover's Algorithm, among others. These algorithms utilize the manipulation of relative phases to generate interference patterns that amplify desired computational outcomes while diminishing undesired ones.

In summary, the precise control and understanding of relative phases are crucial for the advancement of quantum computing. Quantum interference, facilitated by these phases, is a key resource that enables quantum algorithms to outperform classical counterparts. Mastery over phase manipulation not only aids in the development of more efficient quantum algorithms but also deepens our comprehension of quantum mechanics and its applications in technology.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM Journal belongs to the authors.

Acknowledgements or Notes

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