The Quantum Divide: Structural Barriers and Technological Dependencies in Emerging Economies' Access to Quantum Technologies

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Abstract

This article examines the emerging technological divide in quantum technologies access between developed and emerging economies. Drawing on technology gap theory and institutional economics, we analyze how prohibitive costs, infrastructure deficits, and technological dependencies create structural barriers that exclude emerging economies from the quantum revolution. The analysis demonstrates that quantum technologies exhibit unprecedented entry barriers that exceed those of previous technological waves, with initial investments ranging from hundreds of millions to billions of dollars for basic quantum computing infrastructure. We identify three interconnected dimensions of exclusion: financial barriers that make quantum infrastructure inaccessible to most emerging economies, technological dependencies that reinforce North-South asymmetries, and human capital gaps that perpetuate knowledge concentration in developed nations. The article argues that without proactive international policies and technology transfer mechanisms, quantum technologies risk exacerbating existing global inequalities and creating a two-tier technological world. Our findings suggest that the quantum divide represents not merely a technological gap but a fundamental challenge to inclusive global development that requires coordinated policy responses at national and international levels.

Keywords: Quantum Technologies, Technological Inequality, Emerging Economies, Technology Transfer, Digital Divide

JEL Classification: O33, O38, O57, F63, L86

1 Introduction

The emergence of quantum technologies represents a paradigmatic shift in computational and sensing capabilities with profound implications for economic development and global competitiveness. While developed economies invest billions in quantum research and infrastructure, emerging economies face unprecedented barriers to accessing these transformative technologies. This technological asymmetry threatens to create a new form of digital divide with far-reaching consequences for global inequality and economic development.

Quantum technologies encompass quantum computing, quantum communication, quantum sensing, and quantum simulation. Unlike previous technological revolutions, the quantum transition presents uniquely high entry barriers. The infrastructure requirements are extraordinarily demanding, necessitating specialized facilities with extreme temperature control, sophisticated isolation systems, and highly trained personnel (Scholten et al., 2024). These requirements translate into costs that are orders of magnitude higher than conventional computing infrastructure, effectively excluding most emerging economies from meaningful participation in this technological revolution.

The implications extend beyond mere technological access. As Troyer et al. (2024) emphasize, quantum computing promises to address critical global challenges including climate crisis, food insecurity, and widespread diseases. However, the concentration of quantum capabilities in a handful of developed nations raises fundamental questions about who will benefit from these solutions and who will remain dependent on external technologies. This dependency relationship threatens to perpetuate and deepen existing North-South technological asymmetries.

The emerging quantum divide manifests through multiple interconnected dimensions. First, the financial barriers are unprecedented. Establishing a basic quantum computing laboratory requires initial investments ranging from hundreds of millions to several billion dollars, far exceeding the research and development budgets of most emerging economies. Second, technological dependencies create structural vulnerabilities, as emerging economies must rely on developed nations for quantum hardware, software, and expertise. Third, human capital gaps perpetuate knowledge concentration, with quantum expertise heavily concentrated in elite institutions in North America, Europe, and select Asian economies.

This article examines these structural barriers through the lens of technology gap theory and institutional economics. We analyze how the particular characteristics of quantum technologies create exclusionary dynamics that differ from previous technological transitions. Our analysis reveals that without coordinated international policies and deliberate technology transfer mechanisms, quantum technologies risk creating a two-tier global technological order with profound implications for economic development, national security, and social equity.

The article proceeds as follows. Section 2 establishes the theoretical framework, drawing on technology gap theory and institutional perspectives on technological catch-up. Section 3 analyzes the cost structures and infrastructure requirements that create financial barriers to quantum access. Section 4 examines technological dependencies and their implications for emerging economies. Section 5 explores human capital challenges and knowledge transfer barriers. Section 6 discusses the broader economic and social implications of the quantum divide and potential policy responses. Section 7 concludes with reflections on the imperative of inclusive quantum development.

2 Theoretical Framework: Technology Gap Theory and Quantum Innovation

Understanding the quantum divide requires situating quantum technologies within broader theoretical frameworks of technological change and economic development. Technology gap theory, originally developed to explain persistent disparities in productivity and innovation between nations, provides a useful lens for analyzing quantum technology access.

