Beyond the Limits of PQC

The PQC Transition and Beyond: Gap Between Concept and Reality

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Introduction

Motivation

- Quantum computing amplifies the long-recognized fragility of cryptographic longevity.
- Past transitions have been slow (e.g., DES, SHA-1), some of which have taken over a decade to complete, and PQC transition is anticipated to be more complex than any other before [1, 2].
- PQC migration is challenging because cryptography is deeply embedded in complex, large-scale infrastructures, turning migration into an enterprise-level problem [3].
- The inability to replace vulnerable cryptographic mechanisms in a timely manner increases systemic security risk.
- Policy and standards bodies increasingly define firm deprecation timelines, making routine cryptographic replacement an operational necessity.
- Despite early guidance on preparing for post-quantum migration [4], progress toward adopting crypto-agility and cryptographic inventory practices remains limited.

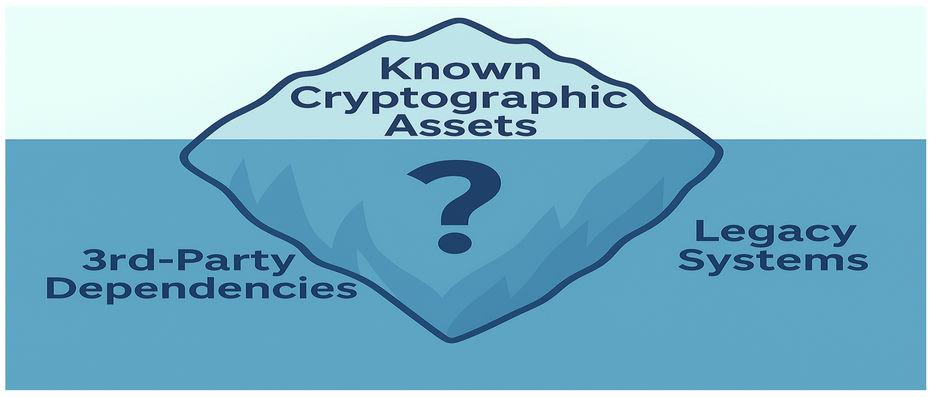
Core Concepts

- **Capability**: Replace, update, or retire cryptographic mechanisms with minimal operational impact.
- **Visibility**: Accurate cryptographic inventories and CBOMs provide the asset awareness required for safe and sequenced transitions.
- **Modularity**: Crypto-agnostic application design with clear abstractions and policy interface enable practical agility.
- **Governance**: Coordinated workflows and enterprise-level change management make transitions repeatable and sustainable.

Real-World Limitations and Research Gaps

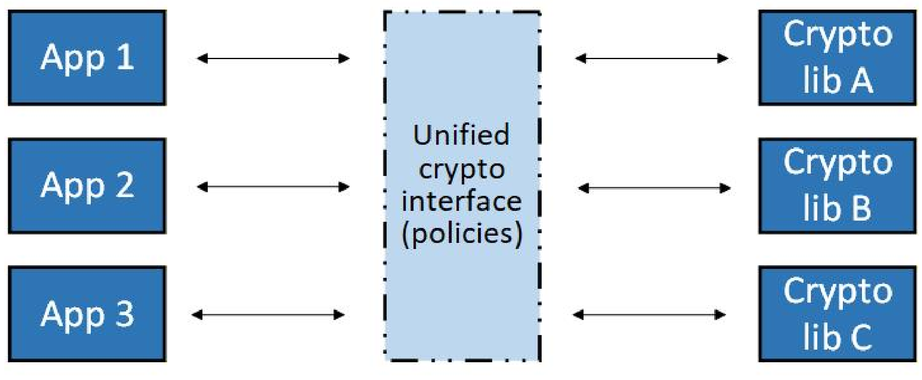
Limitations in Cryptographic Asset Visibility

- Visibility into cryptographic assets is widely identified as a key prerequisite for cryptographic transitions [5, 6, 7, 8]
- Multiple sources indicate that organizations often lack comprehensive visibility into their cryptographic assets [9, 10, 11, 8].
- Creating and maintaining comprehensive cryptographic inventories is widely reported to be challenging in practice, due to complex system dependencies, incomplete asset visibility, and organizational constraints [12, 13, 8].
- As CBOM standardization has only recently emerged [14, 15], available academic and practitioner evidence suggests that the associated tooling ecosystem remains immature and evolving [16, 17].



