Layered Appropriability Strategies in Quantum Software Ecosystems: A Game-Theoretic Analysis of Vertical Integration versus Modular Open Licensing

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Abstract

This paper examines the strategic choices firms face when selecting appropriability mechanisms across different layers of quantum software stacks. Unlike classical computing, quantum software development involves distinct architectural layers with varying degrees of commoditization potential and network effects. Using a game-theoretic framework grounded in collective action theory, we analyze how firms decide between proprietary licensing and open source strategies at the hardware abstraction layer versus the application framework layer. Our analysis reveals that vertical integration incentives diminish when lower-layer standardization occurs through collaborative open licensing, while application-layer firms benefit from maintaining proprietary control. The model demonstrates how coordination failures can lead to fragmentation in the absence of credible commitment mechanisms. We find that hybrid appropriability strategies emerge as equilibrium outcomes when firms face trade-offs between immediate revenue capture and ecosystem development. These findings contribute to understanding innovation appropriability in emerging quantum computing markets and inform policy discussions about standard-setting in dual-use technologies.

Keywords: quantum software, appropriability strategies, open source licensing, game theory, innovation ecosystems

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1 Introduction

The emergence of quantum computing as a commercially viable technology has created novel strategic considerations for firms developing software infrastructure. The quantum computing industry has identified 24 distinct industrial use cases spanning automotive, chemical, pharmaceutical, and insurance sectors (Quantum Technology and Application Consortium – QUTAC, 2021), demonstrating the broad economic potential of this technology. Unlike classical computing, where architectural layers evolved organically over decades, quantum software ecosystems face simultaneous development across multiple interdependent layers. This compression of evolutionary timescales forces firms to make appropriability decisions with imperfect information about both technological trajectories and competitive dynamics.

Recent applications demonstrate quantum computing's practical potential in optimization problems critical for business operations (Ajagekar and You, 2019; Borysiuk and Michuta, 2025). Quantum algorithms have been successfully applied to energy systems optimization, workforce task scheduling, and financial portfolio management (Herman et al., 2022; Takeori et al., 2024). However, the translation of these capabilities into commercial value requires coordinated development across multiple software layers, from hardware abstraction interfaces to domain-specific application frameworks.

This paper develops a game-theoretic analysis of appropriability strategies specifically tailored to quantum software ecosystems. We focus on the strategic interaction between firms operating at different layers of the software stack: hardware abstraction layers that mediate between quantum processors and higher-level programming constructs, and application frameworks that enable domain-specific algorithm development. Our central question is: under what conditions do firms choose open source versus proprietary licensing at each layer, and how do these choices interact strategically?

The analysis draws on cooperative game theory frameworks (Gilles, 2010) and collective action theory (Holahan and Lubell, 2016) to model coordination challenges in ecosystem development. Collective action theory provides insights into how firms overcome coordination failures when joint action would yield superior outcomes but individual incentives discourage cooperation. This framework is particularly relevant for quantum software, where standardization benefits all participants but requires coordinated commitments that individual firms may be reluctant to make unilaterally.

The societal implications of quantum computing extend beyond purely technical considerations. Research reveals significant gaps in addressing social dimensions of quantum technologies, with less than 0.24% of technical abstracts mentioning social considerations and complete absence of equity, diversity, and inclusion frameworks (Wolbring, 2022). This suggests that appropriability strategies must be examined not only for their economic efficiency but also for their implications for equitable access and inclusive innovation.

The strategic environment for quantum software differs fundamentally from classical software in several respects. First, quantum computing requires deep co-design between software and hardware layers due to physical constraints on quantum coherence and error rates. Second, the scarcity of quantum computing expertise creates pronounced network effects around standardized interfaces. Third, the dual-use nature of quantum technologies raises governance considerations that influence appropriability choices (de Jong, 2022). Fourth, the integration of quantum computing into business analytics and decision-making systems creates path dependencies that may lock users into particular software ecosystems (Mudhol, 2024).

Our theoretical framework incorporates three critical features of quantum software markets. First, we model the sequential nature of value creation across layers, where lower-layer standardization generates positive externalities for higher-layer development. Second, we account for the role of complementary assets, particularly specialized human capital and domain expertise, in determining appropriability. Third, we analyze coordination challenges when multiple firms must simultaneously decide on licensing strategies without perfect information about competitors' choices.

The paper contributes to several literatures. We extend game-theoretic analyses of technology adoption and innovation systems by incorporating the vertical structure of technology stacks and the dynamics of emerging ecosystems. We build on research examining appropriability in complex product systems by analyzing how modularity and interdependence shape licensing strategies. Additionally, we contribute to the nascent literature on quantum computing economics by providing formal models of strategic behavior in this domain.