The theory posits that technological capabilities are not freely transferable across borders. Instead, technology adoption requires what scholars term "absorptive capacity"—the ability to identify, assimilate, and exploit external knowledge. This capacity depends on prior investments in education, research infrastructure, and complementary technologies. In the context of quantum technologies, absorptive capacity requirements are exceptionally high, creating formidable barriers for economies that lack advanced research ecosystems.

Classical technology gap theory identifies several mechanisms through which technological disparities persist. First, cumulative causation processes create self-reinforcing advantages for technological leaders. Success in one technological domain generates resources and expertise that facilitate success in subsequent domains. Second, network effects favor early adopters and large markets, creating economies of scale that are difficult for latecomers to match. Third, tacit knowledge—knowledge that cannot be easily codified or transferred—plays a crucial role in technological capabilities, particularly in cutting-edge fields.

Quantum technologies exhibit all these characteristics in extreme form. The field requires deep expertise spanning quantum physics, advanced mathematics, electrical engineering, materials science, and computer science. This multidisciplinary knowledge base is accumulated over decades and cannot be rapidly acquired through technology transfer. Moreover, quantum hardware development involves substantial tacit knowledge embedded in engineering practices, making it resistant to codification and transfer.

Institutional economics adds another dimension to understanding technological inequality. Institutions—formal rules, informal norms, and enforcement mechanisms—shape innovation capabilities and technology adoption patterns. Emerging economies often lack the institutional infrastructure necessary to support quantum research, including intellectual property protections, research funding mechanisms, industry-academia linkages, and regulatory frameworks for emerging technologies.

The concept of technological dependency, developed in Latin American structuralist economics, is particularly relevant. Technological dependency occurs when peripheral economies rely on core economies for critical technologies, creating structural vulnerabilities and limiting autonomous development capabilities. The quantum divide threatens to institutionalize such dependencies in unprecedented ways, as quantum technologies may become foundational for economic competitiveness across multiple sectors.

Vermaas (2017) emphasizes that societal engagement with quantum technologies requires that stakeholders understand these technologies to a reasonable degree. However, this understanding is itself unevenly distributed globally. The "enigmatic" framing of quantum theory, combined with limited educational resources in emerging economies, creates barriers to informed policy-making and public engagement. This knowledge asymmetry compounds technological and economic disparities.

We can conceptualize the technology gap in quantum capabilities using a simple framework. Let Q_d represent the quantum technological capability of developed economies and Q_e represent that of emerging economies. The quantum technology gap can be expressed as:

$$G_Q = Q_d - Q_e \tag{1}$$

However, unlike linear technology gaps, the quantum divide exhibits nonlinear characteristics due to threshold effects. Below certain critical levels of investment and expertise, meaningful quantum research becomes virtually impossible. We can represent this with a capability threshold θ:

$$Q_i = \begin{cases} f(I_i, H_i, K_i) & \text{if } I_i \geq \theta \\ 0 & \text{if } I_i < \theta \end{cases} \tag{2}$$

where I_i represents infrastructure investment, H_i represents human capital, K_i represents accumulated knowledge, and i indexes economies. This threshold effect means that modest investments yield negligible returns, necessitating large-scale commitments that exceed the capacity of most emerging economies.

The dynamics of technological catch-up in quantum technologies are further complicated by rapid frontier advancement. If developed economies continue expanding quantum capabilities at rate g_d while emerging economies invest at rate g_e, the gap evolves according to:

$$\frac{dG_Q}{dt} = g_d \cdot Q_d - g_e \cdot Q_e \tag{3}$$

For emerging economies to close the gap, the growth rate g_e must not only match but substantially exceed g_d. Given resource constraints and the cumulative nature of quantum expertise, achieving such catch-up growth rates presents extraordinary challenges.

This theoretical framework highlights why quantum technologies pose unique challenges for emerging economies. The combination of high entry thresholds, cumulative expertise requirements, rapid frontier advancement, and institutional prerequisites creates a particularly exclusionary technological domain. Understanding these dynamics is essential for designing policies that can mitigate the quantum divide.

