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Article

Neutrosophic Modelling of Qubit Uncertainty in Noisy Quantum Computing Systems

Muhammad Raza Sheikh[1]*

[1]Department of Computer, University of Genova, Italy
* Corresponding Email: sqarazasheikh@gmail.com (M. R. Sheikh)

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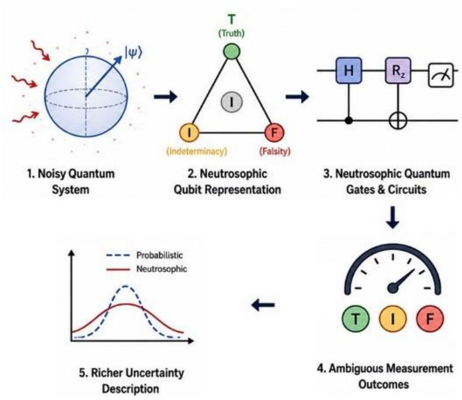
ABSTRACT

Quantum computing exploits superposition and entanglement to perform computations beyond the capabilities of classical machines. However, practical quantum systems operate under substantial environmental noise, measurement uncertainty, and decoherence, leading to ambiguous or partially determined quantum states. Conventional probabilistic descriptions capture stochastic behaviour but do not explicitly represent indeterminacy arising from incomplete information or measurement ambiguity. In this work, we introduce a neutrosophic representation of qubit states that integrates principles of Neutrosophic Logic with the mathematical framework of Quantum Computing. In the proposed model, a qubit is characterised by three independent parameters representing truth, indeterminacy, and falsity. This formulation enables explicit representation of ambiguous quantum states and uncertain measurement outcomes. We extend the neutrosophic formalism to quantum gate operations and analyse how the model captures uncertainty propagation in quantum circuits. Through theoretical examples and graphical analysis, we demonstrate that neutrosophic representation provides a richer description of uncertainty compared with conventional probabilistic approaches. The proposed framework offers a conceptual pathway for improved modelling of noisy intermediate-scale quantum devices and may contribute to the development of uncertainty-aware quantum computing architectures.



Keywords: Ambiguous Quantum States; Neutrosophic Logic; Noisy Quantum Systems; Quantum Circuits; Quantum Computing; Uncertainty Modelling

1. Introduction

The rapid development of quantum technologies has led to increasing interest in quantum computation as a transformative approach to information processing [1],[2],[3],[4]. Unlike classical computers, which process information using deterministic binary bits, quantum computers operate using quantum bits or qubits that obey the laws of quantum physics [5]. Because qubits can exist simultaneously in multiple states, quantum computers can explore a vast computational space through quantum parallelism. The fundamental theoretical framework underlying quantum computation is derived from Quantum Mechanics, which describes the behaviour of physical systems at microscopic scales [6],[7]. Quantum systems exhibit several counterintuitive properties that are central to quantum information processing. Among these properties, superposition allows a qubit to exist in a linear combination of basis states, while entanglement enables strong correlations between multiple qubits.

Despite these advantages, practical quantum computing faces formidable challenges. Quantum systems are extremely sensitive to external disturbances, and interactions with the surrounding environment can quickly destroy the coherence of quantum states [8],[9],[10],[11]. This process, known as Quantum Decoherence, represents one of the major obstacles to the realisation of largescale quantum computers. Even small amounts of noise can accumulate during quantum computations, leading to errors that significantly degrade algorithmic performance. Conventional approaches to modelling quantum uncertainty rely on probabilistic descriptions [12]. In the standard quantum formalism, the outcome of a measurement is described by a probability distribution derived from the square magnitudes of probability amplitudes. While this probabilistic representation successfully captures the stochastic nature of quantum measurements, it does not always distinguish between randomness and ambiguity. In many practical situations, uncertainty arises not only from intrinsic probabilistic behaviour but also from incomplete knowledge of system parameters or limitations of measurement devices.

To address this issue, alternative frameworks capable of representing indeterminacy explicitly have been explored. One such framework is Neutrosophic Logic, which was introduced by Florentin Smarandache as a generalisation of classical and fuzzy logic [13],[14]. Neutrosophic logic represents information using three independent components: truth, indeterminacy, and falsity. Unlike probabilistic approaches, which constrain the sum of probabilities to unity, neutrosophic logic allows these components to vary independently, enabling a more flexible representation of uncertain information.

