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QUANTUM COMPUTING IN THE NISQ ERA: EVALUATING THE PARADIGM SHIFT FROM CLASSICAL ARCHITECTURES TO FTQC

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Abstract: The transition from classical to quantum computation marks a shift from deterministic binary logic to a probabilistic, entanglement-driven framework able to address problems beyond classical reach. Today's Noisy Intermediate - Scale Quantum era features devices that lack full error correction yet already point toward larger, modular systems designed for fault-tolerant operation. This paper examines the evolving paradigm shift from classical and NISQ - era machines toward practical fault-tolerant quantum computing, focusing on how advances in physical qubit technologies, control architectures, and error-correction strategies are converging to bridge noisy prototypes and scalable, useful machines. We synthesize insights from historical semiconductor scaling trends, contemporary roadmaps from leading institutions and industry, and emerging modular designs with real-time error decoding. Our analysis shows that while challenges around decoherence, connectivity, and classical co-processing remain, coordinated progress in hardware, control, and software is laying a coherent foundation for future quantum platforms. The work concludes that quantum computing is maturing into a strategically significant paradigm, poised to redefine the limits of computation in simulation, optimization, and secure communication.

Keywords: FTQC, NISQ, Post-Moore computing, Computational paradigm shift, Quantum Error Correction, Quantum Roadmaps.

I. INTRODUCTION

For over fifty years, the rapid evolution of classical computing has been defined by the consistent miniaturization of CMOS transistors, a trajectory described by Moore's Law [1]. However, as these devices reach atomic scales, physical constraints such as heat dissipation and leakage currents have begun to stall this historical progress, necessitating a shift toward post-CMOS

paradigms [2]. Quantum computing has emerged as a leading candidate in this search, utilizing quantum mechanical phenomena—specifically superposition, entanglement, and interference—as fundamental computational resources [2], [3].

The theoretical promise of quantum computing lies in its ability to address problem classes that are intractable for classical architectures, such as the simulation of many-body quantum systems, complex optimization, and the cryptanalysis of modern encryption standards [4], [5]. These advantages stem from the ability of quantum states to evolve within exponentially large state spaces using significantly fewer physical resources than their classical counterparts [2], [6]. This potential for exponential speedup has catalyzed significant investment across both public and private sectors [3].

Currently, the field has transitioned from purely theoretical models to the "Noisy Intermediate-Scale Quantum" (NISQ) era [6], [7]. Despite this progress, a massive divide persists between today's experimental hardware and the realization of fault-tolerant machines [8], [9]. Contemporary systems are hindered by high error rates, restricted qubit connectivity, and immense control complexity, which generally limits their use to hybrid workflows or small-scale proofs-of-concept [6], [10].

To bridge this gap, industrial and academic roadmaps are now focusing on the engineering requirements for Large-Scale Fault-Tolerant Quantum Computing (LS-FTQC). Notable milestones include IBM's strategic vision for fault-tolerant systems [11] and Microsoft's development of the Majorana 1 processor, which utilizes topological qubits for inherently more stable computation [12]. Additionally, scaling breakthroughs such as QuantWare's VIO-40K™ aim to support up to 10,000 qubits [13]. These advancements in system-level integration and error correction—often involving evolutionary algorithms or deep learning—suggest that quantum hardware is maturing into a coherent platform [10], [14].

The societal implications of such systems are vast, ranging from accelerated drug discovery and materials science to logistics and finance [2], [5]. However, the same power that

enables scientific breakthroughs also poses a systemic threat to current public-key cryptographic infrastructures [4], [15]. This duality has intensified the global debate over whether quantum computing represents a genuine paradigm shift or an insurmountable engineering challenge [9], [3].

This paper argues that while NISQ-era prototypes are essential stepping stones, the true computational paradigm shift will be marked by the arrival of fault-tolerant architectures. The following analysis provides a techno-historical comparison between the evolution of the transistor and the quantum hardware trajectory [1], an assessment of current fault-tolerant roadmaps [11], [12], and an evaluation of the resource demands required for transformative algorithms like Shor's algorithm [15]. By synthesizing device-level progress with system-level implications, this work provides a framework for evaluating quantum computing as a transformative platform for the future of computation.