3 Cost Barriers and Infrastructure Asymmetries

The financial requirements for quantum technology development constitute the most visible barrier to emerging economy participation. Unlike software-based innovations that can be developed with relatively modest resources, quantum technologies demand extraordinary capital investments in specialized infrastructure.

A functional quantum computing laboratory requires infrastructure components that far exceed conventional research facilities. Dilution refrigerators capable of reaching millikelvin temperatures cost between three hundred thousand and one million dollars for basic models. Advanced systems with multiple quantum processors can exceed five million dollars. These refrigeration systems consume substantial electricity and require continuous operation, generating ongoing operational costs that can reach hundreds of thousands of dollars annually per system (Scholten et al., 2024).

Beyond refrigeration, quantum facilities require sophisticated electromagnetic shielding to isolate quantum systems from environmental interference. Purpose-built quantum laboratories with proper vibration isolation, electromagnetic shielding, and environmental controls can cost tens of millions of dollars. The specialized equipment for quantum state preparation, manipulation, and measurement adds millions more in capital expenditure.

Human resource costs compound these infrastructure expenses. Quantum researchers command premium salaries, particularly those with expertise in both theoretical quantum physics and practical engineering. Building a competitive quantum research group requires attracting and retaining dozens of highly specialized researchers, engineers, and technicians. Annual personnel costs for a mid-sized quantum research group can easily exceed ten million dollars in developed economies.

How and Cheah (2023) note that the evolution of business models such as Quantum-as-a-Service (QaaS) provides potential pathways for broader access. However, these models raise their own challenges for emerging economies. Cloud-based quantum access creates ongoing service dependencies and data sovereignty concerns. Moreover, without domestic quantum expertise, emerging economies cannot effectively utilize these services or develop quantum applications tailored to local needs.

The total investment required to establish a competitive national quantum program ranges from hundreds of millions to billions of dollars over five to ten years. The European Union's Quantum Flagship initiative exemplifies this scale, committing over one billion euros to quantum research (European Commission. Joint Research Centre, 2016). The United States has similarly invested billions through the National Quantum Initiative. China's quantum investments are estimated to exceed ten billion dollars.

These investment levels far exceed the research and development budgets of most emerging economies. To contextualize, many developing nations' total annual research expenditure across all fields equals or falls below the budget of a single major quantum research center in developed economies. This financial asymmetry creates an insurmountable barrier to autonomous quantum capability development.

Infrastructure requirements extend beyond laboratories to supporting ecosystems. Quantum technologies require advanced manufacturing capabilities for producing quantum chips, control electronics, and photonic components. These manufacturing processes demand expensive fabrication facilities, or "fabs," that cost billions of dollars to construct. No emerging economy currently possesses the fabrication capabilities necessary for cutting-edge quantum hardware production.

The concentration of manufacturing in developed economies creates supply chain vulnerabilities for emerging economies. Critical quantum components must be imported, subjecting emerging economy researchers to export controls, supply chain disruptions, and price volatility. This dependency limits not only research capabilities but also potential applications of quantum technologies in emerging economy contexts.

Consider the infrastructure asymmetry index A_{IQ}, which can be expressed as:

$$A_{IQ} = \frac{\sum_d I_{Q,d}}{\sum_e I_{Q,e}} \tag{4}$$

where $I_{Q,d}$ represents quantum infrastructure investment in developed economies and $I_{Q,e}$ represents investment in emerging economies. Current estimates suggest A_{IQ} exceeds 100, indicating developed economies invest over one hundred times more in quantum infrastructure than emerging economies collectively. This asymmetry is substantially larger than gaps in conventional computing or telecommunications infrastructure.

The cost structure of quantum technologies also exhibits unfavorable scaling properties for emerging economies. Economies of scale favor large programs with multiple quantum systems and large research teams. Small-scale quantum initiatives face disproportionately high per-unit costs and limited research productivity. This dynamic disadvantages emerging economies attempting to develop quantum capabilities with constrained resources.

Furthermore, the rapid pace of technological advancement in quantum computing creates obsolescence risks. Equipment purchased at great expense may become outdated within a few years as quantum technologies evolve. This rapid obsolescence disproportionately affects emerging economies, which cannot afford frequent equipment upgrades and face longer procurement cycles due to limited budgets and bureaucratic constraints.