The objective of this work is to explore the potential of neutrosophic theory as a framework for modelling uncertainty in quantum computing systems. By extending the conventional description of qubit states to include indeterminacy, we aim to provide a richer representation of the uncertainties encountered in realistic quantum hardware. In particular, we focus on noisy quantum computing platforms where measurement errors, gate imperfections, and environmental disturbances introduce ambiguity into quantum operations.

2. Conventional Quantum State Representation

2.1. Mathematical Description of Qubits

In quantum computing, the fundamental unit of information is the quantum bit, or qubit. Unlike a classical bit, which can exist only in one of two definite states, 0 or 1, a qubit can exist in a superposition of these basis states. Mathematically, a single qubit can be represented as a vector in a two-dimensional complex Hilbert space, expressed as in (1) [15],[16],[17]:

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle \qquad (1)$$

Here, $|0\rangle$ and $|1\rangle$ denote the computational basis states of the qubit, and $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ are complex probability amplitudes. These amplitudes encode the quantum information of the system and determine the probability distribution of measurement outcomes [18]. Importantly, the normalisation condition must be satisfied as in (2):

$$|\alpha|^2 + |\beta|^2 = 1 \qquad (2)$$

This ensures that the total probability of measuring the qubit in one of the two possible states is unity, consistent with the axioms of probability theory. The squared magnitudes of the amplitudes, $|\boldsymbol{\alpha}|^2$ and $|\boldsymbol{\beta}|^2$, represent the probabilities of finding the qubit in state $|0\rangle$ or $|1\rangle$, respectively, upon measurement.

The probabilistic nature of quantum measurement is a fundamental feature of quantum mechanics. When a measurement is performed, the qubit's wavefunction collapses into one of the basis states, a process dictated by the Born rule [19],[20]. This collapse is inherently stochastic: repeated measurements of identically prepared qubits will yield outcomes consistent with the probabilities $|\boldsymbol{\alpha}|^2$ and $|\boldsymbol{\beta}|^2$, but individual results cannot be predicted deterministically. This probabilistic behaviour is central to quantum theory and underpins phenomena such as quantum interference, entanglement, and nonlocal correlations. Qubits can be manipulated through unitary operations, represented by 2×2 matrices acting on the state vector [21]. These operations allow rotations on the Bloch sphere, enabling the creation of arbitrary superpositions [22]. For instance, the Hadamard gate, a single-qubit unitary operation, transforms a qubit from a basis state into an equal superposition of $|0\rangle$ and $|1\rangle$ [23],[24]. Such transformations are the foundation of quantum algorithms, allowing the construction of complex computational processes through sequences of unitary operations.

The mathematical representation of qubits is compact yet highly expressive. In addition to single-qubit states, multi-qubit systems are described by tensor products of individual qubits. For example, a two-qubit system may exist in a linear combination of the four basis states $|00\rangle$, $|01\rangle$, $|10\rangle$, $|11\rangle$, with complex amplitudes assigned to each [25],[26]. These higher-dimensional Hilbert spaces enable entanglement, a uniquely quantum correlation with no classical analog, which forms the basis of many quantum computing advantages, including quantum teleportation and superdense coding.

2.2. Limitations of Probabilistic Descriptions

While probabilistic descriptions form the foundation of quantum mechanics, they are often insufficient to capture the full spectrum of uncertainties in practical quantum computing systems. Real-world quantum devices, including superconducting qubits, trapped ions, and photonic systems, experience environmental and operational imperfections that introduce additional layers of uncertainty beyond ideal probabilistic behaviour [27],[28],[29],[30],[31].