II. LITERATURE REVIEW

The contemporary landscape is characterized as the Noisy Intermediate-Scale Quantum (NISQ) era [6]. In this stage, processors operate with a limited number of physical qubits and are hindered by high gate error rates and a lack of full functional error correction [3], [7]. Consequently, current research heavily emphasizes Variational Quantum Algorithms (VQAs) and sophisticated error-mitigation strategies to facilitate short-depth circuits and hybrid classical-quantum workflows [6], [10]. While industrial progress shows steady improvements in coherence times and gate fidelities, these systems remain constrained by decoherence, crosstalk, and the immense complexity of quantum feedback control [9], [10].

The next critical technical milestone is the realization of Fault-Tolerant Quantum Computing (FTQC). This paradigm relies on the quantum threshold theorem and the implementation of quantum error-correction (QEC) codes, such as surface codes, to maintain computational fidelity over long durations [3], [14]. While FTQC requires substantial hardware overhead to encode logical qubits, major industrial roadmaps from leaders like IBM and Microsoft detail modular, scalable strategies to achieve this stability [11], [12]. Notably, Microsoft's Majorana 1 processor utilizes topological qubits to enhance inherent qubit stability [12], while QuantWare's VIO-40K™ architecture represents a breakthrough in managing the control requirements for up to 10,000 physical qubits [13]. The literature consistently underscores the profound algorithmic prospects of FTQC in fields such as quantum chemistry, complex optimization, and materials science [5]. Specifically, transformative algorithms such as Shor's algorithm—which poses a systemic risk to global public-key cryptographic standards—require the deep, error-corrected circuits that only a fault-tolerant system can provide [4], [15]. While recent discourse often treats

quantum computing as an established field, this paper uniquely evaluates whether the technology constitutes a true paradigm shift, arguing that the transition from noisy NISQ prototypes to fully fault-tolerant architectures marks the decisive turning point in computational history [8], [6].

III. PROPOSED STUDY

This study evaluates whether quantum computing constitutes a genuine paradigm shift by comparing classical, NISQ, and fault-tolerant architectures across three core dimensions: computational complexity, error handling, and resource requirements. The methodology employs a mixed-methods approach, combining a qualitative synthesis of published industrial roadmaps, national academy reports, and white papers with quantitative resource estimations for representative algorithms. The central hypothesis posits that the transition from NISQ to fault-tolerant quantum computing (FTQC)—rather than the NISQ era itself—marks the decisive turning point in the computational model.

The analysis begins by mapping the migration of specific problem classes from classical intractability within the P/NP framework toward potential tractability in BQP, drawing representative workloads from quantum chemistry, many-body physics, optimization, and cryptanalysis. Asymptotic complexity is compared against state-of-the-art classical methods using benchmarking frameworks that characterize both NISQ-circuit constraints and FTQC-scale resource estimates, highlighting how scaling behavior shifts fundamentally once full error correction is assumed. The methodology further distinguishes between the probabilistic error mitigation of the NISQ era—assessed through surveys of variational algorithms, gate fidelities, coherence times, and noise-aware compilation—and the systematic QEC required for FTQC, analyzed through surface code implementations and the quantum threshold theorem. This dual framing enables a direct comparison of the onset of practical advantage as computation moves from shallow, noisy circuits to deep, error-corrected ones.

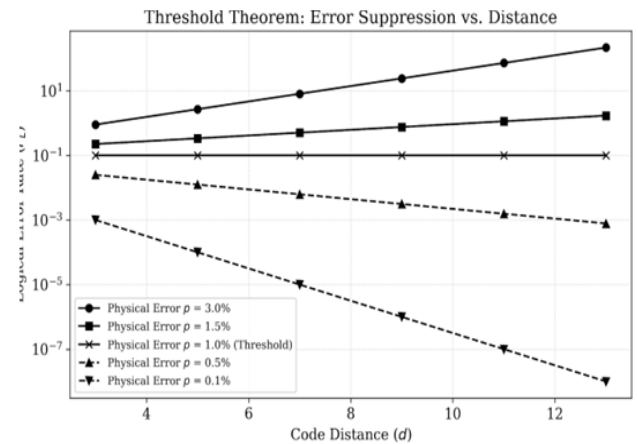


Fig. 1. Circuit fidelity in NISQ and FTQC architectures.

Figure 1 demonstrates the quantum threshold theorem, showing how code distance (d) affects logical error rates (ϵ_L) across physical error rates (ϵ_P). Above the threshold (e.g., 1.5%–3.0%), increasing distance raises errors; at or below it (e.g., 0.1%–1.0%), higher distance suppresses errors, fulfilling a core requirement for fault-tolerant quantum computing.

