Post-Quantum Cryptography in ARM Processors

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ARM Research Summit

Austin, TX

Sept. 2019

Quantum Threat to Information Security

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Large-scale quantum computers could break some encryption schemes

Need to migrate encryption to quantum-resistant algorithms

When we should start the process?

Questions:

- When will quantum computers arrive?
- When will they be a threat?
- When do we switch?
- How do we have live and agile transition?
- What do we transition to?
- …

“In 25 years we’ll be working on quantum resistant crypto standardization based on elliptic curves in some way!”

—Dustin Moody, NIST (NSF CCC Workshop 2019)

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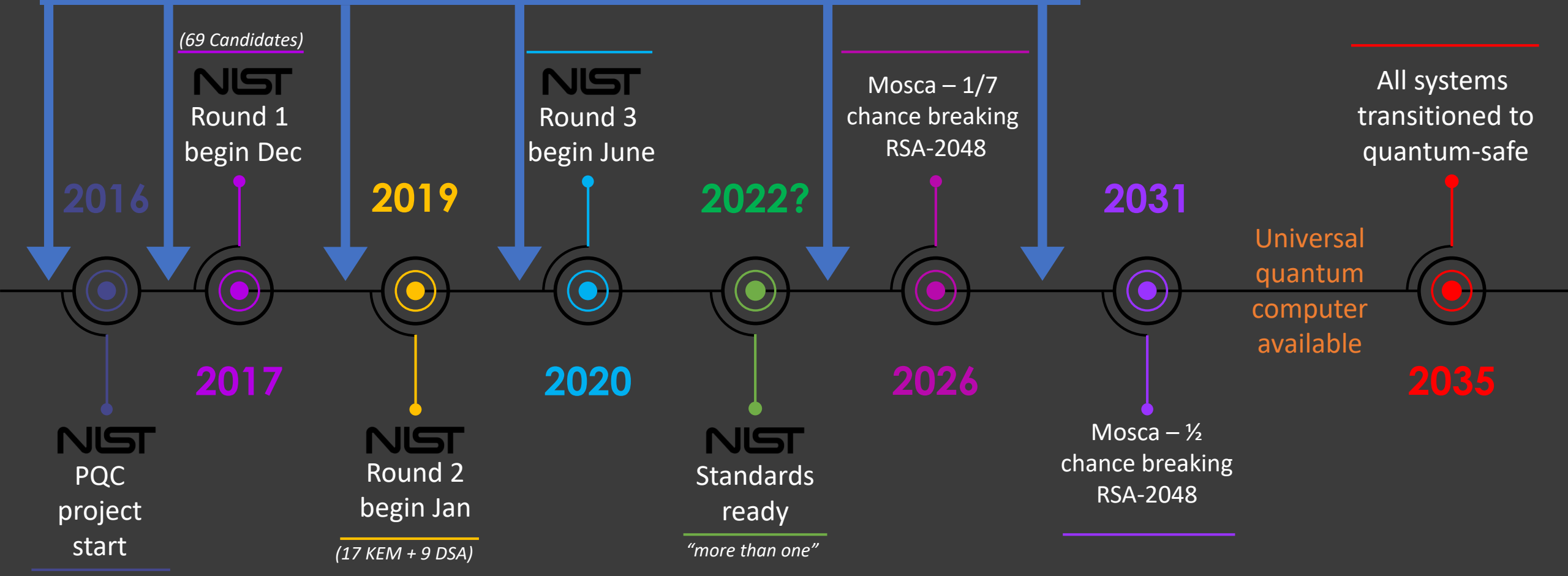
Retroactive decryption:
Record encrypted communication now,
Decrypt once quantum computers are available



Open Questions about Post-Quantum Cryptography

- Design better post-quantum cryptosystems
- Improve classical and quantum attacks
- Pick parameter sizes
- Develop fast, efficient, and secure implementations
- Integrate them into the existing infrastructures

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Post-Quantum Key-Exchange

- Lattice-based
- Code-based
- Isogeny-based

Post-Quantum Signatures

- Lattice-based
- Hash-based
- Multivariate-based
- Zero-Knowledge based

Quick Overview

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- **[2006]:** Birth of a supersingular isogeny-based cryptosystem
  - **Charles** – **Goren** – **Lauter**
  - built hash function from supersingular isogeny graph
- **[2011]:** Supersingular isogeny key exchange
  - Jao – De Feo
- **[2017]:** Supersingular isogeny key encapsulation
  - SIKE Team

SIKE Team


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evolution

Isogeny-Based Cryptography

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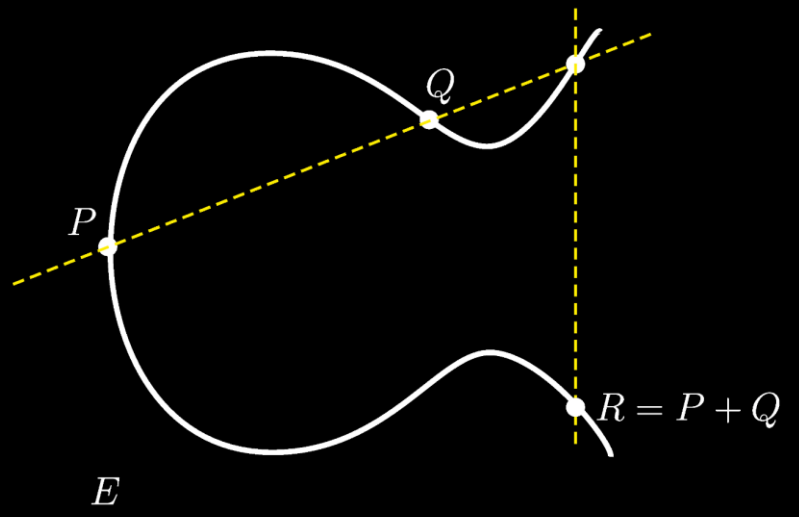
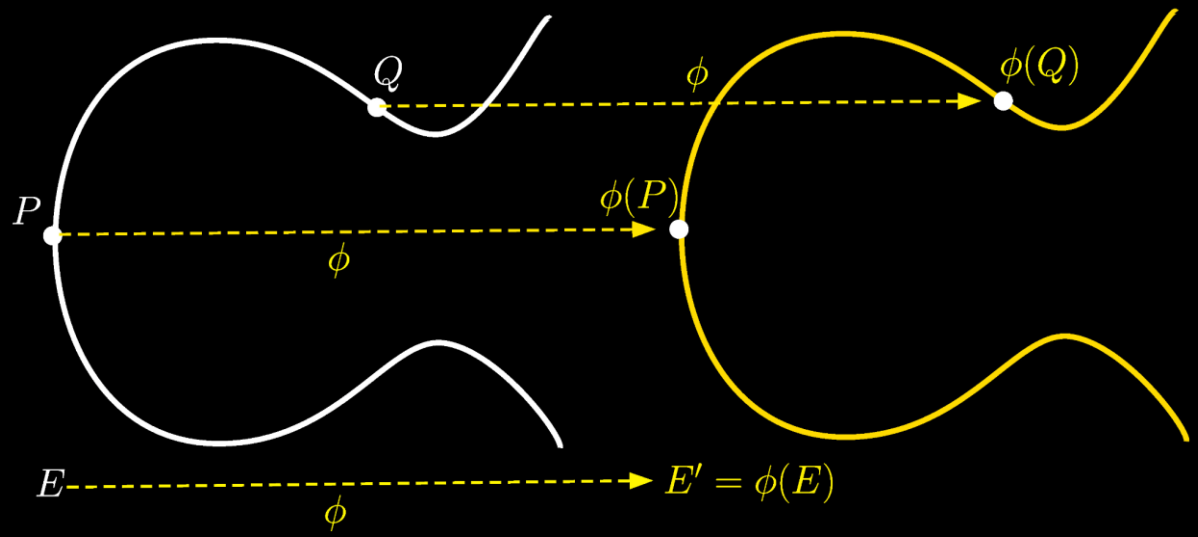
- Isogeny-based cryptography is constructed on a set of curves.
- Given two curve E and $E' = \phi(E)$ find ϕ?