- A primary source of such uncertainty is environmental noise, arising from interactions between qubits and their surroundings. Thermal fluctuations, electromagnetic interference, and residual couplings can perturb qubit states, leading to deviations from ideal evolution. These effects contribute not only to stochastic errors but also to ambiguity, as qubits may occupy partially decohered states where outcome probabilities are not sharply defined.
- Imperfect control pulses further exacerbate uncertainty. Quantum gates rely on precisely tuned electromagnetic or optical pulses; small deviations in amplitude, duration, or phase can cause unintended rotations. While some errors are statistical, others produce indeterminate states that do not align neatly with standard probabilistic distributions. Calibration errors, affecting qubit frequencies, coupling strengths, or timing, introduce systematic biases that can distort evolution and generate outcomes that remain uncertain despite being deterministic.
- Finally, measurement ambiguity limits the extraction of reliable information. Noise in readout devices, overlapping signal distributions, or finite resolution can produce results that are intrinsically indeterminate. For instance, in dispersive readout of superconducting qubits, intermediate voltage signals may prevent unambiguous assignment to $|0\rangle$ or $|1\rangle$. Conventional probabilistic models interpret this as a weighted average but fail to capture the qualitative indeterminacy of such outcomes.

Collectively, these considerations highlight the need for frameworks that explicitly account for both stochastic and indeterminate uncertainties, enabling more accurate modelling and robust design of quantum systems.

Despite the effectiveness of probabilistic and density-matrix-based models, existing frameworks do not explicitly distinguish between intrinsic quantum randomness and uncertainty arising from ambiguity or incomplete information. In practical quantum systems, measurement outcomes may be indeterminate rather than purely probabilistic, particularly under conditions of noise, partial decoherence, or limited readout resolution. Conventional metrics such as fidelity or error rates aggregate these effects into a single value, thereby obscuring their physical origin. This limitation motivates the need for an extended framework capable of explicitly representing and separating stochastic, indeterminate, and erroneous contributions to quantum uncertainty.

3. Neutrosophic Representation of Qubit States

3.1. Neutrosophic Logical Framework

In classical and quantum information theory, uncertainty is traditionally represented using probabilities. However, probabilistic models primarily capture stochastic randomness and often fail to explicitly represent indeterminacy arising from incomplete knowledge or ambiguous measurement outcomes. To address this limitation, neutrosophic logic offers a generalised framework capable of representing both randomness and indeterminacy.

Neutrosophic logic, introduced by Florentin Smarandache, extends the principles of fuzzy logic by incorporating three independent components to characterise any statement or system state [14],[32]. A neutrosophic entity is defined as a triplet (3):

$$N = (T, I, F) \qquad (3)$$

Where:

- ***T*** represents the degree of truth, quantifying the extent to which a proposition is verified or confirmed.
- ***I*** represents the degree of indeterminacy, reflecting uncertainty, ambiguity, or incomplete knowledge.
- ***F*** represents the degree of falsity, capturing contradictory or erroneous information.

Unlike conventional probabilities, these components are independent; they are not required to sum to unity. Each can vary freely within a defined range, allowing the representation of conflicting, incomplete, or ambiguous information. This flexibility is particularly relevant for modelling real-world quantum systems, where noise, decoherence, and measurement imperfections create states that cannot be fully described by standard probabilistic amplitudes alone.

The neutrosophic framework is versatile and can represent classical deterministic states (where $\boldsymbol{T} = 1$, $\boldsymbol{I} = 0$, $\boldsymbol{F} = 0$), fully indeterminate states (where I dominates), or conflicting information (where ***T*** and ***F*** are both significant). It thus provides a richer language for describing uncertainty in both theoretical and experimental contexts.

It is important to emphasise that the proposed neutrosophic representation is not intended to replace the standard formalism of quantum mechanics, but rather to complement it as an additional uncertainty modelling layer. The triplet ($\boldsymbol{T}$, $\boldsymbol{I}$, $\boldsymbol{F}$) can be interpreted as a phenomenological abstraction derived from measurement statistics associated with quantum states described in Hilbert space. In this context, the component ***T*** is consistent with probabilities obtained via the Born rule, while ***I*** capture indeterminacy arising from measurement ambiguity, noise, and incomplete information and ***F*** reflects erroneous or contradictory outcomes due to imperfections in quantum operations or readout. Similarly, the framework is compatible with density matrix descriptions and completely positive trace-preserving (CPTP) maps, in the sense that neutrosophic parameters can be viewed as higher-level descriptors derived from the action of noisy quantum channels on measurement outcomes. Thus, the proposed model should be understood as an extension that augments, rather than modifies, the underlying quantum mechanical structure.