The remainder of this paper proceeds as follows. Section 2 reviews relevant literature on software appropriability, innovation ecosystems, and quantum computing applications. Section 3 develops our theoretical framework, establishing the basic structure of the quantum software stack and the strategic environment facing firms. Section 4 presents our game-theoretic model and derives equilibrium predictions. Section 5 discusses strategic implications for firms and policymakers. Section 6 examines empirical patterns consistent with our theoretical predictions. Section 7 concludes with implications for future research and policy development.

2 Literature Review

The economics of innovation appropriability has evolved considerably as information technologies have transformed from standalone products to interconnected ecosystems. Traditional analyses emphasized formal intellectual property protection mechanisms, but contemporary research recognizes diverse appropriability strategies including open source licensing, platform governance, and ecosystem orchestration. Understanding appropriability in quantum software requires synthesizing insights from multiple research streams.

The application of game theory to innovation policy provides foundational insights for our analysis. Saleem and Higuchi (2014) develop game-theoretic models of government-university interactions in technology adoption, demonstrating that autonomous regulatory bodies can promote innovation and technology diffusion. Their framework shows how strategic interactions between institutional actors shape technology trajectories, with implications for quantum computing ecosystem development. The model identifies equilibrium conditions under which preferential policies lead to quality education that fosters economic development.

Collective action theory offers crucial insights into coordination challenges in technology ecosystems. Holahan and Lubell (2016) analyze how governance arrangements resolve collective action dilemmas by creating institutional frameworks that redefine payoffs and encourage cooperation. Their analysis distinguishes between top-down mandates and bottom-up self-organization, with implications for standard-setting in quantum software. Effective governance requires institutional frameworks that positively alter cooperation payoffs and facilitate monitoring and enforcement, particularly relevant when multiple firms must coordinate on technical standards.

Cooperative game theory provides analytical tools for understanding coalition formation and value distribution in collaborative innovation. Gilles (2010) present frameworks for analyzing networks and hierarchies in cooperative settings, offering insights into how firms might organize collaborative standardization efforts while maintaining competitive differentiation. This framework helps explain when firms prefer proprietary competition versus cooperative standard development in quantum software layers.

The industrial applications of quantum computing reveal diverse use cases that create different appropriability incentives. Quantum Technology and Application Consortium – QUTAC (2021) identify 24 distinct industrial applications through a consortium representing major industries, proposing an application-centric approach to commercialization based on demonstrated business impact. This diversity suggests that optimal appropriability strategies may vary across application domains, with some favoring open platforms and others supporting proprietary specialization.

Quantum computing has demonstrated practical capabilities in optimization problems critical for economic operations. Ajagekar and You (2019) analyze quantum algorithms for energy systems optimization, comparing performance against classical approaches and describing trade-offs between quantum architectures. Their findings suggest that quantum advantage depends on problem structure and hardware capabilities, creating uncertainty about which software layers will sustain competitive differentiation. Borysiuk and Michuta (2025) explore quantum optimization algorithms for logistics, finance, and resource management, demonstrating significant computational acceleration through quantum parallelism and superposition.

The integration of quantum computing into business analytics creates new appropriability considerations. Mudhol (2024) examine opportunities and challenges in business analytics integration, noting that quantum computing offers enhanced data processing capabilities and advanced algorithms for complex optimization problems. However, technical limitations, cost, and integration challenges remain significant barriers. These barriers may influence whether firms pursue proprietary integration approaches or collaborate on open standards to reduce collective adoption costs.

The financial services sector represents a particularly promising application domain for quantum computing. Herman et al. (2022) provide a comprehensive survey of quantum computing applications in finance, identifying specific problem classes where quantum algorithms offer theoretical advantages. The survey reveals that financial institutions face strategic decisions about whether to develop proprietary quantum capabilities or rely on platform providers, with implications for software layer appropriability.

Practical implementations demonstrate quantum computing's viability for industrial scheduling problems. Takeori et al. (2024) utilize IBM quantum devices with 127 qubits to manage workforce task scheduling involving hundreds of decision variables and thousands of constraints. This proof-of-concept demonstrates practical quantum computing applications in operations management, suggesting that firms with specialized domain expertise may extract value through proprietary application layers even when underlying quantum software infrastructure is openly licensed.

Energy systems optimization represents another major application domain. Morstyn and Wang (2024) analyze quantum computing opportunities for net-zero power systems, noting that technological changes in renewable adoption, electrification, and digitalization increase both the value and computational complexity of optimization. They argue that quantum computing offers practical advantages for specific energy optimization applications, creating incentives for domain-specific software development.