Supersingular Isomorphism Classes

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- We are interested in the set of supersingular curves (up to isomorphism) over a specific field
- Prime $p = 2^{e_A} \cdot 3^{e_B} \cdot f \pm 1$
- Elliptic curves over $\mathbb{F}_{p^2}$, $\#E = (p \mp 1)^2$
- Supersingular j-invariants: $\#S_{p^2} \approx \left\lfloor \frac{p}{12} \right\rfloor$ (isogenous elliptic curves)

Prime $p = 2^3 \cdot 3^2 - 1 = 71$, $\#E = 72^2$, $\#S_{p^2} = 7$

Isogeny Graphs

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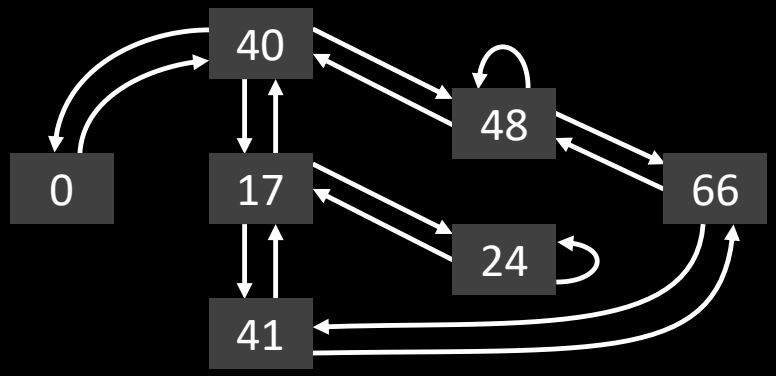
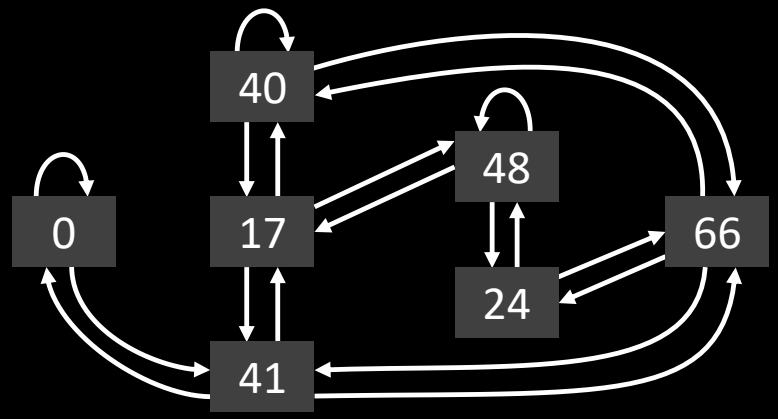
Vertices: All isogenous elliptic curves over $\mathbb{F}_{p^2}$.

Edges: Isogenies of degree ℓ

With isogeny of degree ℓ, we get a connected $(\ell + 1)$-regular graph.



2-isogeny graph



3-isogeny graph

Key Exchange based on Isogeny Graphs

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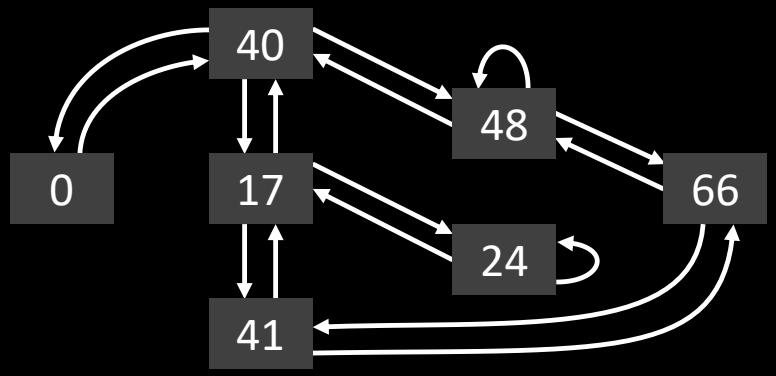
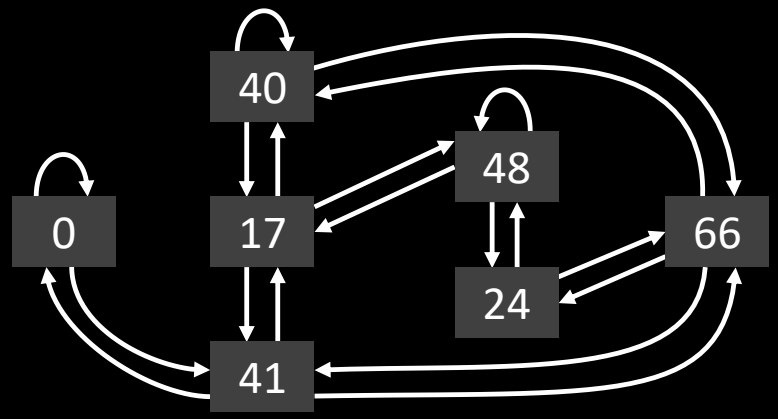
Alice



2-isogeny graph

Bob



3-isogeny graph

Public Parameters

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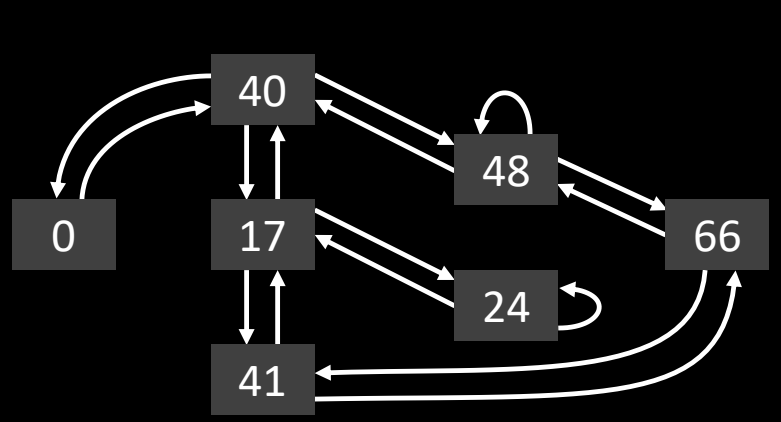
$$E_0/\mathbb{F}_{p^2}$$
$$\{P_A, Q_A\} \in E_0[2^{e_A}]$$
$$\{P_B, Q_B\} \in E_0[3^{e_B}]$$