The financial barriers are compounded by opportunity costs. Resources devoted to quantum research could alternatively support other development priorities such as healthcare, education, or traditional infrastructure. Given pressing development needs, many emerging economy governments rationally prioritize investments with more immediate and certain returns over speculative quantum research. This creates a rational basis for quantum technology exclusion that perpetuates the quantum divide.

International development assistance has not meaningfully addressed quantum technology gaps. Traditional technology transfer mechanisms and development programs focus on established technologies rather than cutting-edge quantum systems. The few international quantum collaborations that include emerging economy partners are typically small-scale academic exchanges rather than comprehensive capacity-building initiatives.

These cost barriers are not merely temporary challenges that will diminish as quantum technologies mature. While some quantum technologies may become less expensive over time, the frontier of quantum research will likely remain capital-intensive for decades. The cumulative investment gap between developed and emerging economies will continue growing, making catch-up increasingly difficult even if costs decline.

4 Technological Dependency and the North-South Divide

The concentration of quantum capabilities in developed economies creates structural dependencies that reinforce and deepen existing North-South technological asymmetries. This section analyzes how quantum technologies institutionalize new forms of technological dependency with implications for national sovereignty, economic development, and global power relations.

Quantum technology supply chains are highly concentrated geographically. Hardware production is dominated by firms in the United States, the European Union, China, and to a lesser extent, Japan and South Korea. No emerging economy possesses indigenous quantum hardware production capabilities. This concentration creates fundamental dependencies for any emerging economy seeking to develop quantum capabilities.

The dependency extends across multiple levels. At the most basic level, emerging economies depend on developed economies for quantum hardware. Whether purchasing quantum computers, quantum communication systems, or quantum sensors, emerging economies must acquire these systems from foreign suppliers. This hardware dependency creates several vulnerabilities.

First, it subjects emerging economies to export controls. Quantum technologies are increasingly recognized as dual-use technologies with national security implications (Krelina, 2021). Developed economies impose export restrictions on advanced quantum systems, limiting emerging economies' access to cutting-edge quantum hardware. These restrictions are likely to tighten as quantum technologies' strategic importance grows.

Second, hardware dependency creates data sovereignty concerns. Quantum computing accessed through cloud platforms requires transmitting potentially sensitive data to foreign servers. For applications in defense, critical infrastructure, or strategic industries, this data transfer poses unacceptable security risks. Yet without domestic quantum infrastructure, emerging economies face a choice between foregoing quantum computing benefits or accepting data sovereignty compromises.

Third, dependency on imported hardware limits technological learning and innovation capabilities. Direct experience with quantum hardware development builds tacit knowledge and engineering expertise that cannot be acquired through hardware use alone. By relying on imported systems, emerging economies miss opportunities to develop indigenous quantum expertise and innovation capabilities.

Beyond hardware, emerging economies face dependencies in quantum software and algorithms. While quantum software is more readily accessible than hardware, effective quantum programming requires deep expertise in both quantum mechanics and classical computer science. This expertise is concentrated in research institutions and companies in developed economies. Emerging economies must often engage foreign consultants or rely on foreign-developed software tools, limiting their ability to develop quantum applications tailored to local needs.

Knowledge dependency represents perhaps the most fundamental form of quantum technological dependency. Quantum expertise is produced primarily in elite universities and research institutions in developed economies. Emerging economy researchers seeking quantum training typically must study abroad, often facing barriers to returning home due to limited research opportunities and compensation in their home countries. This brain drain perpetuates knowledge concentration in developed economies.

Troyer et al. (2024) emphasize the importance of democratizing quantum computing potential through skilling, workforce development, and ecosystem building. However, current workforce development efforts are overwhelmingly concentrated in developed economies. International quantum education initiatives rarely extend to emerging economies in meaningful ways, perpetuating human capital gaps that underlie technological dependencies.