3.2. Definition of a Neutrosophic Qubit

Building on this framework, we define a Neutrosophic Qubit (NQ) as a quantum state augmented with explicit measures of indeterminacy and falsity. Formally, a neutrosophic qubit is represented as (4):

$$NQ = (T, I, F) \qquad (4)$$

Where:

- ***T*** corresponds to the confirmed probability of a quantum state, analogous to the conventional amplitude-derived probability in standard quantum mechanics.
- ***I*** quantify indeterminacy arising from noise, decoherence, measurement ambiguity, or incomplete knowledge of the system.
- ***F*** represents contradictory or erroneous information, such as outcomes inconsistent with the prepared state due to errors in gate operations or readout devices.

Unlike traditional quantum states, which are normalised by the sum of squared amplitudes, the neutrosophic qubit obeys a relaxed condition (5):

$$0 \leq T + I + F \leq 30 \qquad (5)$$

This allows the three components to vary independently, reflecting the realistic scenario where some portion of uncertainty may be ambiguous rather than purely stochastic. In this way, the neutrosophic qubit provides a multi-dimensional characterisation of uncertainty, separating deterministic, random, and indeterminate contributions.

The constraint $0 \leq \boldsymbol{T}, \boldsymbol{I}, \boldsymbol{F} \leq 1$ with $0 \leq \boldsymbol{T} + \boldsymbol{I} + \boldsymbol{F} \leq 3$arises naturally from neutrosophic logic, where each component represents an independent degree of truth, indeterminacy, and falsity. Unlike probabilistic representations, these components are not required to sum to unity. This independence allows the framework to model incomplete information ($\boldsymbol{T} + \boldsymbol{I} + \boldsymbol{F} < 1$), fully specified but non-exclusive information ($\boldsymbol{T} + \boldsymbol{I} + \boldsymbol{F} = 1$), and conflicting or redundant information ($\boldsymbol{T} + \boldsymbol{I} + \boldsymbol{F} > 1$). In quantum systems, this flexibility is physically meaningful, as measurement outcomes may simultaneously exhibit partial correctness, ambiguity due to decoherence, and error due to noise or miscalibration. Therefore, the relaxed constraint is not arbitrary but reflects the multi-source nature of uncertainty in realistic quantum hardware.

3.3. Example 1: Measurement Under Noise

To illustrate the utility of this representation, consider a qubit prepared in an equal superposition state (6):

$$|\,\psi\rangle = \frac{1}{\sqrt{2}}(|\,0\rangle + |\,1\rangle) \qquad (6)$$

In an idealised measurement scenario, the probabilities of observing $|0\rangle$ or $|1\rangle$ are both 0.5. However, in realistic experimental conditions, measurement devices are subject to noise, finite resolution, and other imperfections. Suppose that upon repeated measurement, the outcomes yield the following characterisation as in Table 1:

Table 1:
Parameters for measurement

Parameter	Value
Truth (correct state identification)	0.48
Indeterminacy (ambiguous outcome)	0.32
Falsity (incorrect identification)	0.20

Here, $\boldsymbol{T} = 0.48$ reflects the fraction of measurements correctly identifying the state. The indeterminacy component $\boldsymbol{I} = 0.32$ accounts for outcomes that cannot be confidently assigned to either basis state due to noise or measurement overlap. Finally, $\boldsymbol{F} =$

0.20 represents erroneous results, arising from misclassification or experimental error. Thus, the neutrosophic qubit can be written as (7):

$$NQ = (0.48, 0.32, 0.20) \quad (7)$$

This representation provides several advantages over conventional probabilistic descriptions. Firstly, it explicitly separates ambiguity from randomness, offering a more accurate depiction of experimental reality. Secondly, it provides a clear metric to evaluate the quality of qubit preparation and measurement: a high indeterminacy component signals that improvements in readout or environmental isolation may be necessary, whereas a high falsity component indicates systematic errors. Lastly, this framework is extensible to multi-qubit systems, allowing the quantification of indeterminacy and error propagation in complex quantum circuits.