Alice

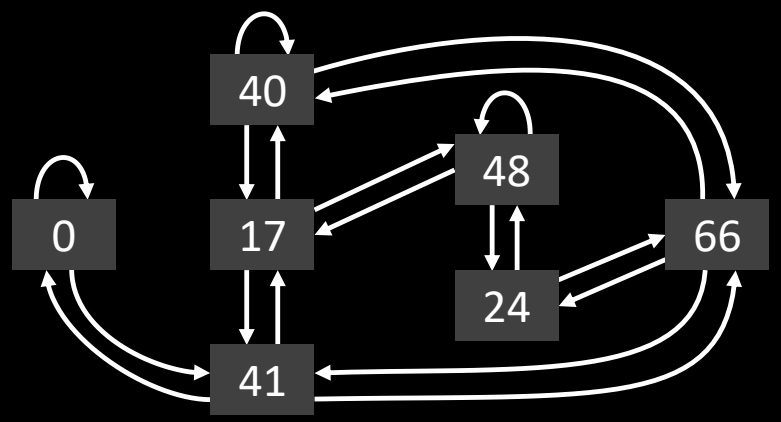


$P_A = (53, 55)$

$Q_A = (18, 27w + 44)$

$E_0: y^2 = x^3 + x$

Bob



$P_B = (7w + 20, 31w + 50)$

$Q_B = (21w + 64, 38w + 13)$

Secret Key

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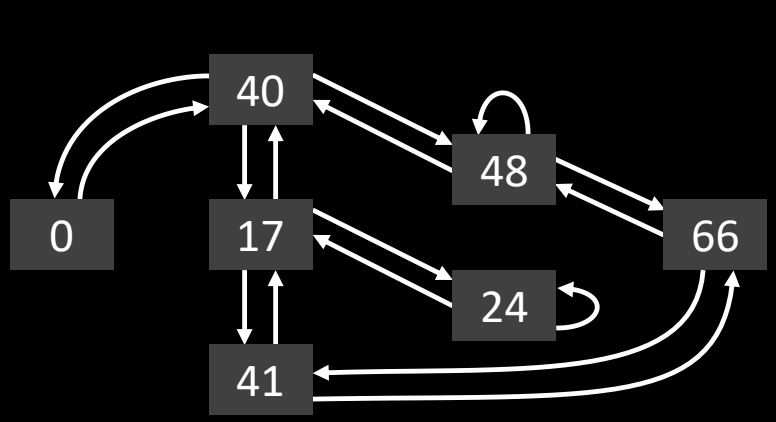
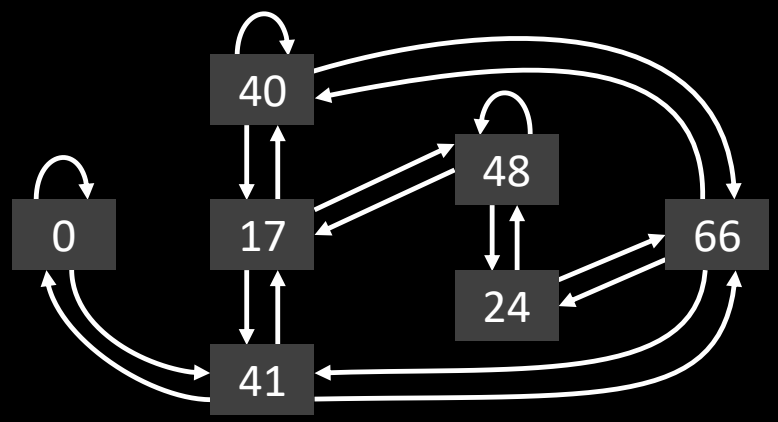
$s_A \in [0,2^{e_A})$
$s_B \in [0,3^{e_B})$

Alice



$s_A = 6$

Bob



$s_B = 3$

Public Key Generation

E_0

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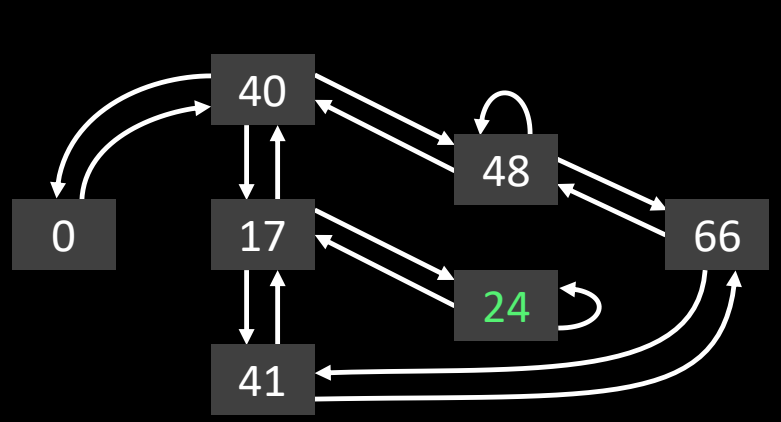
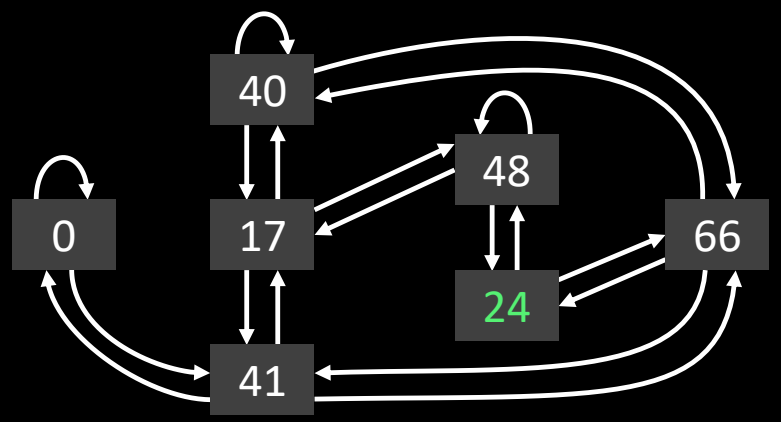


$E_0: y^2 = x^3 + x$

Bob



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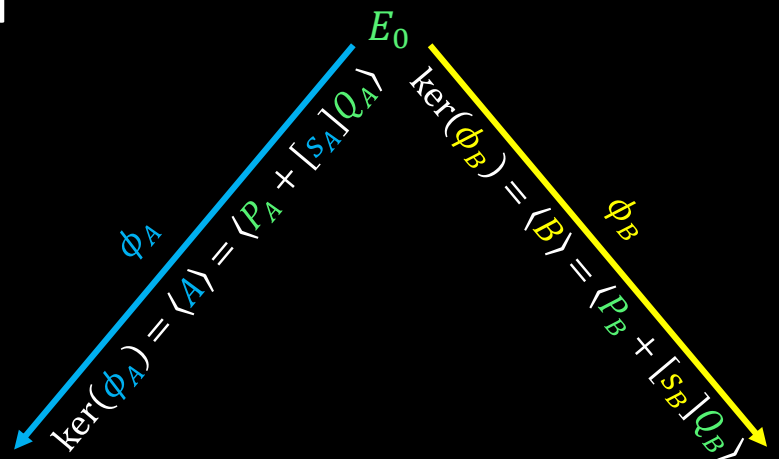
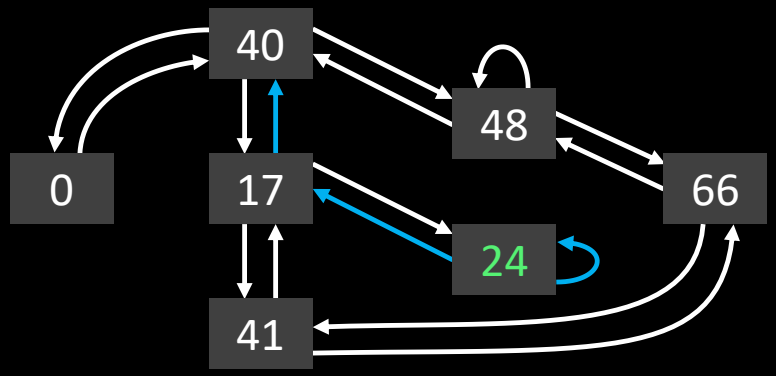
Public Key Generation