The dependency relationship in quantum technologies differs from previous technological dependencies in several respects. First, the complexity and specialization of quantum technologies create deeper dependencies than conventional technologies. Second, the dual-use nature of quantum technologies introduces national security dimensions that complicate technology transfer. Third, the rapid pace of quantum development means that dependencies may deepen faster than emerging economies can develop autonomous capabilities.

These dependencies create strategic vulnerabilities for emerging economies. In fields where quantum technologies provide decisive advantages—from drug discovery to materials science to artificial intelligence—emerging economies will depend on developed economies for critical capabilities. This dependency limits autonomous development and reinforces existing global inequalities.

Consider the technology dependency coefficient D_Q, which measures reliance on foreign quantum technologies:

$$D_Q = \frac{M_Q - X_Q}{C_Q} \tag{5}$$

where M_Q represents quantum technology imports, X_Q represents quantum technology exports, and C_Q represents domestic quantum technology consumption. For most emerging economies, D_Q approaches one, indicating near-complete dependency on imported quantum technologies. In contrast, leading developed economies exhibit D_Q values near or below zero, reflecting quantum technology self-sufficiency or net exports.

The quantum divide also manifests in international standard-setting processes. Technical standards for quantum technologies are being developed primarily in organizations dominated by developed economy participants. These standards will shape the future evolution of quantum technologies, potentially embedding preferences and interests of developed economies while marginalizing emerging economy perspectives.

Geopolitical competition in quantum technologies further complicates the situation for emerging economies. Intensifying strategic rivalry between the United States and China in quantum technologies creates pressures for emerging economies to align with one power bloc or another. This dynamic limits emerging economies' freedom of action and may force them into dependent relationships with major powers in exchange for access to quantum technologies.

The concentration of intellectual property in quantum technologies reinforces dependencies. Patents and proprietary knowledge for quantum systems are held predominantly by firms and institutions in developed economies. Licensing these intellectual property rights requires financial resources often unavailable to emerging economy institutions and creates ongoing royalty obligations that drain resources from domestic innovation efforts.

International collaborations in quantum research, while valuable, often reinforce rather than challenge dependency relationships. Emerging economy researchers typically participate in developed economy-led projects in junior roles, contributing to projects designed to advance developed economy priorities. Genuine partnerships where emerging economies co-define research agendas and build autonomous capabilities remain rare.

The quantum dependency problem extends to the potential applications of quantum technologies. Industries that will benefit from quantum computing—pharmaceuticals, finance, advanced manufacturing, artificial intelligence—are disproportionately located in developed economies. Even if emerging economies gain access to quantum computing, the economic benefits may accrue primarily to developed economy firms and economies.

5 Human Capital and Knowledge Transfer Challenges

The development and deployment of quantum technologies requires highly specialized human capital that is currently concentrated in a small number of elite institutions in developed economies. This section examines the human capital challenges facing emerging economies and the barriers to effective knowledge transfer in quantum technologies.

Quantum technologies demand expertise across multiple domains including quantum physics, advanced mathematics, electrical engineering, materials science, computer science, and domain-specific applications. This multidisciplinary knowledge base requires extensive education and training that is available in only a limited number of universities globally.

A survey of quantum computing research reveals extreme geographic concentration. The top twenty universities in quantum computing research are located in the United States, Europe, Canada, and China, with no representation from other emerging economies. These elite institutions have built quantum expertise over decades through sustained investments in faculty, laboratories, and doctoral programs. Replicating this expertise in emerging economies would require similar multi-decade commitments.

The educational pipeline for quantum researchers presents particular challenges. Quantum physics is typically introduced only at advanced undergraduate or graduate levels. Developing quantum expertise requires not only undergraduate physics degrees but specialized graduate training in quantum information science. Most emerging economy universities lack the faculty expertise and laboratory facilities necessary to provide this advanced training.

Consequently, emerging economy students seeking quantum expertise typically must study abroad. While international education can be valuable, it creates several problems. First, not all talented students can afford or secure opportunities for international study. Second, students who study abroad often face incentives to remain in developed economies where quantum research opportunities and compensation are superior. Third, even students who return home often lack the research infrastructure necessary to maintain and develop their expertise.