Fragmentation and Complexity in Crypto-Agility

- Many systems were not originally designed for cryptographic change: tightly coupled implementations and historically static design decisions make updates or algorithm replacements difficult without significant modifications [1, 18].
- Early and recent studies highlight the absence of a unified definition of crypto-agility, noting that a precise and concrete definition remains difficult to establish [19, 20].
- The identified need for universal cryptographic interface designs [1] suggests that widely adopted abstractions for achieving crypto-agility are still lacking, which can lead to heterogeneous implementations that reduce interoperability.
- Introducing crypto-agility increases system complexity, which may in turn expand the attack surface [1, 21].



External Constraints on Cryptographic Transitions

- Few available sources provide quantitative estimates, suggesting PQC migration may require 2–15+ years depending on enterprise size [22, 23, 24], raising concerns about alignment with current policy timelines (e.g., NIST, UK, EU) [2, 25, 26].
- As standardization efforts remain ongoing [27, 28], the limited time available for migration further emphasizes the need for agile adoption.
- A wide range of sources indicate that the PQC transition imposes a sustained economic burden, with cost and budget constraints consistently identified as significant barriers to adoption [29, 30, 31, 32, 33].
- Taken together with the widely held view that the PQC transition exceeds previous cryptographic transitions in scope and complexity [1, 2], the estimated timelines and economic constraints outlined above suggest that current policy timelines can reasonably be described as aggressive [29] and challenging to meet.
- Insufficient international coordination during the PQC transition may contribute to diverging implementation approaches and standardization practices, potentially leading to ecosystem fragmentation and complicating interoperability across PQC-compliant systems and protocols [29, 33].

Organizational Drag in Cryptographic Migration

- Prior work [34] indicates that cryptographic maintenance may be deprioritized under operational pressure, leading to ad hoc and prolonged transitions, a finding supported by interview evidence suggesting that such updates are often delayed or skipped in practice due to competing priorities and unclear benefits [35].
- Recent work [3] identifies limitations in prior crypto-agility approaches and proposes an enterprise-level architecture, but concrete methodologies for evolving existing systems toward such architectures remain lacking.
- From an enterprise-level perspective [3], control over cryptographic configuration is often limited at the organizational level, further complicating coordinated cryptographic change.
- An interview study [35] indicates that structured processes for cryptographic updates are often lacking in practice, complicating the systematic management of such transitions.
- This indicated lack of structured support is reflected at the developer level, where developers often report limited expertise, guidance, and confidence in performing cryptographic updates, leading to uncertainty and hesitation that can contribute to delayed, ad hoc, or skipped update practices [35].

Lack of Systematic Cryptographic Transition Engineering

- An early survey [36] is consistent with our observation that the literature predominantly focuses on PQC algorithms and protocol integration, while higher-level concerns such as migration and system-level transition strategies remain comparatively underexplored and are identified as open challenges.
- Prior work [20, 37] indicates that guidance for cryptographic migration remains largely abstract and incomplete, leaving much of the practical realization to practitioners.
- Building on both the literature [20, 37] and our observations, concrete engineering methodologies for achieving crypto-agility appear to be lacking.

Closing the Transition Gap

- **Develop and deploy automated, open-source cryptographic inventory and CBOM tooling to enable visibility into cryptographic assets.**
- **Establish shared models for crypto-agility along with standardized abstractions and policy interfaces to support modular, crypto-agnostic system architectures.**
- **Implement coordinated governance, repeatable workflows, and dedicated support to enable organizations to manage cryptographic change at scale.**
- **Accelerate migration planning to align with long transition timelines and early-2030s policy deadlines, requiring immediate investment and international coordination.**
- **Develop a dedicated engineering discipline for cryptographic transitions, including lifecycle frameworks, metrics, and validated methodologies for achieving crypto-agility.**

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