- **Interpretation and Significance**

The neutrosophic qubit formalism highlights a key distinction: while classical probabilities capture stochastic uncertainty, they do not adequately describe epistemic uncertainty or ambiguous outcomes. In practice, both types of uncertainty coexist. For example, a qubit in a noisy superconducting circuit may occasionally produce measurements that are neither strictly $|0\rangle$ nor $|1\rangle$, reflecting the combined effects of decoherence, control errors, and detector limitations. Standard probabilistic models would interpret these outcomes as averaged probabilities, masking the qualitative difference between random and indeterminate contributions. The neutrosophic approach preserves this distinction, providing a richer, more informative characterisation.

Furthermore, the framework can inform error mitigation and quantum algorithm design. By quantifying indeterminacy, one can identify operations or gates that contribute disproportionately to ambiguous outcomes, enabling targeted hardware or software corrections. It also facilitates the assessment of measurement strategies: for instance, repeated or ensemble measurements can reduce the indeterminacy component, converting ambiguous information into confirmed probabilities while still accounting for residual errors.

4. Neutrosophic Modelling of Quantum Gates

Quantum computation relies on the precise manipulation of qubits through quantum gates, which perform unitary operations on quantum states [33],[32],[35]. In the idealised framework of quantum mechanics, these gates are deterministic and invertible, transforming qubit states with perfect fidelity. For instance, single-qubit gates such as the Hadamard or Pauli-X gates rotate qubits on the Bloch sphere, while multi-qubit gates such as the Controlled-NOT (CNOT) entangle qubits to enable non-classical correlations [36]. However, in practical implementations, gates are subject to a variety of imperfections, including control errors, environmental disturbances, and decoherence. These imperfections introduce uncertainty in the resulting quantum states, which cannot be fully captured by standard probabilistic descriptions alone.

To address this limitation, we extend the neutrosophic framework to model quantum gate operations. In this approach, a Neutrosophic Gate (NG) is defined as a triplet (8):

$$G_N = (T_g, I_g, F_g) \quad (8)$$

Where:

- ***Tg*** quantifies the degree to which the gate performs its intended operation correctly.
- ***Ig*** represents the indeterminacy arising from factors such as environmental noise, control imprecision, or incomplete knowledge of system parameters.
- ***Fg*** captures errors or contradictory outcomes generated during gate execution.

Unlike conventional fidelity metrics, which typically reduce all uncertainties to a single probability of correct operation, the neutrosophic gate model separates stochastic errors from ambiguous or indeterminate behaviours, providing a more nuanced description of real quantum operations.

4.1. Single-Qubit Gates

Consider a single-qubit gate, such as the Hadamard gate, designed to create an equal superposition from a computational basis state [37]. In a noise-free environment, the transformation of $|0\rangle$ yields (9):

$$|\,0\rangle \xrightarrow{H} = \frac{1}{\sqrt{2}}(|\,0\rangle + |\,1\rangle) \quad (9)$$

In a realistic experimental scenario, however, imperfections in pulse amplitude, duration and phase may prevent the qubit from reaching this ideal superposition. Additionally, interaction with the environment can introduce partial decoherence, leaving the qubit in an intermediate state that is not accurately represented by probabilities alone. Using the neutrosophic framework, we can characterise the gate operation as (10):

$$G_N = (0.92, 0.05, 0.03) \quad (10)$$

Here, $\boldsymbol{T_g}$ = 0.92 indicates that the gate correctly produces the desired superposition with 92% certainty, $\boldsymbol{I_g}$ = 0.05 quantifies the ambiguous fraction of operations where the qubit state is indeterminate due to noise and $\boldsymbol{F_g}$ = 0.03 represents the probability of erroneous outcomes caused by miscalibration or control errors. This decomposition allows experimenters to identify and quantify sources of uncertainty beyond conventional fidelity measures.

4.2. Multi-Qubit Gates

Multi-qubit gates, such as the CNOT gate, are central to entanglement generation and complex quantum algorithms [38], [39]. In practice, these gates are highly sensitive to crosstalk, timing errors, and environmental perturbations. Suppose a two-qubit system is intended to undergo a CNOT operation:

$$|\,00\rangle \xrightarrow{CNOT} |\,00\rangle, |\,01\rangle \xrightarrow{CNOT} |\,01\rangle, |\,10\rangle \xrightarrow{CNOT} |\,11\rangle, |\,11\rangle \xrightarrow{CNOT} |\,10\rangle$$

In the presence of noise, the resulting state may deviate from these ideal mappings. Some outcomes may be probabilistically correct, others may result in indeterminate superpositions due to decoherence, and a fraction may be completely erroneous. A neutrosophic characterisation of the CNOT gate might be (11):

$$G_N = (0.87, 0.08, 0.05) \quad (11)$$

This decomposition indicates that 87% of operations yield the intended transformation, 8% result in indeterminate outcomes, and 5% are erroneous. Notably, the indeterminacy component $\boldsymbol{I_g}$ captures the ambiguity introduced by partial entanglement or decoherence, information that standard probabilistic fidelity metrics cannot isolate.