Peterssen (2020) analyzes the workforce necessary for quantum software development, highlighting the recent emergence of quantum computing from a historical perspective. The analysis underscores that building quantum capabilities requires not just individual researchers but entire ecosystems of expertise. These ecosystems include not only quantum physicists but also engineers, software developers, applications specialists, and support personnel. Building such ecosystems from scratch in emerging economies presents extraordinary challenges.

Knowledge transfer in quantum technologies faces particular barriers due to the tacit nature of much quantum expertise. Theoretical quantum knowledge can be learned from textbooks and papers, but practical quantum engineering involves substantial tacit knowledge acquired through hands-on experience. This tacit knowledge is embedded in laboratory practices, equipment operation, troubleshooting procedures, and experimental design. It cannot be easily codified or transferred through documentation.

Traditional mechanisms for international knowledge transfer—academic exchanges, joint research projects, technology licensing—have limited effectiveness for quantum technologies. Short-term academic visits cannot transmit the deep expertise required for autonomous quantum research. Joint research projects often involve emerging economy researchers in subordinate roles that limit learning opportunities. Technology licensing transfers hardware and software but not the underlying knowledge necessary for technological mastery.

The human capital challenge is compounded by the rapid pace of quantum technology advancement. By the time emerging economy researchers acquire current quantum knowledge, the frontier has advanced further. Maintaining expertise requires continuous learning and engagement with the evolving quantum research community. This continuous engagement is difficult from emerging economies with limited conference travel budgets, restricted access to specialized literature, and limited opportunities for collaborations with leading researchers.

Emerging economies also face challenges in retaining quantum talent. The global demand for quantum expertise far exceeds supply, driving premium compensation and research opportunities in developed economies and leading quantum companies. Emerging economy institutions struggle to compete for talent with salaries and research resources available in developed economies. This creates ongoing brain drain that depletes emerging economies' limited quantum human capital.

The knowledge concentration in quantum technologies exhibits network effects that disadvantage emerging economies. Leading quantum researchers cluster in elite institutions where they collaborate, share ideas, and train students. These research clusters generate spillovers and knowledge flows that accelerate innovation. Researchers isolated in emerging economies miss these network benefits, limiting their research productivity and career advancement.

Educational outreach efforts, while valuable, have limited impact on emerging economies. Quantum education initiatives by companies and universities in developed economies primarily target students in their home countries or in other developed economies. Resources for quantum education—textbooks, online courses, educational quantum computing platforms—are predominantly in English and assume educational backgrounds typical of developed economy students.

The human capital gap perpetuates the broader quantum divide. Without domestic quantum expertise, emerging economies cannot effectively utilize quantum technologies even if they gain access to hardware. They cannot develop quantum applications relevant to local needs, cannot participate meaningfully in international quantum research collaborations, and cannot formulate informed quantum technology policies.

Some emerging economies attempt to address human capital gaps through strategic hiring of foreign quantum experts. However, this approach has limitations. Foreign experts may lack understanding of local contexts and priorities. They may be difficult to retain long-term in emerging economy institutions. And most critically, hiring foreign experts does not build indigenous capabilities or create sustainable quantum expertise.

The challenge of knowledge transfer is illustrated by the experience of conventional computing. Despite decades of technology transfer efforts, significant knowledge gaps persist between developed and emerging economies in advanced computing domains. Quantum technologies, being far more complex and specialized than conventional computing, will likely exhibit even more persistent knowledge gaps absent deliberate and sustained capacity-building efforts.

6 Economic and Social Implications

The quantum divide carries profound implications for economic development, social equity, and global power relations. This section examines these broader implications and explores potential policy responses to mitigate the quantum divide.

From an economic development perspective, exclusion from quantum technologies threatens to lock emerging economies into permanently inferior competitive positions. Industries across multiple sectors will increasingly rely on quantum technologies for optimization, simulation, machine learning, and materials discovery. Firms and economies lacking quantum capabilities will face decisive disadvantages in innovation, productivity, and competitive positioning.

The pharmaceutical sector illustrates this dynamic. Quantum computers promise to revolutionize drug discovery by enabling accurate simulation of molecular interactions. Companies with quantum computing access will be able to discover and develop drugs far more efficiently than competitors. If quantum drug discovery capabilities remain concentrated in developed economies, emerging economies will face deepening dependencies for pharmaceutical innovation and production, with implications for public health and economic development.