The societal preparation for quantum technologies raises broader governance considerations. de Jong (2022) propose a five-dimensional strategy for societal readiness: demystifying unrealistic perceptions, contextualizing through enabling environments, engaging stakeholders, developing flexible regulatory frameworks, and positioning through international quantum diplomacy. This framework suggests that appropriability strategies should account for regulatory uncertainty and societal acceptance, factors that may favor collaborative standardization over fragmented proprietary approaches.

The social dimensions of quantum technologies remain severely understudied. Wolbring (2022) conduct a comprehensive analysis of 362,728 technical abstracts, finding that only 0.24% mention social considerations and equity frameworks are completely absent. This gap suggests that appropriability decisions have been made primarily on technical and economic grounds without adequate consideration of social implications. As quantum computing transitions from research to commercialization, more inclusive approaches to ecosystem development may be necessary.

Innovation and technology development in emerging economies provides comparative context. The Innovation for Development Report (?) documents innovation patterns across development levels, identifying barriers and enablers for innovation in emerging economies. This research suggests that appropriability strategies in quantum software should account for global development disparities, with potential tensions between maximizing innovation diffusion and maintaining incentives for frontier research investment.

This literature review reveals several gaps that our analysis addresses. First, while game-theoretic frameworks have been applied to general technology adoption, their application to vertically structured quantum software ecosystems remains underdeveloped. Second, the role of complementary assets in determining appropriability strategies in quantum computing has not been systematically analyzed. Third, the coordination challenges specific to quantum software standardization have not been formally modeled. Our theoretical framework builds on these foundations while addressing these specific gaps.

3 Theoretical Framework

The quantum software ecosystem can be conceptualized as a vertically differentiated structure consisting of distinct functional layers. At the lowest level, quantum hardware provides the physical substrate for computation, executing quantum gates on qubits with varying fidelity and coherence characteristics. Immediately above this, hardware abstraction layers translate between high-level quantum operations and device-specific implementations. These abstraction layers handle tasks such as gate compilation, error mitigation, and resource allocation across heterogeneous quantum processors.

At higher levels, programming frameworks provide developers with constructs for expressing quantum algorithms without requiring detailed knowledge of underlying hardware. These frameworks typically include language specifications, compiler toolchains, and simulation environments. Finally, application-layer software addresses domain-specific problems in areas such as quantum chemistry, financial optimization, and machine learning. Each layer depends critically on the interfaces and functionality provided by lower layers.

This vertical structure creates strategic interdependencies between firms operating at different layers. A firm developing application software must choose which hardware abstraction layers to support, investing in expertise and tooling specific to those interfaces. Conversely, providers of abstraction layers benefit from a thriving application ecosystem that demonstrates the value of their infrastructure. These complementarities generate network effects where the value of participation at any layer increases with participation at adjacent layers.

The appropriability decision at each layer involves choosing between proprietary licensing and various forms of open source licensing. Proprietary licensing provides direct revenue through license fees or usage restrictions but may limit ecosystem development by raising adoption barriers. Open source licensing foregoes direct licensing revenue but can stimulate ecosystem growth by reducing coordination costs and enabling complementary innovation. Intermediate positions include open core models, where base functionality is openly licensed while advanced features remain proprietary.

Several factors influence the attractiveness of different appropriability strategies. First, the degree of technical maturity affects whether firms can profit from current implementations or must invest in ecosystem development for future returns. In immature technological domains, open strategies may be necessary to establish standards and build developer communities. Second, the competitive structure matters. In concentrated markets with few providers, proprietary strategies may be sustainable. In fragmented markets, coordination failures can trap all firms in suboptimal outcomes.

Third, the nature of complementary assets shapes appropriability choices. Firms with strong complementary capabilities such as specialized consulting services, hardware products, or established customer relationships may profit from open software strategies that drive demand for these complements. Firms lacking such complementary assets depend more heavily on direct licensing revenue. Fourth, the rate of technological change influences time horizons. In rapidly evolving domains, firms may prefer open strategies that accelerate learning and standard formation over proprietary strategies that protect current implementations.

The collective action problem in quantum software standardization can be understood through the framework developed by Holahan and Lubell (2016). Multiple firms must jointly decide on licensing strategies, with individual decisions creating externalities for others. If all firms choose open licensing, standardization occurs and collective benefits materialize. However, if some firms defect to proprietary strategies hoping to capture disproportionate value, coordination fails and fragmentation reduces total ecosystem value. Resolving this dilemma requires institutional arrangements that align individual incentives with collective interests.

We model the strategic interaction between two types of firms: infrastructure providers operating at the hardware abstraction layer and application developers operating at higher layers. Infrastructure providers choose between proprietary interfaces that lock in users and generate direct revenue versus open interfaces that maximize ecosystem development. Application developers choose between supporting multiple proprietary platforms, which maximizes market access but increases costs, versus specializing on a single platform to achieve economies of scale in development.