Alice

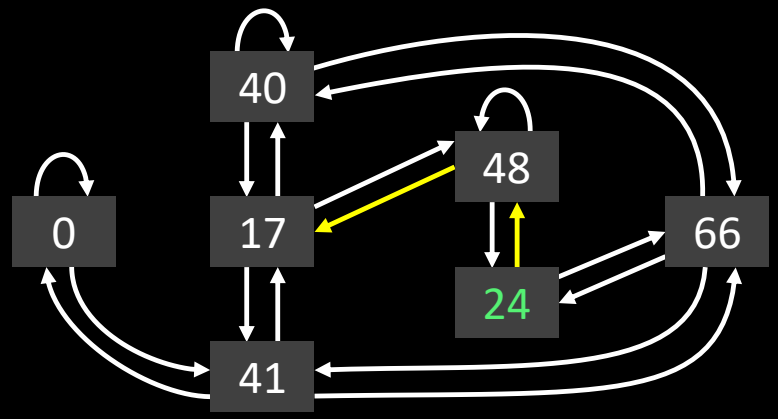


$E_0: y^2 = x^3 + x$

$\phi_A: E_0 \rightarrow E_A$

$p = 2^3 \cdot 3^2 - 1 = 71$

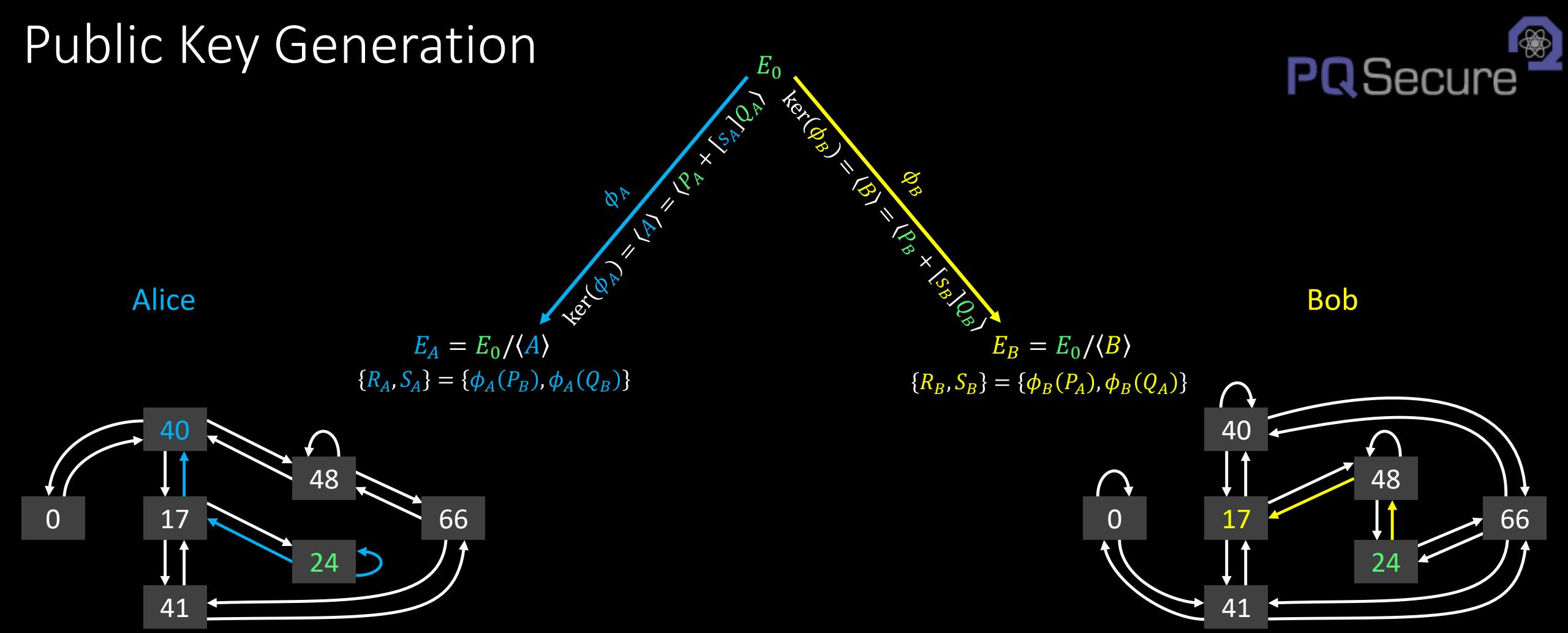
Bob



$E_0: y^2 = x^3 + x$

$\phi_B: E_0 \rightarrow E_B$

Public Key Generation



$E_0: y^2 = x^3 + x$

$\phi_A: E_0 \to E_A$

$E_A: y^2 = x^3 + 22x + 35$

$E_0: y^2 = x^3 + x$

$\phi_B: E_0 \to E_B$

$E_B: y^2 = x^3 + 63x + (55w + 16)$

Key Exchange

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E_0

ϕ_A

$\ker(\phi_A) = \langle A \rangle = \langle P_A + [s_A]Q_A \rangle$

ϕ_B

