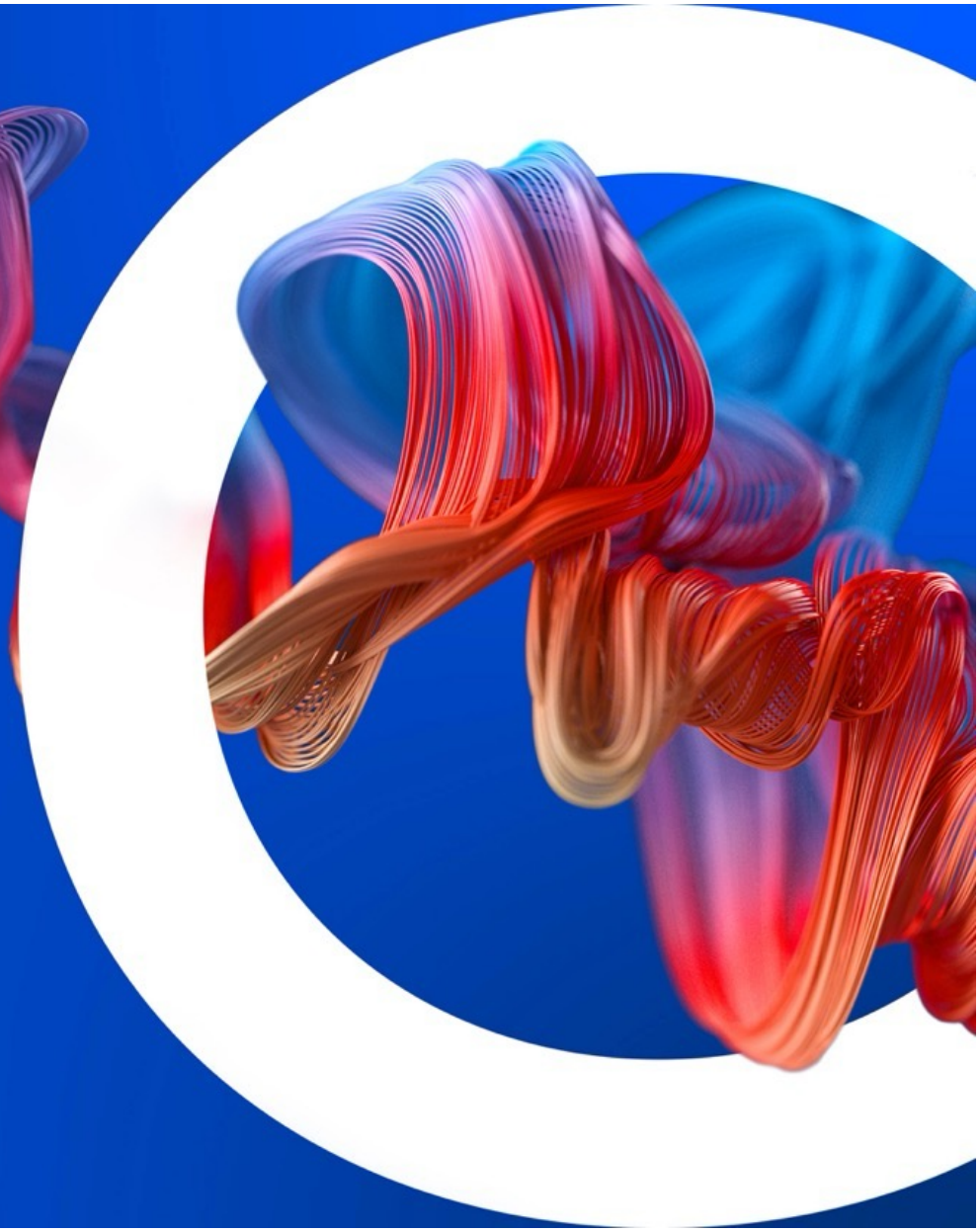
Cryptography in the Quantum Era

An IP transport perspective

Paresh Khatri

CTO IP Networks APAC



Agenda

1. Quantum computing
2. Impact of quantum computing on cryptography
3. The post-quantum future

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Quantum Technology

Quantum technology 1.0 and 2.0

Quantum Technology 1.0

Technology that exploits the *ensemble behavior* of **discrete quantum** particles, such as electrons, photons, and atoms