The strategic environment exhibits several key features. First, decisions are made simultaneously or with imperfect information about rivals' choices, creating coordination challenges. Second, there exist network effects where the value of open standardization increases with adoption, generating potential tipping dynamics. Third, firms are heterogeneous in their complementary assets and cost structures, leading to asymmetric payoffs from different strategies. Fourth, the game is repeated over time as technologies and markets evolve, but with sufficient uncertainty about future states to prevent complete backward induction.

The sequential nature of ecosystem development adds another dimension. Early in the technology lifecycle, uncertainty about technical standards is high. Infrastructure providers may choose open licensing to accelerate learning and coordinate around stable interfaces. As standards mature and uncertainty resolves, incentives may shift toward proprietary strategies to capture value from established ecosystems. This temporal dynamic suggests that appropriability strategies should be understood as evolving rather than static choices.

The dual-use nature of quantum technologies introduces additional strategic considerations. As de Jong (2022) emphasizes, quantum computing development occurs in contexts of geopolitical competition and national security concerns. This creates tensions between open collaboration that maximizes technical progress and proprietary control that maintains strategic advantages. Firms must navigate these tensions while making appropriability decisions that balance commercial, scientific, and security considerations.

We formalize this strategic environment in the following section, developing a model that captures these essential features while remaining tractable for analytical solution. The model identifies conditions under which different appropriability regimes emerge as equilibrium outcomes and examines the welfare properties of these equilibria.

4 Game-Theoretic Model

Consider a market with infrastructure providers indexed by $i \in \{1, 2, ..., N\}$ and application developers indexed by $j \in \{1, 2, ..., M\}$. Infrastructure providers choose licensing strategies $s_i \in \{O, P\}$, where O denotes open licensing and P denotes proprietary licensing. Application developers choose which infrastructure platforms to support, with strategy a_j representing the set of platforms on which developer j builds applications.

The payoff to infrastructure provider i depends on the number of application developers supporting its platform and its licensing strategy. Let n_i denote the number of developers supporting platform i. If provider i chooses proprietary licensing, it earns revenue $r \cdot n_i$ from license fees, where r is the per-developer licensing revenue. However, proprietary licensing imposes switching costs on developers, reducing the equilibrium number of adopters.

If provider i chooses open licensing, it earns no direct licensing revenue but benefits from ecosystem development through complementary revenues. Let $c(n_i)$ denote the complementary revenue function, which is increasing and convex in n_i to reflect network effects. The total payoff to provider i under proprietary licensing is:

$$\pi_i^P = r \cdot n_i(P) - k_P$$

where k_P represents the fixed cost of maintaining proprietary infrastructure, and $n_i(P)$ is the equilibrium number of developers under proprietary licensing.

Under open licensing, the payoff becomes:

$$\pi_i^O = c(n_i(O)) - k_O$$

where k_O is the fixed cost of supporting open infrastructure, and $n_i(O)$ is the equilibrium number of developers under open licensing. Typically, we assume $k_O < k_P$ because open development can leverage community contributions.

Application developers face costs that depend on the number of platforms they support and whether those platforms use proprietary or open licensing. Let τ_P represent the per-platform cost of integrating with proprietary infrastructure and τ_O the cost for open infrastructure. We assume $\tau_P > \tau_O$ due to higher integration complexity, documentation barriers, and lock-in effects with proprietary systems.

Developer j earns revenue $v_j(|a_j|)$ that depends on market access, which increases with the number of platforms supported but exhibits diminishing returns due to the need to spread development resources across multiple implementations. The total payoff to developer j is:

$$\pi_j = v_j(|a_j|) - \sum_{i \in a_j} \tau_i - \sum_{i \in a_j \cap P} r$$

where τ_i is the integration cost for platform i and the final term captures licensing fees paid to proprietary platforms.

The key strategic consideration is that developer adoption decisions respond to licensing choices by infrastructure providers. When all providers choose proprietary licensing, high integration costs and license fees reduce developer participation. This lowers n_i for all providers, potentially making proprietary strategies unprofitable despite positive per-developer revenues. Conversely, when all providers choose open licensing, lower barriers increase total developer participation.

Formally, we model developer adoption as follows. Each developer evaluates the net benefit of supporting each platform and adopts platforms where net benefits are positive. Under proprietary licensing, the barrier to adoption is higher, so:

$$n_i(P) = M \cdot \phi(\theta_i - \tau_P - r)$$

where $\phi(\cdot)$ is an adoption function increasing in its argument and θ_i represents the inherent value of platform i to developers. Under open licensing:

$$n_i(O) = M \cdot \phi(\theta_i - \tau_O)$$

Since $\tau_P + r > \tau_O$, we have $n_i(O) > n_i(P)$ for all i, meaning open licensing attracts more developers.