$\ker(\phi_B) = \langle B \rangle = \langle P_B + [s_B]Q_B \rangle$

Alice

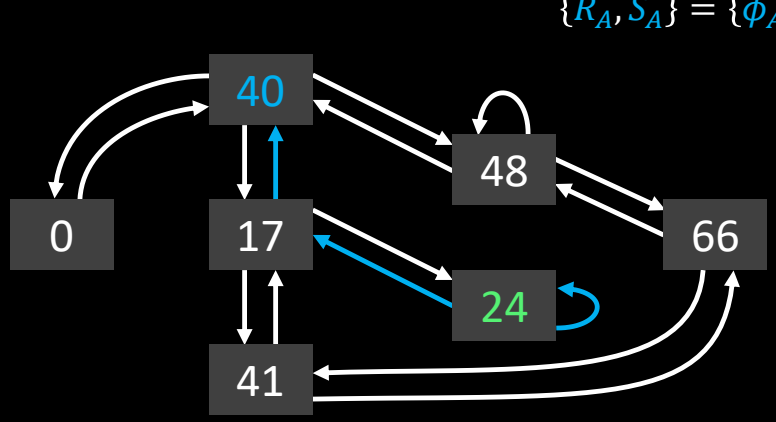
Bob

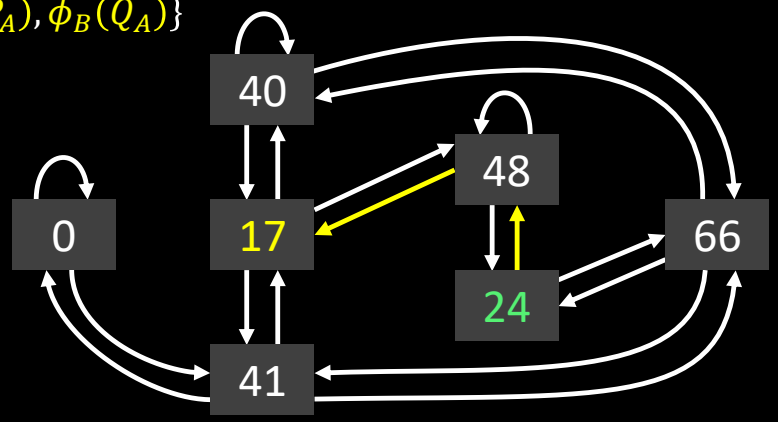
$E_A = E_0/\langle A \rangle$

$\{R_A, S_A\} = \{\phi_A(P_B), \phi_A(Q_B)\}$

$E_B = E_0/\langle B \rangle$

$\{R_B, S_B\} = \{\phi_B(P_A), \phi_B(Q_A)\}$





$E_0: y^2 = x^3 + x$

$\phi_A: E_0 \to E_A$

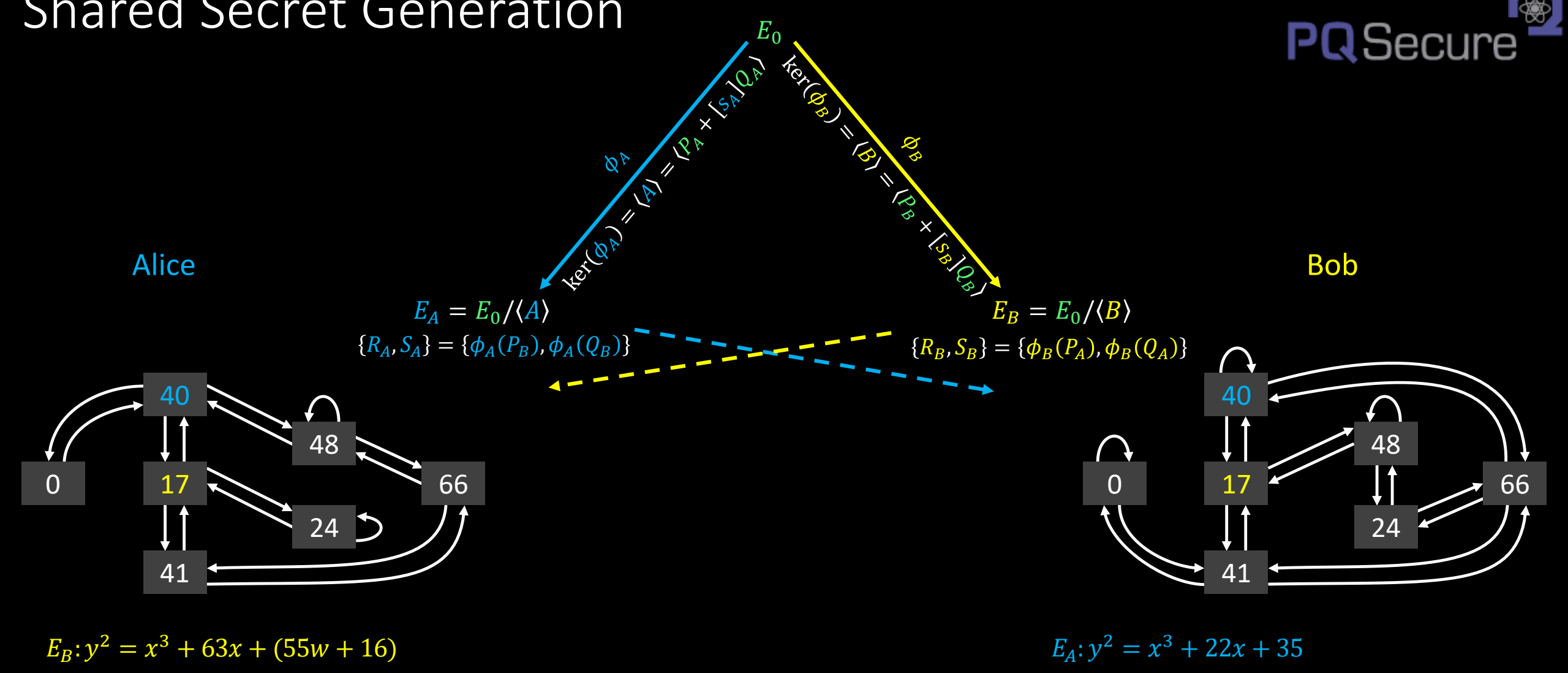
$E_A: y^2 = x^3 + 22x + 35$

$E_0: y^2 = x^3 + x$

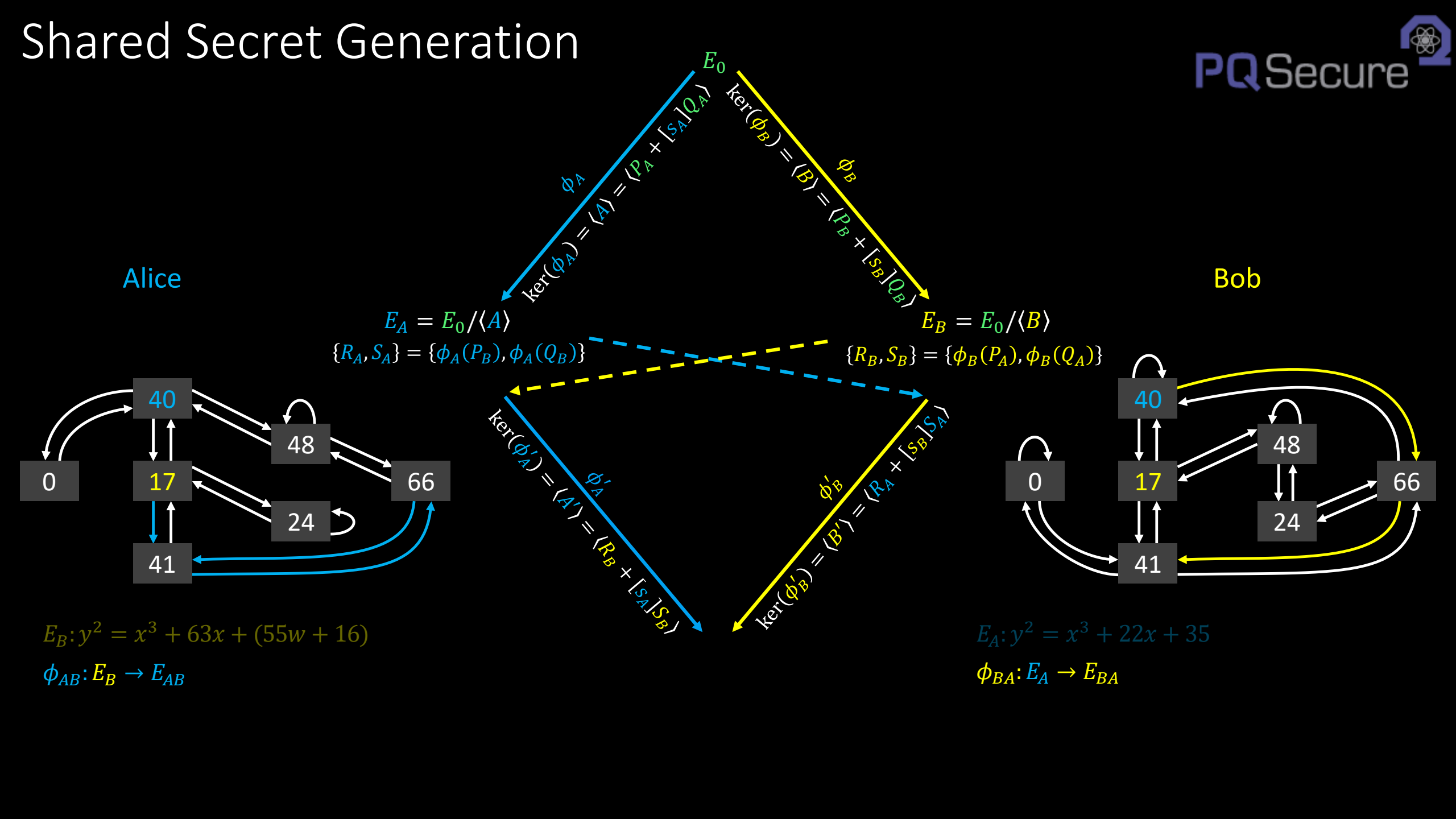
$\phi_B: E_0 \to E_B$

$E_B: y^2 = x^3 + 63x + (55w + 16)$

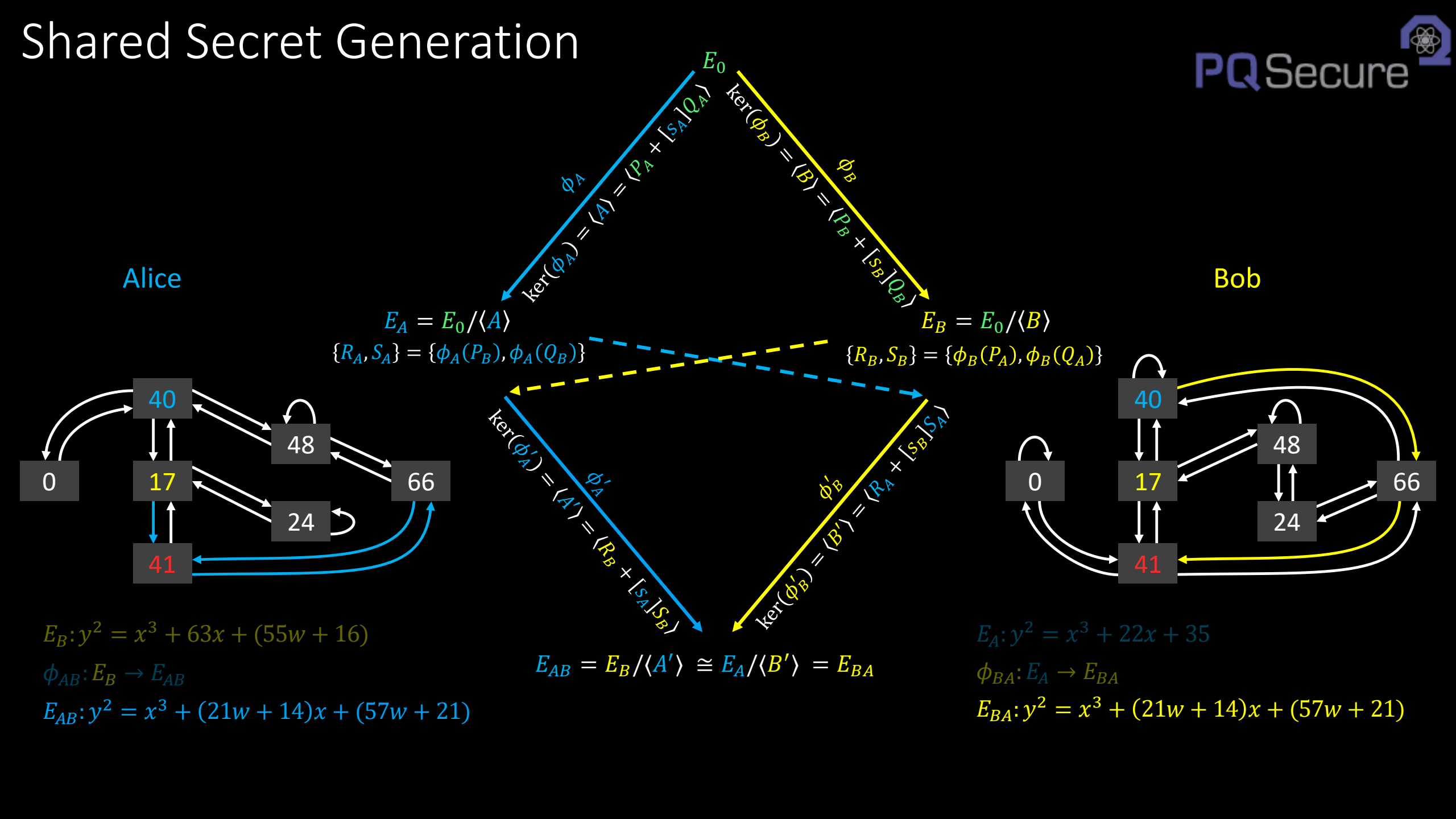