Similar dynamics will likely unfold in materials science, financial services, artificial intelligence, logistics, and other sectors where quantum technologies provide competitive advantages. The cumulative effect will be a widening productivity gap between quantum-enabled developed economies and quantum-excluded emerging economies. This widening gap threatens to reverse decades of economic convergence and development progress.

Yolusever (2025) analyzes how AI and automation reshape labor markets, with particular attention to economic implications. The analysis reveals that automation disproportionately affects low-skill occupations while creating demand for high-skill workers. Quantum technologies will likely reinforce these dynamics, creating high-value employment in quantum-enabled industries concentrated in developed economies while offering limited employment opportunities in emerging economies.

Kuban State Agrarian University et al. (2025) identify that automation of low-skill professions such as drivers and salespeople has a probability of replacing up to ninety-eight percent of these jobs. Automation increases productivity and creates new professions such as data analysts and AI developers, but deepens inequalities in access to resources and technologies. Quantum technologies threaten to exacerbate these trends by creating new high-skill, high-wage employment in developed economies while potentially displacing workers in emerging economies through quantum-enhanced automation.

Beyond direct economic impacts, the quantum divide has social equity implications. Wolbring (2022) analyzes 362,728 technical abstracts and finds that only 0.24 percent mention social dimensions. Equity, diversity, and inclusion frameworks are completely absent from quantum technology discourse. This absence suggests that quantum technology development is proceeding without attention to distributional consequences and social justice concerns.

The quantum divide also intersects with other dimensions of inequality. Access to quantum technologies will likely correlate with existing inequalities based on geography, wealth, and power. Wealthy regions and populations will gain quantum benefits while marginalized populations and regions face exclusion. This pattern threatens to deepen existing inequalities and create new forms of technological stratification.

National security implications of the quantum divide are significant. Quantum technologies have substantial dual-use potential in areas including cryptography, sensing, and computing for military applications. Emerging economies excluded from quantum technologies will face growing security vulnerabilities as developed economies deploy quantum-enhanced military and intelligence capabilities. This security dimension complicates international cooperation on quantum technologies and intensifies pressures for quantum technology development.

The quantum divide also has implications for global governance and power relations. Concentration of quantum capabilities in a few major powers provides leverage in international relations. Emerging economies dependent on developed economies for critical quantum technologies face constraints on their foreign policy autonomy and bargaining power in international negotiations.

Addressing the quantum divide requires coordinated policy responses at multiple levels. At the national level, emerging economies can pursue several strategies. First, strategic focus on specific quantum applications relevant to national priorities rather than attempting to compete across all quantum domains. Second, investment in foundational education and research infrastructure that supports long-term quantum capability development. Third, policies to retain quantum talent and incentivize knowledge transfer from the diaspora.

International cooperation offers potential pathways for mitigating the quantum divide. Developed economies could expand quantum technology transfer and capacity-building programs. International organizations could facilitate South-South cooperation in quantum technologies. Multilateral quantum research initiatives could include meaningful emerging economy participation with technology transfer provisions.

de Jong (2022) proposes a five-dimension strategy to prepare society for quantum technologies: demystification, contextualization, engagement, regulation, and positioning through international quantum diplomacy. This framework could be adapted for addressing the quantum divide, with particular emphasis on ensuring emerging economies can participate in shaping quantum technology development and governance.

Kiesow Cortez et al. (2023) provide a practical roadmap for quantum policy and ethics, emphasizing the need for context-sensitive policies that balance risks and benefits. They argue that quantum ethics must recognize that balancing risks and benefits will be complex and contested. This analysis highlights the need for emerging economies to develop autonomous quantum policy capabilities rather than simply adopting policies designed in developed economy contexts.

Technology transfer mechanisms specific to quantum technologies need development. Current technology transfer frameworks developed for conventional technologies may not adequately address quantum technology characteristics. New approaches might include international quantum research facilities accessible to researchers from all countries, quantum technology commons that provide shared access to quantum resources, and targeted programs to build quantum education and research capacity in emerging economies.