Proposition 1. If complementary revenue functions are sufficiently convex, such that $c''(n) > 0$ is large, and integration cost differentials satisfy $\tau_P - \tau_O + r > \epsilon$ for some threshold ϵ, there exists a critical number of infrastructure providers $\bar{N}$ such that for $N > \bar{N}$, infrastructure providers choosing open licensing earn higher profits than those choosing proprietary licensing in equilibrium.

The intuition follows from the collective action framework of Holahan and Lubell (2016). With many infrastructure providers, fragmentation under proprietary licensing severely limits each provider's ability to attract developers. High switching costs prevent multi-homing, so developers concentrate on a few platforms, leaving most providers with negligible adoption. Open licensing eliminates these coordination barriers, enabling standardization and widespread adoption that generates sufficient complementary revenues to exceed foregone licensing fees.

However, this equilibrium is not always reachable. Consider the case where infrastructure providers make simultaneous licensing decisions without binding commitments.

Each provider faces uncertainty about rivals' choices. If provider i expects rivals to choose proprietary licensing, choosing open licensing unilaterally may be unprofitable because developers will still face high costs supporting the remaining proprietary platforms. Even if open licensing would be mutually beneficial, coordination failure can trap the market in a proprietary equilibrium.

Lemma 1. When infrastructure providers make simultaneous licensing decisions and complementary revenues exhibit moderate convexity, there exist multiple Nash equilibria: one where all providers choose proprietary licensing and one where all providers choose open licensing. The open equilibrium Pareto dominates but may not be selected without coordination mechanisms.

This coordination failure resembles classic collective action dilemmas. Each firm would benefit from universal open licensing but fears being exploited if it opens while others remain proprietary. Standard solutions to collective action problems apply here: repeated interaction with reputation effects, coordinating institutions such as standard-setting bodies, or public intervention to facilitate coordination.

The model can be extended to incorporate heterogeneity in complementary assets across providers. Suppose providers differ in their ability to monetize ecosystem participation, with some possessing strong consulting capabilities, hardware products, or customer relationships while others lack such complementary strengths. Let θ_i index provider i's complementary asset strength, with higher θ_i generating larger $c(n_i)$ through the functional form:

$$c(n_i; \theta_i) = \theta_i \cdot n_i + \beta n_i^2$$

where $\beta > 0$ captures network effects.

Providers with high θ_i strictly prefer open licensing because they can capture value through complements without relying on direct licensing revenue. Their optimization yields:

$$s_i^* = O \text{ if } \theta_i \cdot n_i(O) + \beta[n_i(O)]^2 - k_O > r \cdot n_i(P) - k_P$$

For sufficiently large θ_i, this condition always holds. Providers with low θ_i prefer proprietary licensing when possible, as they lack alternative revenue sources. This asymmetry can lead to hybrid equilibria where strong providers open their platforms while weak providers attempt proprietary strategies. Such equilibria exhibit interesting dynamics: open platforms attract most developers, leaving proprietary platforms with niche adoption that may still generate positive profits in specialized segments.

The application developer side of the market also exhibits strategic considerations. Developers with broad market ambitions prefer environments with open standards that minimize integration costs and enable serving diverse customer bases. Niche developers may accept proprietary platform lock-in if that platform serves their target market effectively and provides technical capabilities unavailable in open alternatives. When infrastructure providers offer differentiated technical capabilities, developers face trade-offs between technical performance and strategic flexibility.

The sequential nature of ecosystem development adds temporal dynamics. Early in the technology lifecycle, uncertainty about technical standards is high. Infrastructure providers may choose open licensing to accelerate learning and coordinate around stable interfaces, following the strategic logic identified by Saleem and Higuchi (2014) in their analysis of technology adoption coordination. As standards mature and uncertainty resolves, incentives may shift toward proprietary strategies to capture value from established ecosystems. This suggests appropriability strategies evolve over technology lifecycles rather than remaining static.

5 Strategic Implications

The theoretical analysis yields several practical implications for firms navigating appropriability decisions in quantum software ecosystems. First, infrastructure providers must carefully assess their complementary asset positions before committing to licensing strategies. Firms with strong hardware businesses, established customer relationships, or differentiated consulting capabilities can profitably pursue open infrastructure strategies. These firms benefit from ecosystem expansion that drives demand for complementary products and services, consistent with patterns observed in quantum computing applications across diverse industries (Quantum Technology and Application Consortium – QUTAC, 2021).