Shared Secret Generation



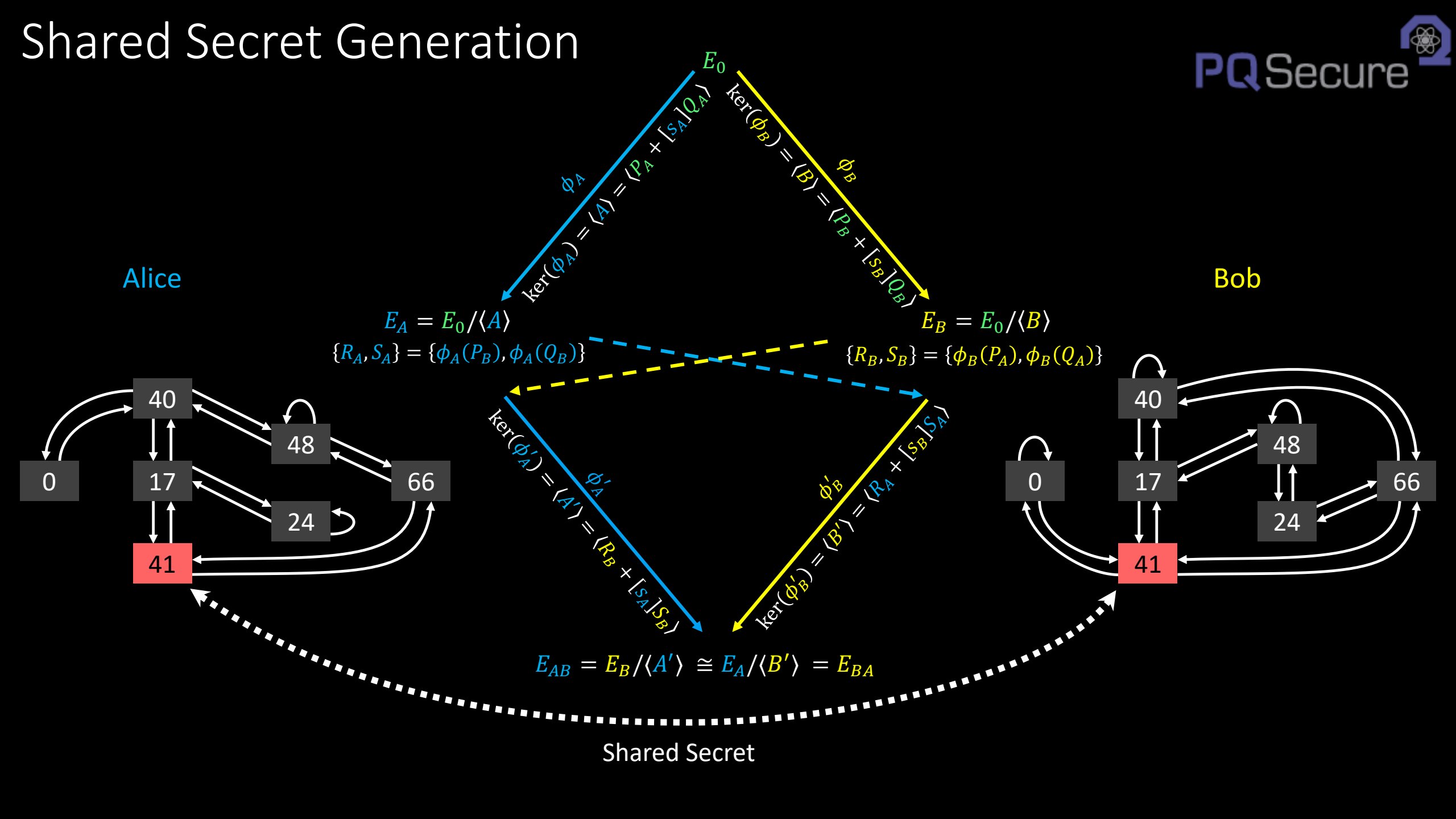
Shared Secret Generation



Shared Secret Generation



Shared Secret Generation



SIKE Key sizes

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NIST Level	Prime size (bits)	Prime	Public key size (bytes)	Compressed PK size (bytes)
1	434	$2^{216}3^{137}-1$	330	196
2	503	$2^{250}3^{159}-1$	378	224
3	610	$2^{305}3^{192}-1$	462	273
5	751	$2^{372}3^{239}-1$	564	331

SIDH Computations

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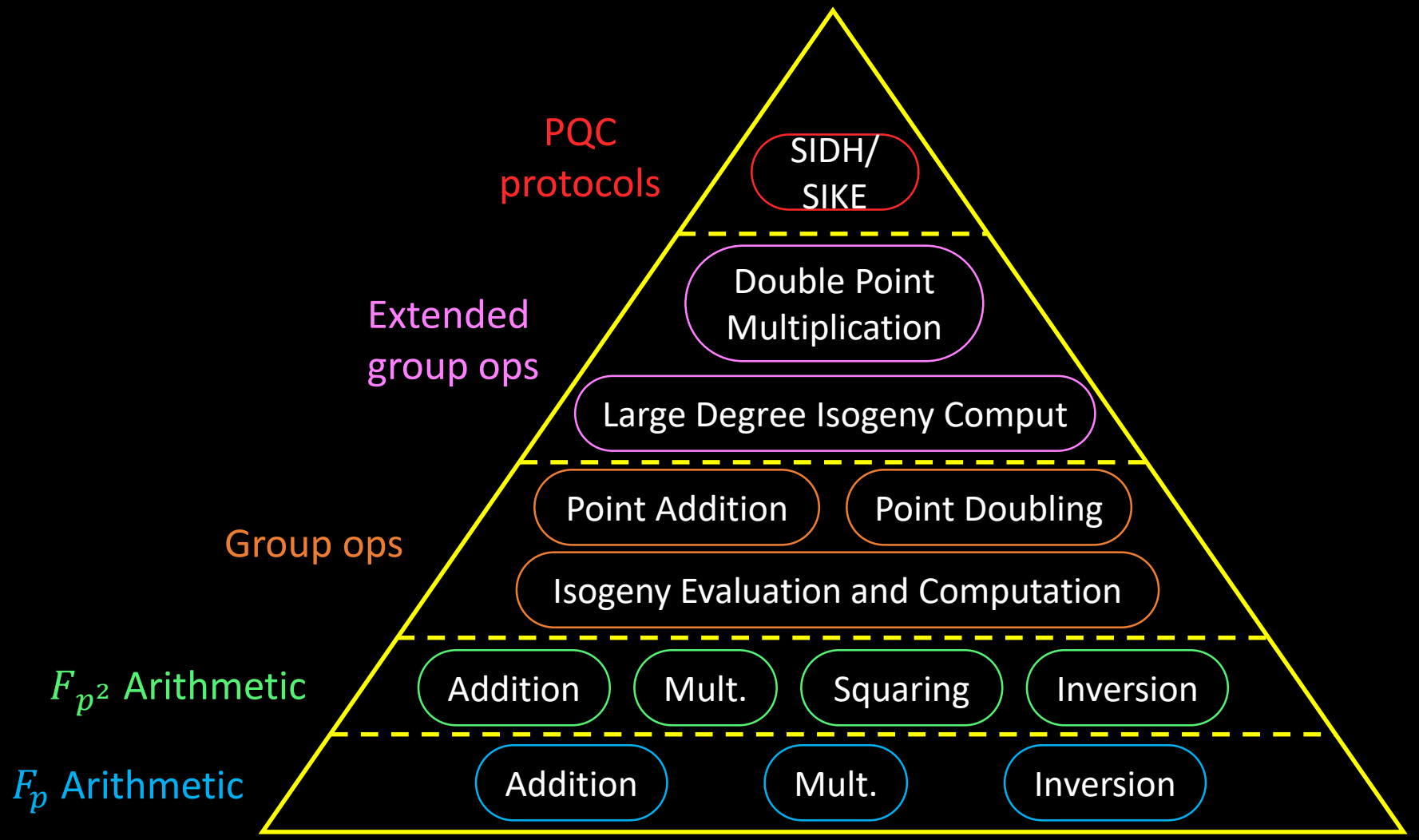