A critical quantitative step translates algorithmic complexity into hardware-level resource estimates by mapping logical-level characterizations onto standard FTQC architectures using error-correction codes and established device parameters, then instantiating those mappings against the concrete roadmap scenarios of IBM's large-scale fault-tolerant systems Microsoft's topological qubit approach via the Majorana 1 processor, and QuantWare's VIO-40K control architecture designed for 10,000-qubit processors. Comparing physical-qubit counts, connectivity constraints, and classical control demands identifies the threshold at which quantum systems cross into practical advantage.

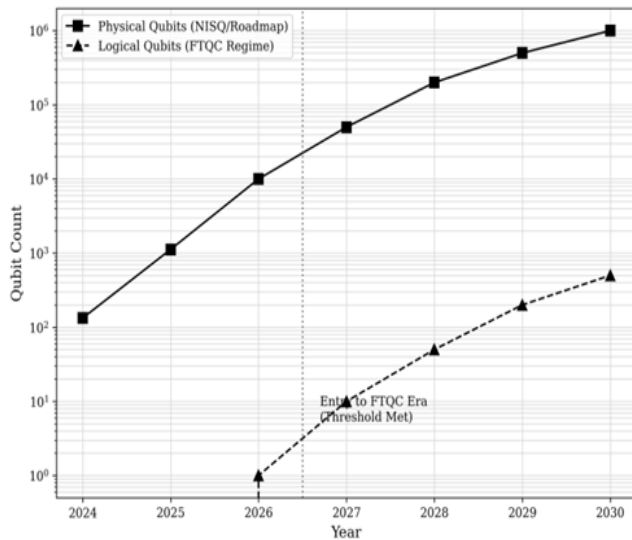


Fig. 2. Projected scaling of physical vs. logical qubits (2024–2030).

Figure 2 analyzes growth by projecting physical qubit counts against the logical qubits needed for fault tolerance. It illustrates the gap between NISQ-era roadmaps, focused on raw qubit increases, and the emerging FTQC regime, where logical scaling occurs as error-correction thresholds are met. This visualization highlights the significant hardware overhead and timeline necessary to transition from noisy processors to reliable, error-corrected logical platforms.

The final stage synthesizes techno-historical trends with roadmap-based scenarios to assess quantum computing's status as a paradigm shift. Conclusions are cross-validated against national academy reports and economic impact studies, with sensitivity analysis performed on critical

parameters such as error rates, qubit yields, and control overhead. This layered approach moves beyond capability-focused narratives to ground the claim that fault-tolerant architectures represent the true evolution of computational models.

IV. COMPARATIVE ANALYSIS OF THE COMPUTATIONAL PARADIGM SHIFT

The shift from Classical CMOS-based Computing to the NISQ era represents the first major break in the five-decade-long dominance of Moore's Law [1]. While classical systems are defined by near-perfect deterministic operations and binary logic, the current NISQ landscape introduces a probabilistic model where superposition and entanglement are used as active resources [2], [3]. In the NISQ era, variational algorithms like VQE and QAOA serve as heuristic benchmarks, though they are currently limited by high error rates and modest qubit counts [5], [6], [10]. As a result, NISQ-era demonstrations are largely confined to small problem instances or proof-of-concept benchmarks, with performance that often scales poorly as problem size increases and where noise rapidly degrades solution quality [9], [7].

In contrast, Fault-Tolerant Quantum Computing (FTQC) is expected to enable algorithms such as Shor's factoring and Grover's search to operate at scale, leveraging full error correction rather than heuristic mitigation [15], [3]. Under FTQC, Shor's algorithm can in principle break widely used public-key cryptosystems by exploiting exponential speedup, while Grover's algorithm provides a quadratic speedup for unstructured search [4]. However, both require deep circuits and high-fidelity operations that are only feasible with logical qubits protected by quantum error-correcting codes [14]. Recent analyses indicate that these speedups become practically meaningful only when the underlying hardware supports fault-tolerant operation, underscoring that the full algorithmic promise of quantum computing is tied to FTQC rather than NISQ [8], [6].

Table 1: Comparison Of Computing Paradigms

Feature	Classical (HPC)	NISQ (Current)	FTQC (Future)
Data Integrity	Very High	Low	High
Programming	Deterministic	Probabilistic	Algorithmic
Hardware	Mature	Noisy Devices	Scalable Architecture
Example	Modern GPC/CPU clusters used in high-performance computing.	Google Willow, IBM Heron	Planned systems with continuously active, fault tolerant operation.