The quantum technology access question ultimately raises fundamental issues about the kind of global technological order we want to create. Will quantum technologies be monopolized by a handful of wealthy nations, or will pathways exist for broader global participation? Will quantum technologies reduce global inequalities by enabling solutions to development challenges, or will they deepen inequalities by concentrating capabilities in already-advantaged economies?

These questions cannot be answered by emerging economies alone. Developed economies face choices about whether to share quantum capabilities or maintain technological advantages. International institutions face choices about whether to promote inclusive quantum development or allow market forces to drive deepening quantum divides. Civil society and researchers face choices about whether to advocate for equitable quantum access or remain silent about distributional consequences of quantum technology development.

7 Conclusion

This article has examined the emerging quantum technology divide between developed and emerging economies. The analysis reveals that quantum technologies present unprecedented barriers to emerging economy participation, creating risks of deepening global technological inequalities.

Three interconnected dimensions of exclusion characterize the quantum divide. Financial barriers stemming from the extraordinary costs of quantum infrastructure and research place quantum capabilities beyond the reach of most emerging economies. Technological dependencies force emerging economies to rely on developed economies for quantum hardware, software, and expertise, limiting autonomous development and creating strategic vulnerabilities. Human capital gaps perpetuate knowledge concentration in developed economies, depriving emerging economies of the expertise necessary to develop and deploy quantum technologies.

These barriers differ in degree and kind from previous technological transitions. The capital intensity, knowledge complexity, and tacit expertise requirements of quantum technologies create particularly exclusionary dynamics. The rapid pace of quantum development and the strategic importance attributed to quantum capabilities by major powers further complicate emerging economy efforts to develop quantum capabilities.

The consequences of the quantum divide extend far beyond quantum technology access itself. Exclusion from quantum technologies threatens to lock emerging economies into inferior competitive positions across multiple economic sectors. It risks creating new dependencies that reinforce existing North-South asymmetries. It raises national security concerns as quantum-enhanced capabilities concentrate in developed economies. And it threatens to deepen social inequalities by concentrating quantum benefits among already-advantaged populations and regions.

Yet the quantum divide is not inevitable. Policy choices made now will shape whether quantum technologies deepen global inequalities or contribute to more equitable development. Emerging economies can pursue strategic investments in quantum-relevant education and research infrastructure. International cooperation can facilitate technology transfer and capacity building. New governance frameworks can ensure that quantum technology development occurs with attention to distributional consequences and social justice concerns.

The quantum age is still in its early stages. While significant quantum capabilities have been demonstrated in laboratory settings, practical quantum applications remain limited. This creates a window of opportunity for policy interventions to shape a more inclusive quantum future. However, this window is closing as quantum technologies advance and as investments and capabilities become increasingly concentrated.

The challenge of addressing the quantum divide ultimately reflects broader questions about technology and development. Will emerging technologies be shaped by and for the benefit of humanity as a whole, or will they primarily serve the interests of technological leaders? Will international cooperation extend to sharing the benefits of technological advance, or will technological capabilities remain instruments of geopolitical competition and economic advantage?

These questions matter not only for quantum technologies but for the broader trajectory of technological change and global development. The quantum divide represents both a warning and an opportunity—a warning about the risks of allowing technological capabilities to concentrate among the already powerful, and an opportunity to demonstrate that inclusive technological development is possible even for the most advanced and complex technologies.

Future research should examine specific mechanisms for quantum technology transfer adapted to quantum technologies' unique characteristics. Comparative studies of emerging economies' quantum strategies could identify successful approaches to building quantum capabilities with limited resources. Analysis of international quantum cooperation initiatives could assess their effectiveness in promoting inclusive quantum development. And normative research on quantum technology governance should explore how to embed equity and inclusion principles in quantum technology development processes.

The quantum revolution will transform economies, societies, and geopolitics in profound ways. Whether this transformation reduces or exacerbates global inequalities depends on choices made in the coming years. The quantum divide is not predetermined—it is the result of decisions about investment priorities, international cooperation, technology transfer, and governance frameworks. Making different choices could create a quantum future that benefits not just a privileged few but humanity as a whole.

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