Comparisons

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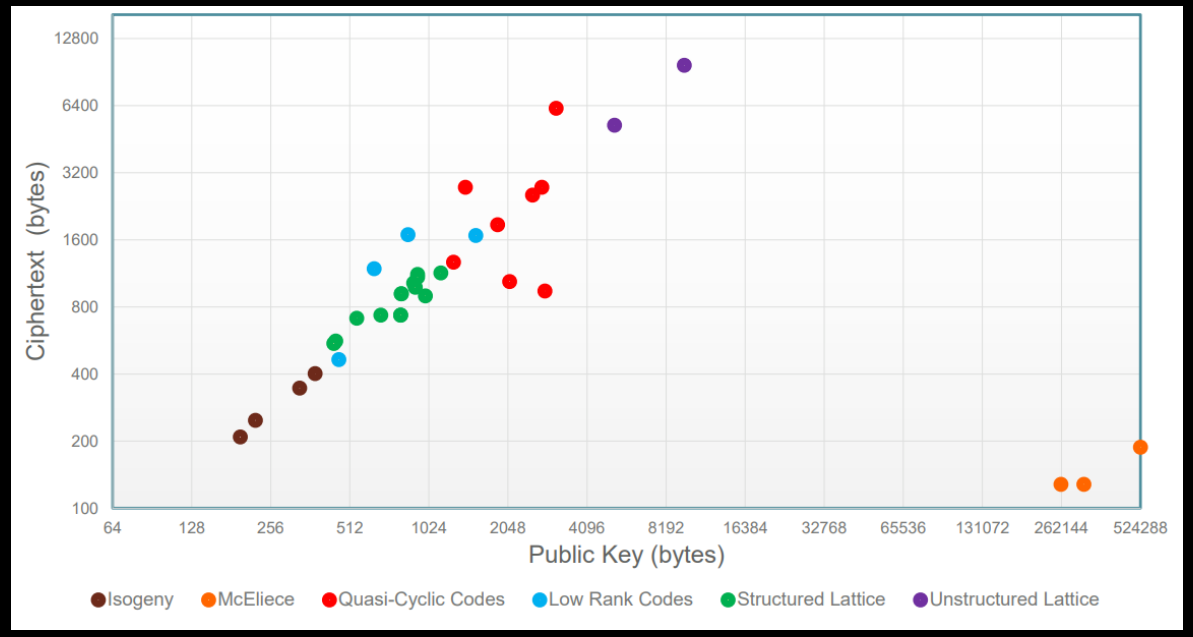
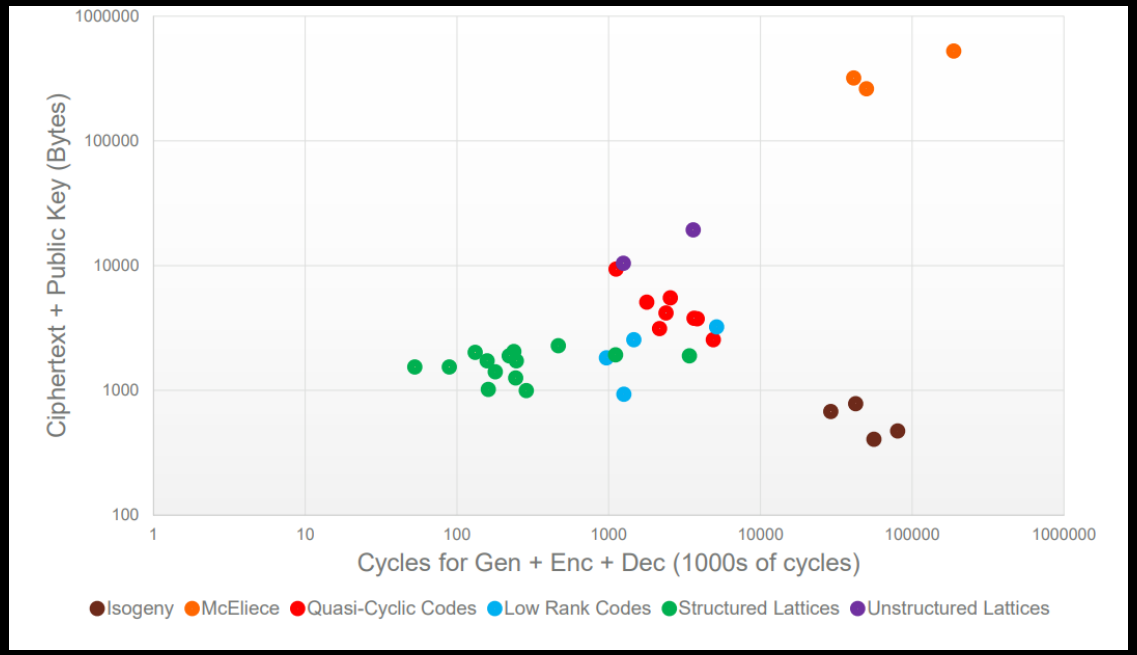
Public Key vs Ciphertext Size



Speed vs Size



Post-quantum on Small Devices

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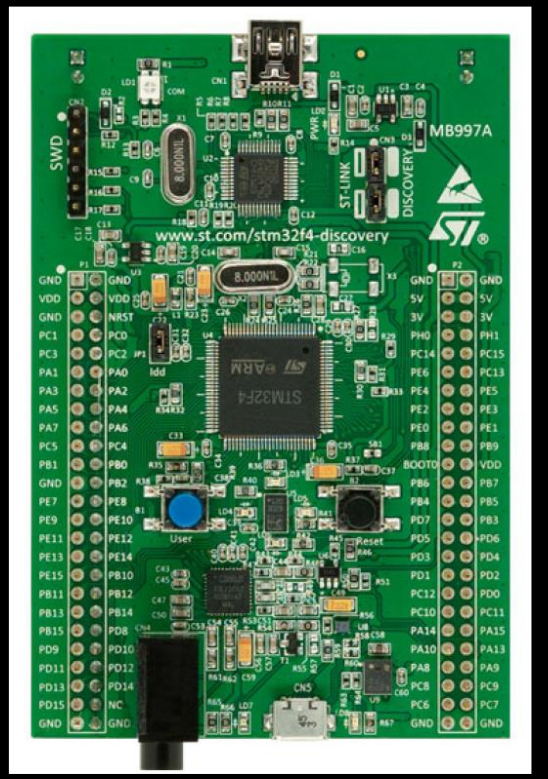
- STM32F4DISCOVERY
  - Recommended by NIST for PQC evaluation
  - ARM Cortex-M4
  - 32-bit, ARMv7E-M
  - 192 KiB RAM, 168 MHZ