Table 1 describes a comparison of CMOS, NISQ, and FTQC computing paradigms across data integrity, programming models, hardware, and applications, highlighting the evolution from classical deterministic systems to scalable fault-tolerant quantum computing. The transition from the Transistor Era to NISQ highlights a move from stable, macro-scale semiconductor switches to fragile, atomic-scale quantum states [1]. Current NISQ devices are characterized by modest qubit counts, limited connectivity, and relatively short coherence times, which collectively restrict the depth and size of executable circuits [2], [6]. Gate and measurement error rates, along with crosstalk and calibration drift, introduce noise that rapidly degrades circuit fidelity as depth increases, confining most NISQ applications to hybrid or heuristic roles where quantum processors act as co-processors rather than standalone computational engines [10], [7], [6].

Moving toward FTQC, architectures built around quantum error-correcting codes — such as surface codes and Steane-type codes — encode logical qubits into many physical qubits and perform continuous syndrome measurements and corrections [3], [14]. Experimental demonstrations on superconducting platforms have validated the threshold theorem, confirming that provided physical error rates lie below a critical threshold, arbitrarily long computations become feasible [3]. Roadmaps from IBM, Microsoft, and QuantWare emphasize modular, large-scale architectures integrating thousands of physical qubits and advanced control electronics, positioning FTQC as the regime in which quantum computing can deliver robust, repeatable performance [11], [12], [13].

The transition from the Noisy Intermediate-Scale Quantum (NISQ) era to Fault-Tolerant Quantum Computing (FTQC) represents a fundamental shift in computational capabilities. Regarding reliability, NISQ systems are inherently limited by noise and hardware imperfections, whereas FTQC utilizes systematic quantum error correction to ensure resilience and predictable behavior. Scalability also differentiates these paradigms: NISQ devices face severe constraints from increasing error rates and control complexity, while FTQC architectures leverage significant physical qubit overhead to achieve stable, logical performance. In terms of applicability, NISQ is primarily restricted to exploratory research and heuristic hybrid algorithms, whereas FTQC is projected to unlock transformative utility in quantum simulation, cryptanalysis, and large-scale optimization.

The progression from NISQ toward FTQC is fundamentally defined by engineering hurdles in scalability, error mitigation, and system-level integration [6], [8]. Contemporary NISQ architectures are characterized by significant decoherence, crosstalk, and high gate error rates, whereas fault tolerance necessitates a massive physical overhead, requiring thousands of noisy qubits to stabilize a single logical resource [3], [14]. Establishing large-scale

platforms relies on synchronized breakthroughs in qubit coherence, manufacturing precision, and modular architectures linked via high-fidelity quantum interconnects [11], [13]. Concurrently, quantum processors are maturing as specialized accelerators within hybrid quantum-classical frameworks, where classical co-processors orchestrate optimization routines and real-time syndrome decoding [10], [12]. Ultimately, the definitive computational paradigm shift will be driven not by isolated NISQ prototypes, but by the convergence of scalable, error-corrected logical qubits and distributed hybrid systems capable of delivering transformative industrial advantage [2], [9].

V. CONCLUSION

This research demonstrates that quantum computing represents a fundamental paradigm shift defined by a qualitatively different computational model — one grounded in the exploitation of superposition, entanglement, and interference as active resources rather than an incremental extension of classical CMOS scaling. The emerging hardware ecosystem, spanning superconducting, neutral-atom, and topological platforms, mirrors historical "device wars" while introducing entirely new constraints related to decoherence, quantum control, and error correction.

The findings confirm that NISQ-era devices remain critical for refining hybrid algorithms and error-mitigation techniques, yet fall far short of the logical-qubit counts required for cryptographically relevant factoring or large-scale industrial simulations. Error mitigation can partially bridge this gap but cannot substitute for genuine fault tolerance, as overheads grow unsustainably with system size. Industrial milestones from IBM, Microsoft, and QuantWare signal a credible trajectory toward integrated, scalable systems; however, resource-estimation studies and national-level assessments converge on the conclusion that practical utility demands millions of physical qubits and deeply integrated quantum-classical stacks.

In conclusion, the decisive turning point is not the existence of NISQ prototypes but the successful transition to fault-tolerant, error-corrected architectures — a shift that simultaneously unlocks transformative computational capability and poses systemic risks to existing cryptographic infrastructures. Future work must refine resource estimates under evolving hardware parameters and develop standardized metrics to track global progress toward a fully realized fault-tolerant quantum era.

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