4.3. Propagation of Neutrosophic Uncertainty in Quantum Circuits

One of the key advantages of the neutrosophic framework is its ability to track uncertainty through sequential gate operations. In conventional models, the fidelity of a quantum circuit is typically approximated by the product of individual gate fidelities, assuming purely stochastic errors. However, this approach does not account for the accumulation of indeterminate states, which can significantly impact algorithm performance.

Using the neutrosophic approach, if a circuit consists of sequential gates $G_1, G_2, \ldots, G_n$, the resulting qubit state can be represented as (12):

$$NQ_{final} = (T_{final}, I_{final}, F_{final}) \quad (12)$$

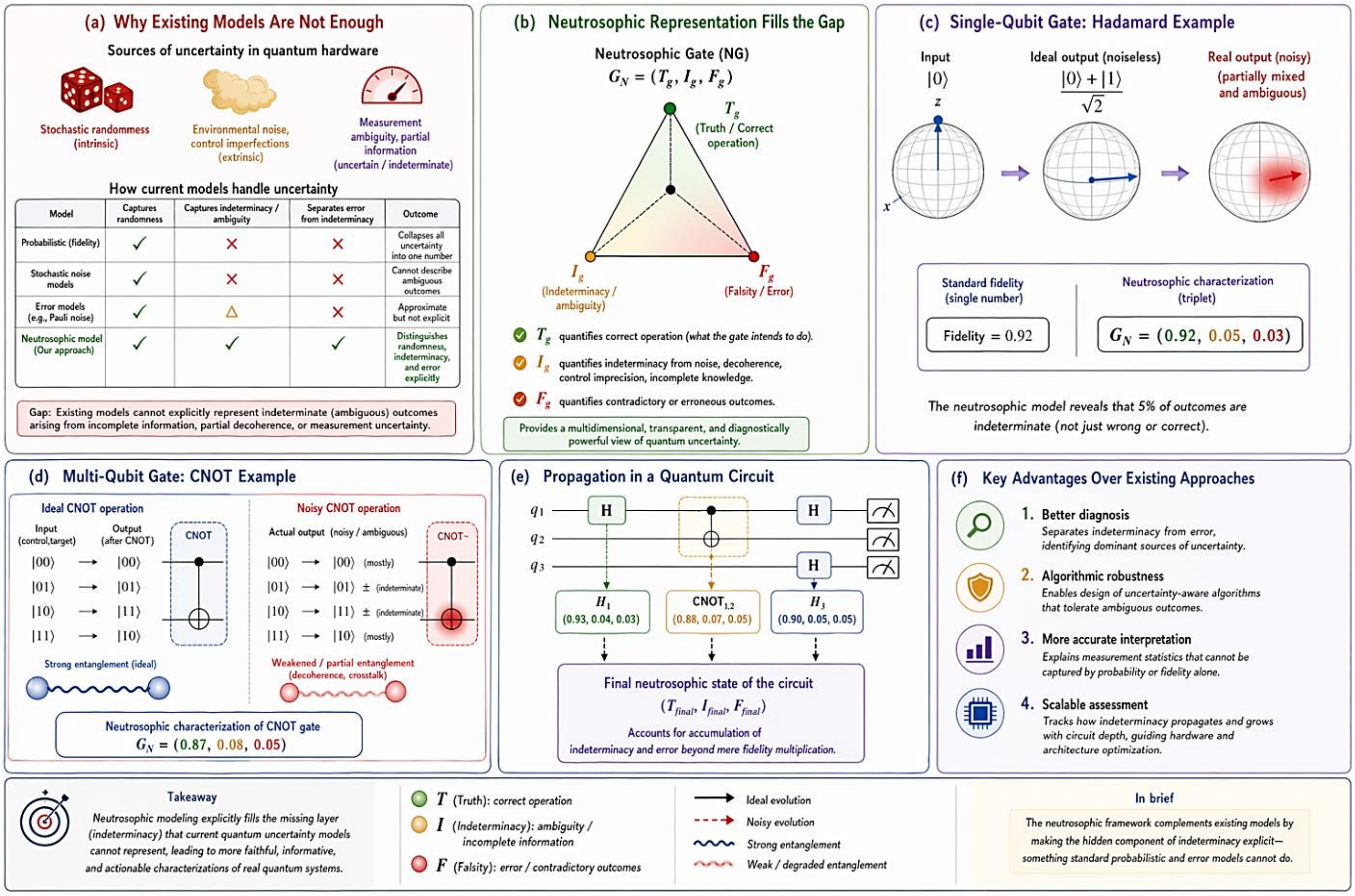


Figure 1: Conceptual illustration of neutrosophic modeling of quantum gates. (a) Comparison between ideal unitary evolution and noisy gate operation. (b) Neutrosophic representation of a quantum gate using the triplet (Tg, Ig, Fg), capturing correct operation, indeterminacy and error. (c) Application to a single-qubit Hadamard gate under realistic noise. (d) Extension to multi-qubit CNOT gate with partial entanglement and decoherence. (e) Propagation of neutrosophic uncertainty in a quantum circuit.

Where each component is updated according to the cumulative effects of gate imperfections, indeterminacy, and errors. For example, if the sequential application of two gates produces:

$$G_1 = (0.90, 0.05, 0.05),\ G_2 = (0.85, 0.10, 0.05)$$

Then the resulting neutrosophic state accounts for both propagation of correct operations and accumulation of indeterminacy. Techniques from neutrosophic algebra can be used to combine these triplets systematically, providing a comprehensive model of uncertainty in complex circuits.

4.4. Propagation of Neutrosophic Uncertainty in Quantum Circuits

The neutrosophic representation of quantum gates offers several practical benefits:

- **Error Diagnosis**: By separating correct operation, indeterminacy, and error, experimenters can identify which sources of uncertainty dominate, guiding hardware improvements and control optimisations.