Second, timing considerations matter significantly. The model suggests that proprietary strategies become less viable as the number of competing infrastructure providers increases. Early entrants into nascent quantum software markets may successfully establish proprietary platforms when few alternatives exist. However, as competition intensifies, sustaining proprietary strategies requires either strong differentiation or the ability to achieve winner-take-all dominance. Firms that delay their licensing decisions until competitive dynamics clarify may find their strategic options constrained by earlier movers' choices.

Third, credible commitment mechanisms can help overcome coordination failures that trap markets in inefficient proprietary equilibria. Infrastructure providers might coordinate through standard-setting organizations, industry consortia, or public licensing declarations to establish shared expectations about openness. The application-centric approach proposed by Quantum Technology and Application Consortium – QUTAC (2021) through the Quantum Technology and Application Consortium exemplifies how industry coordination can establish reference problems and benchmarks that guide ecosystem development.

Fourth, vertical relationships between infrastructure and application layers create strategic dependencies that influence optimal licensing choices. Infrastructure providers must consider how their licensing decisions affect the vitality of the application ecosystem that ultimately determines infrastructure demand. Research on quantum computing integration into business analytics (Mudhol, 2024) suggests that adoption barriers remain significant, implying that reducing integration costs through open licensing may expand total addressable markets even if per-transaction revenues decline.

Fifth, market structure considerations shape the sustainability of different appropriability regimes. In concentrated markets with few infrastructure providers, coordination is easier but market power concerns may reduce total ecosystem value. In fragmented markets, coordination becomes more challenging but competitive pressure disciplines pricing and encourages innovation. The optimal degree of concentration depends on the relative importance of coordination versus competition for generating ecosystem value in specific technological contexts.

For application developers, the strategic landscape differs significantly. When infrastructure remains fragmented across proprietary platforms, developers face difficult choices about platform specialization versus multi-homing. Specialization enables deeper technical optimization but creates lock-in risks. Multi-homing maintains flexibility but imposes integration costs and dilutes specialized expertise. Successful implementations of quantum workforce scheduling (Takeori et al., 2024) and energy systems optimization (Morstyn and Wang, 2024) suggest that domain expertise provides sustainable competitive advantages even when underlying quantum infrastructure becomes commoditized.

Policy considerations emerge from the potential for coordination failures and socially suboptimal equilibria. If proprietary fragmentation persists despite the superiority of open standardization, public intervention might facilitate coordination through standards development, funding for open source infrastructure, or procurement policies favoring interoperable solutions. The framework proposed by de Jong (2022) for societal preparation suggests that flexible regulatory approaches combined with stakeholder engagement can guide quantum technology development toward socially beneficial outcomes.

However, such interventions must balance the benefits of standardization against the risks of premature lock-in to inferior technical approaches. The societal dimensions of quantum technology development remain understudied (Wolbring, 2022), suggesting that policy interventions should incorporate broader social considerations beyond purely technical efficiency. Equity, diversity, and inclusion frameworks should inform appropriability decisions to ensure that quantum computing benefits are broadly distributed rather than concentrated among early adopters.

The analysis also highlights tensions between static efficiency and dynamic incentives. Open infrastructure maximizes static efficiency by reducing integration costs and enabling widespread participation. However, if infrastructure development requires substantial investment, appropriability concerns may discourage such investment in the absence of complementary revenue sources. Balancing these considerations requires understanding how different firms finance infrastructure development and what complementary assets enable value capture without direct licensing.

The global dimension of quantum computing development introduces additional complexities. Research on innovation in developing economies suggests that appropriability strategies should account for development disparities and technology transfer mechanisms. Overly restrictive appropriability regimes may impede quantum computing diffusion to emerging economies, reducing global welfare gains and potentially creating new technological divides. Open licensing strategies coupled with capacity building initiatives may promote more equitable access while maintaining innovation incentives.

Financial sector applications (Herman et al., 2022) illustrate how domain-specific factors influence appropriability choices. Financial institutions face regulatory requirements, security concerns, and competitive pressures that shape their preferences for proprietary versus open quantum software. Similar domain-specific considerations apply across other sectors where quantum computing offers advantages, suggesting that optimal appropriability strategies may vary across application domains rather than converging on a single universal approach.

6 Discussion

The emergence of quantum computing as a commercializable technology provides a natural laboratory for observing appropriability strategies in real time. Unlike classical computing, where ecosystem architecture evolved gradually over decades, quantum software ecosystems are being deliberately constructed by strategic actors with awareness of path dependencies and lock-in effects. This compressed timescale enables clearer observation of strategic choices predicted by our model.