STM32 F4

SIKE: Results for NIST level 1

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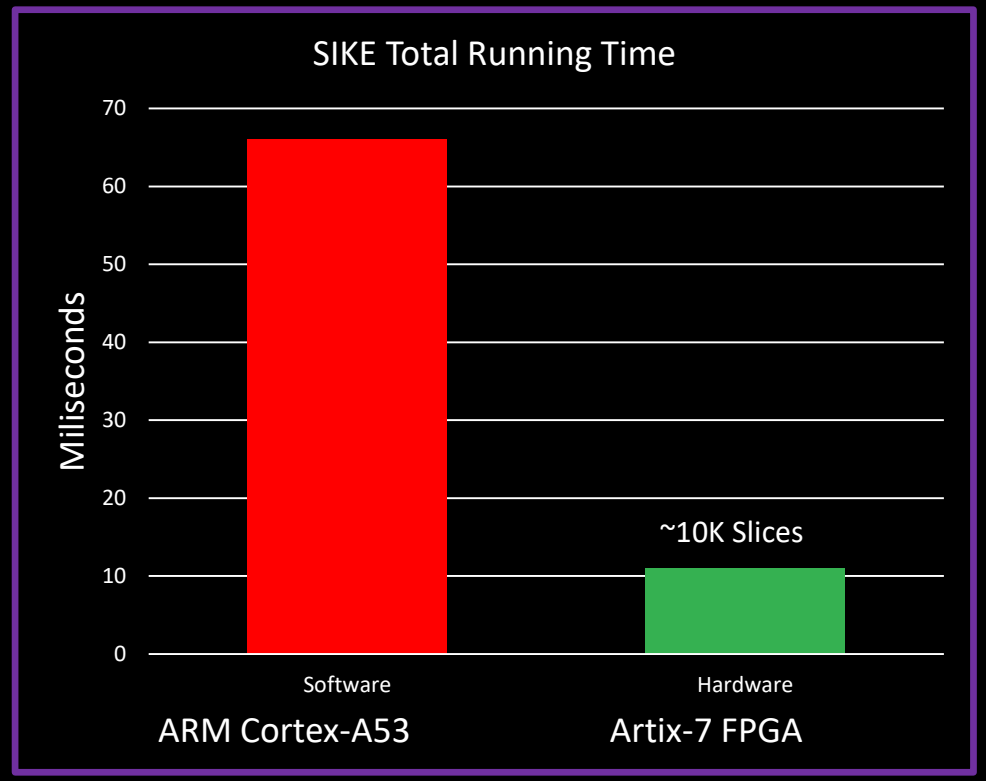
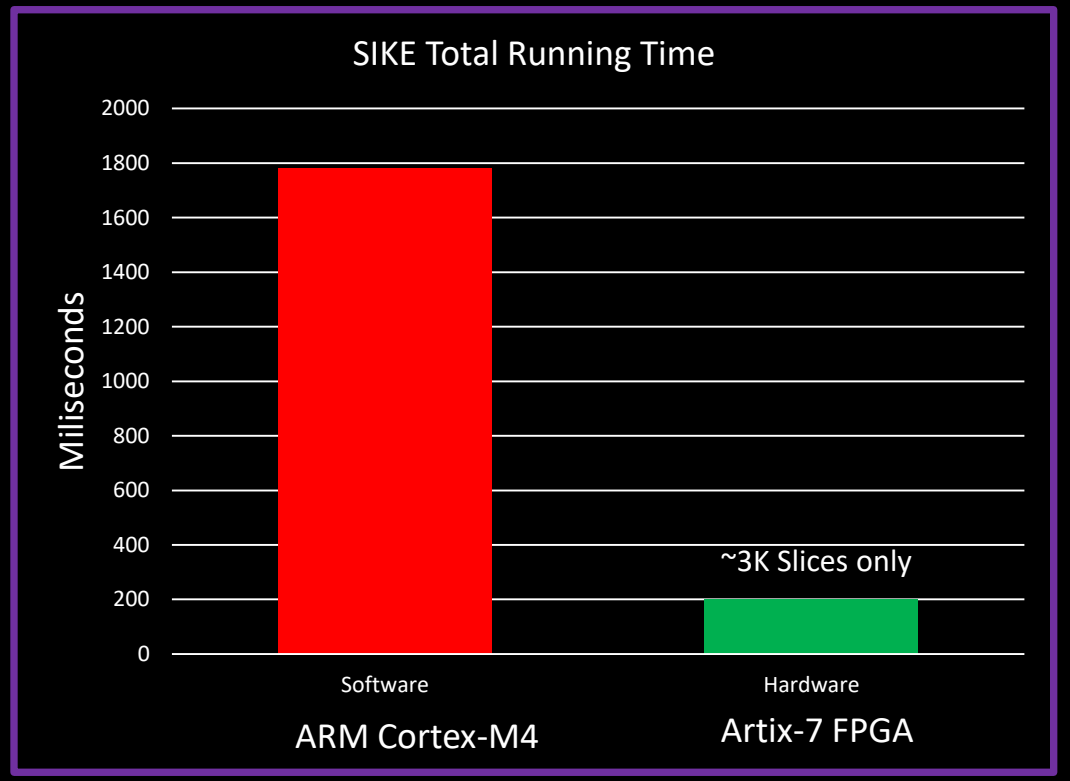
Target: High Performance Edge



Target: Resource-constrained IoT



Hybrid Key Exchange and Signatures

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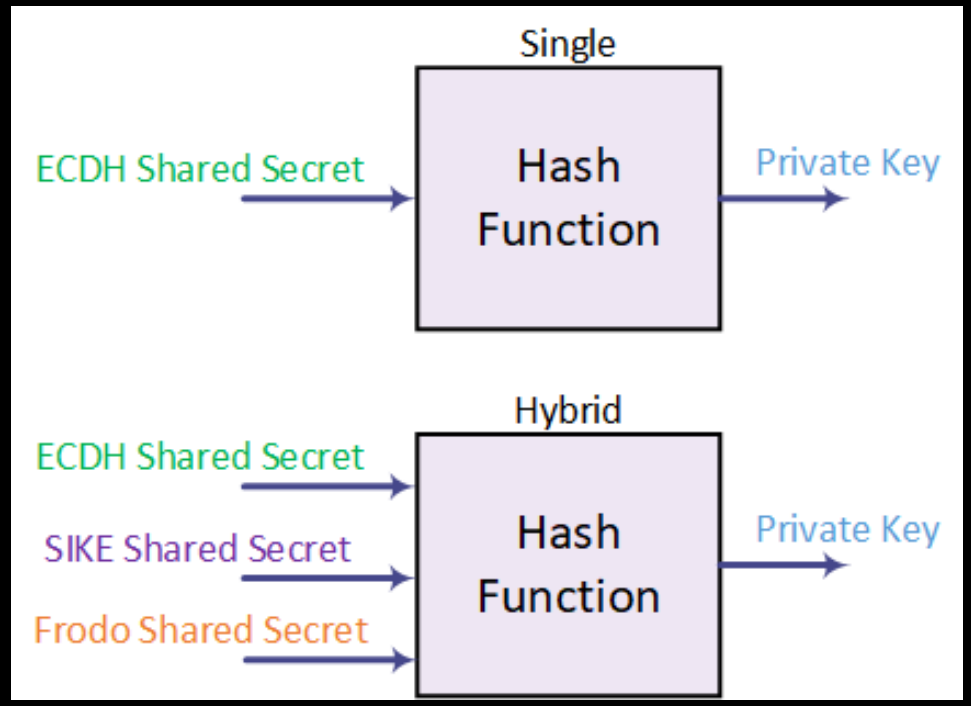
- Hybrid → combine multiple cryptosystems at once
  - Classical PKC still in use
  - Classical is Smaller/Faster/Efficient
  - PQC still being studied: i.e. may be broken
  - Multiple choices for different environments
- Goal: Leverage risk among multiple schemes

- Example:
  - Hash shared secret from multiple cryptosystems to get private key for AES

BROKEN if ECDH is broken



BROKEN if ECDH, SIKE, AND Frodo are broken

The case for SIKE

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- The post-quantum landscape is uncharted territory:
  - The smallest scheme is the slowest, and the fastest scheme is the largest.
  - Compare with traditional cryptography, where the fastest scheme (ECC) is also the smallest.

- This situation introduces a new set of tradeoffs.
  - SIKE's advantages will become more pronounced over time.
  - SIKE's disadvantages will become less pronounced over time.

The future of SIKE: Computational Costs

- Hardware gets faster over time.
- Software also gets faster over time.
- The above happens naturally, without effort or expenditure.
- An across-the-board performance increase reduces the performance penalty of SIKE (in absolute terms).
- We can also spend more money for faster hardware.
- Certain expenditures (e.g. hardware acceleration) provide good value per unit cost.

The future of SIKE: Communication Costs

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- As hardware and software gets faster, attacks get faster.
- Faster attacks require larger keys to counteract.
- An across-the-board key size increase enlarges the communication cost benefits of SIKE (in absolute terms).
- Variance in communication channels is much higher than variance in cycle counts. SIKE already wins today on desktop browsers when including variance.

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Thank you!

Questions?