- **Algorithm Robustness**: Quantifying indeterminacy allows algorithm designers to account for ambiguous states, developing error-resilient strategies and redundancy schemes.
- **Measurement Interpretation**: By combining neutrosophic qubits with neutrosophic gates, the model provides a more accurate description of readout statistics, distinguishing between probabilistic and ambiguous outcomes.
- **Scalability Assessment**: As circuits grow in depth, the propagation of indeterminacy can be explicitly quantified, offering insights into the limits of practical quantum hardware and helping optimise circuit architectures.

4.5. Example: Noisy Quantum Circuit

Consider a three-qubit circuit consisting of a Hadamard gate on qubit 1, followed by a CNOT between qubits 1 and 2, and a second Hadamard on qubit 3. Suppose the gates are characterised as:

$$H_1 = (0.93, 0.04, 0.03),\ CNOT_{1,2} = (0.88, 0.07, 0.05),\ H_3 = (0.90, 0.05, 0.05)$$

The neutrosophic formalism allows systematic computation of the final state neutrosophic triplet, capturing how indeterminacy and error propagate through the circuit. The resulting representation can then be compared against experimental measurements to validate hardware performance and refine error mitigation strategies.

5. Discussion

The neutrosophic representation of quantum states and operations presented in this work offers a significant conceptual extension of conventional probabilistic models used in quantum computing, as mentioned in Figure 1. Traditional descriptions of qubits rely primarily on probabilities derived from amplitude magnitudes to characterise stochastic uncertainty. While this approach effectively captures the inherent randomness associated with quantum measurement, it does not fully address situations where uncertainty arises from incomplete information, measurement ambiguity, or experimental noise. The neutrosophic framework explicitly incorporates a third component, indeterminacy, alongside truth and falsity, enabling a more nuanced and multidimensional description of quantum states.