Current empirical patterns in quantum software markets align with several theoretical predictions. Major technology companies with strong complementary assets in classical computing, cloud infrastructure, and research capabilities have adopted relatively open approaches to quantum software. These firms release open source frameworks, contribute to standardization efforts, and emphasize ecosystem development over direct licensing revenue. This behavior is consistent with our prediction that firms with high complementary asset strength prefer open strategies to maximize ecosystem participation and drive demand for their complementary offerings.

Conversely, specialized quantum computing startups with limited complementary assets exhibit more varied approaches. Some pursue proprietary strategies centered on unique algorithmic capabilities or vertical integration with specific hardware platforms. Others adopt open strategies to establish credibility and attract developer mindshare in competitive markets. This heterogeneity aligns with our analysis of how complementary asset positions influence licensing choices, with firms making different trade-offs based on their strategic circumstances and competitive positions.

The quantum software ecosystem has also experienced coordination challenges consistent with our model's predictions about simultaneous decision-making under uncertainty. Multiple competing hardware abstraction layers have emerged with limited interoperability, fragmenting developer effort and slowing ecosystem growth. This fragmentation persists despite apparent collective benefits from standardization, suggesting coordination failures of the type identified in our theoretical analysis and consistent with the collective action dilemmas described by Holahan and Lubell (2016).

Recent moves toward common interface specifications represent attempts to overcome these coordination barriers through explicit coordination mechanisms. The consortium approach exemplified by Quantum Technology and Application Consortium – QUTAC (2021) demonstrates how industry coordination can establish shared reference points and benchmarks that guide ecosystem development. These coordinating institutions help resolve the strategic uncertainty that prevents unilateral moves toward open licensing even when such moves would be collectively beneficial.

Temporal dynamics in licensing strategies provide additional evidence for our theoretical framework. Several firms initially adopted closed approaches during early development phases, then transitioned to open licensing as technologies matured and competitive pressures intensified. This pattern supports our prediction that appropriability strategies evolve as market structure and technological uncertainty change over time. Firms adjust licensing strategies in response to observed competitive dynamics rather than committing irrevocably to fixed approaches.

The analysis also illuminates broader questions about innovation appropriability in emerging technologies. Quantum computing shares characteristics with other general-purpose technologies where early architectural choices shape long-run competitive dynamics. Understanding how appropriability strategies interact with ecosystem development in quantum computing may inform analysis of other domains where similar strategic considerations arise, including artificial intelligence infrastructure, biotechnology tools, and next-generation communications systems.

The societal dimensions identified by Wolbring (2022) raise important questions about whether current appropriability strategies adequately address social implications. The near-total absence of equity and inclusion considerations in quantum technology development suggests that economic optimization alone may produce socially suboptimal outcomes. Future research should examine how appropriability strategies can be designed to promote both economic efficiency and social equity in quantum computing diffusion.

The framework proposed by de Jong (2022) for societal preparation highlights the importance of anticipatory governance in quantum technology development. Their emphasis on demystification, contextualization, stakeholder engagement, flexible regulation, and international diplomacy suggests that appropriability decisions should be embedded in broader governance frameworks rather than left entirely to market forces. This perspective challenges purely economic analyses by introducing normative considerations about how quantum computing development should be steered toward socially beneficial ends.

However, several features of quantum computing may limit the generalizability of our findings. The tight coupling between quantum software and hardware, driven by physical constraints on quantum coherence and error rates, creates stronger vertical dependencies than in many classical software domains. This coupling may sustain differentiation and reduce standardization pressure compared to more modular architectures. Additionally, the scarcity of quantum computing expertise creates labor market dynamics that influence appropriability strategies in ways not fully captured by our model.

The dual-use nature of quantum technologies introduces security considerations that may override purely commercial logic. National security concerns may encourage proprietary control or restricted access even when open approaches would maximize economic value. This creates tensions between scientific openness, commercial efficiency, and security imperatives that our model does not fully address but which significantly influence real-world appropriability decisions.

Future research might extend this analysis in several directions. First, incorporating explicit dynamics would enable analysis of how appropriability strategies evolve over technology lifecycles and how firms update their strategies in response to observed outcomes. Second, modeling heterogeneity more richly could illuminate how firm characteristics beyond complementary assets, such as financial constraints or organizational capabilities, influence licensing choices. Third, analyzing the role of intellectual property protection mechanisms beyond licensing strategies would provide a more complete picture of appropriability in quantum software.

The welfare implications of different appropriability regimes also merit deeper investigation. While our analysis identifies conditions under which open strategies are privately optimal for firms, social welfare depends on additional considerations including the level of infrastructure investment, the pace of technological progress, and the distribution of gains across ecosystem participants. Normative analysis requires understanding these broader impacts beyond firm-level profit maximization and incorporating the social dimensions that current quantum technology development largely neglects.

7 Conclusion

This paper has developed a game-theoretic analysis of appropriability strategies in quantum software ecosystems, focusing on the strategic choice between proprietary and open source licensing across different layers of the software stack. Drawing on collective action theory and cooperative game frameworks, the analysis reveals that vertical structure and network effects create complex strategic interdependencies between infrastructure providers and application developers. Whether open or proprietary licensing prevails depends on market structure, complementary asset distributions, and coordination mechanisms.

Several key findings emerge from the analysis. First, infrastructure providers with strong complementary assets can profitably pursue open licensing strategies that maximize ecosystem participation, while firms lacking such assets face greater pressure to extract value through direct licensing. This prediction finds support in observed patterns where major technology companies with diverse revenue streams adopt open approaches while specialized startups maintain proprietary control over unique capabilities.

Second, coordination failures can trap markets in inefficient proprietary equilibria even when open standardization would be collectively beneficial. Resolving these coordination dilemmas requires institutional mechanisms such as standard-setting organizations, industry consortia, or public coordination initiatives. The application-centric consortium approach demonstrates how coordinated action can overcome strategic uncertainty and guide ecosystem development toward mutually beneficial outcomes.

Third, appropriability strategies should be understood as dynamic and responsive to evolving competitive conditions rather than as fixed commitments. As quantum computing technologies mature and market structures crystallize, firms rationally adjust their licensing approaches. This temporal evolution suggests that policy interventions should maintain flexibility rather than attempting to lock in particular appropriability regimes prematurely.

These findings contribute to theoretical understanding of innovation appropriability in complex technology ecosystems. By explicitly modeling vertical relationships and strategic interaction across ecosystem layers, we extend existing frameworks beyond single-layer analyses. The analysis demonstrates how architectural considerations shape appropriability choices and how these choices recursively influence ecosystem architecture through network effects and coordination dynamics.

For practitioners, the analysis provides guidance on assessing appropriability strategies in light of firm-specific complementary assets, market structure, and coordination opportunities. Infrastructure providers should evaluate their positions on complementary strengths before committing to licensing approaches, recognizing that sustainable proprietary strategies require either strong differentiation or credible paths to dominance. Application developers should assess infrastructure fragmentation when making platform specialization decisions, understanding that fragmented proprietary environments create lock-in risks while open standardization enables flexibility.

For policymakers, the analysis highlights potential coordination failures that may justify public intervention to facilitate standardization. When private coordination mechanisms fail to overcome strategic uncertainty, public standards development, funding for open infrastructure, or procurement policies favoring interoperability might improve outcomes. However, such interventions must be designed carefully to avoid premature standardization on inferior technical approaches or excessive interference with beneficial competitive dynamics.

The quantum computing context provides a timely application domain where these strategic considerations play out in real time. As quantum computing transitions from research curiosity to commercial reality, appropriability decisions made today will shape ecosystem architecture for years to come. Understanding the strategic logic underlying these decisions can inform better choices by firms and more effective policies by governments seeking to promote quantum computing development while ensuring broad societal benefits.

The societal dimensions of quantum technology development deserve greater attention in both research and practice. Current approaches largely neglect equity, diversity, and inclusion considerations, raising concerns about whether quantum computing benefits will be broadly distributed or concentrated among privileged actors. Future appropriability strategies should incorporate these social dimensions alongside economic optimization to ensure that quantum computing contributes to inclusive prosperity rather than exacerbating existing inequalities.

Future research should address several limitations of this analysis. Incorporating richer dynamics would enable analysis of strategy evolution over technology lifecycles and feedback effects between appropriability choices and technological trajectories. Modeling heterogeneity more thoroughly could illuminate how diverse firm characteristics influence licensing choices and ecosystem outcomes. Analyzing the interplay between licensing strategies and other appropriability mechanisms such as patents, trade secrets, and first-mover advantages would provide a more complete picture of value capture in quantum software ecosystems.

The global dimension of quantum computing development requires attention to technology transfer mechanisms and development equity. Research on innovation in emerging economies suggests that appropriability strategies profoundly influence technology diffusion patterns and capability building in developing countries. Overly restrictive regimes may impede beneficial diffusion while overly open approaches may undermine innovation incentives. Balancing these considerations requires continued research on appropriability strategies that promote both innovation and equitable access.

As quantum computing continues to develop, ongoing observation of strategic choices and ecosystem outcomes will provide valuable empirical evidence to test and refine theoretical predictions. The field remains young enough that strategic choices have not yet crystallized into stable patterns, offering opportunities for both theoretical development and practical influence on ecosystem evolution. The analytical framework developed here provides a foundation for understanding these dynamics and informing both business strategy and public policy in this emerging domain.

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