One of the key advantages of this framework lies in its ability to distinguish between randomness and indeterminacy. In practical quantum hardware, these two forms of uncertainty have distinct origins and implications. Randomness is intrinsic to quantum mechanics and is captured naturally by standard probability theory. Indeterminacy, on the other hand, arises from extrinsic factors such as environmental noise, control imperfections, calibration errors, and limitations of measurement devices. By treating these components separately, the neutrosophic representation provides a richer depiction of quantum states and operations, allowing researchers to identify and quantify the contributions of each source of uncertainty. For example, in superconducting qubits, a portion of observed measurement errors may be due to stochastic processes, while another portion may reflect indeterminate outcomes caused by partial decoherence or finite readout resolution. Conventional probability metrics would aggregate these effects into a single fidelity measure, potentially obscuring the underlying physics.

The framework also provides practical advantages for characterising noisy quantum hardware. Quantifying indeterminacy offers insight into the quality of control and measurement protocols, allowing experimentalists to identify specific operations or hardware components that contribute disproportionately to ambiguous outcomes. This information can be invaluable for targeted hardware improvements, calibration adjustments, and optimisation of gate operations. By explicitly separating falsity from indeterminacy, one can distinguish between systematic errors and ambiguous states, facilitating more precise error diagnostics and performance evaluation.

Furthermore, neutrosophic modelling has significant implications for quantum algorithm design and error mitigation strategies. In conventional error correction, the focus is primarily on stochastic errors. However, when indeterminate states are present, algorithms may fail in ways not predicted by standard probability-based models. Incorporating neutrosophic representations into the design and simulation of quantum circuits allows for uncertainty-aware optimisation, where both ambiguous and erroneous outcomes are considered. Such an approach could improve algorithmic robustness, guide the development of error-resilient circuits, and help allocate resources for measurement repetitions or gate calibration more efficiently.

Another promising avenue is the integration of neutrosophic modelling with quantum information measures. Entropy, mutual information, and coherence metrics are central to understanding quantum systems, but conventional formulations do not explicitly account for indeterminacy arising from incomplete knowledge. Extending these measures within a neutrosophic framework could provide a more comprehensive description of information flow, decoherence, and uncertainty propagation in complex quantum circuits. Similarly, neutrosophic formalism can be incorporated into quantum error correction protocols, enhancing their ability to distinguish between random errors and ambiguous states, potentially improving correction performance in near-term noisy devices.

From a broader perspective, the neutrosophic approach provides a conceptual bridge between theoretical quantum mechanics and experimental realities. It offers a systematic way to quantify uncertainty in systems where noise and partial information play critical roles, which is particularly relevant for noisy intermediate-scale quantum (NISQ) devices. As quantum hardware scales up, the cumulative effects of gate imperfections, decoherence, and readout ambiguity will become increasingly significant. Neutrosophic modelling provides a framework to anticipate and quantify these effects, informing both hardware development and algorithm design.

In brief, the neutrosophic representation enriches the existing quantum computational toolkit by providing a multidimensional, explicit characterisation of uncertainty. It complements standard probabilistic models, offering insights into measurement ambiguity, indeterminate outcomes, and error propagation that are not captured by conventional methods. Future research directions include systematic experimental validation, integration with quantum error correction protocols, extension to multi-qubit and hybrid quantum-classical systems, and development of neutrosophic metrics for quantum information measures. Collectively, these developments may contribute to more reliable, scalable, and uncertainty-aware quantum computation, bridging the gap between idealised theory and the realities of experimental quantum hardware.

6. Conclusion

This study has introduced a neutrosophic representation of quantum states and gates, extending conventional probabilistic models by explicitly incorporating indeterminacy alongside truth and falsity. This framework enables a multidimensional characterisation of uncertainty, distinguishing between stochastic randomness, ambiguous outcomes, and erroneous results. NQ provides a clear description of real-world qubit behaviour, while neutrosophic modelling of quantum gates allows tracking of uncertainty propagation in circuits, informing robust algorithm design and error mitigation strategies. By bridging theoretical quantum models and experimental realities, the framework supports diagnostics, hardware optimisation, and evaluation of noisy intermediate-scale quantum devices. Overall, neutrosophic modelling offers a practical, flexible approach to enhance reliability, scalability, and robustness in quantum computation.

Declaration

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Author(s) Bio

Muhammad Raza Sheikh from Department of Computer, University of Genova, Italy**.**
Email: sqarazasheikh@gmail.com