- Transistors
- LEDs/Lasers
- Solar Panels
- MRI

Quantum Technology 2.0

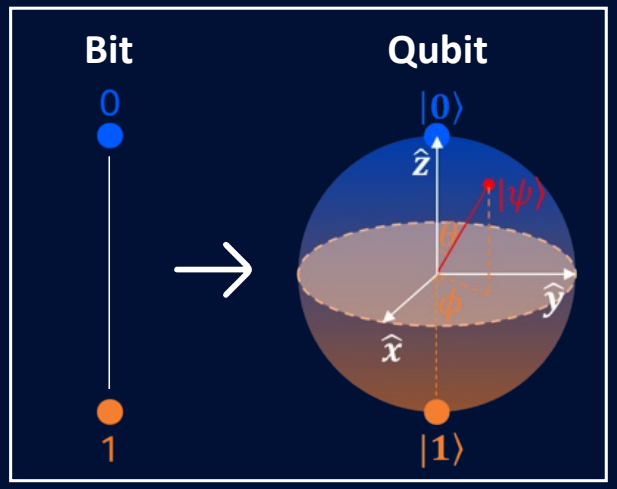
Technology that utilizes *individual quantum systems*, harnessing **quantum superposition** and **quantum entanglement**

- Quantum Computing
- Quantum Communication
- Quantum Sensing

Qubits, superposition, and entanglement

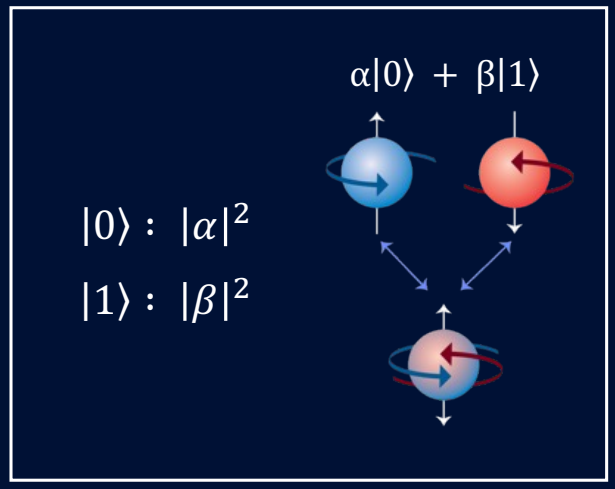
Foundation of Quantum 2.0 revolution

Qubit



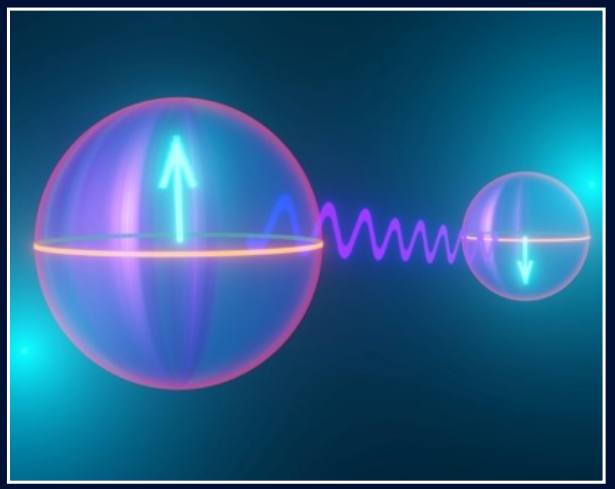
A qubit is the fundamental information container in a quantum system

Superposition



Qubits exist in multiple states at once, only collapsing to a single state when measured

Entanglement



Entangled qubits' states can't be separated. Measuring one immediately reveals the other.

Quantum computing

Computers that harness the properties of quantum mechanics, such as superposition, interference, and entanglement, to perform calculations

Quantum Computing

Classical bit

0 1 → 0 1 0 1

Each bit is either 0 or 1

Each 4-bit combination is one out of 2^4 possible permutations

Quantum bit (qubit)

0|1 → 0|1 0|1 0|1 0|1

Each bit is both 0 and 1 at once

Four bits represent all of the 2^4 possible permutations

Threats

Availability of Cryptographically Relevant Quantum Computer (**CRQC**) [**Q-Day**]

=

Current asymmetric cryptography (**PKC**)

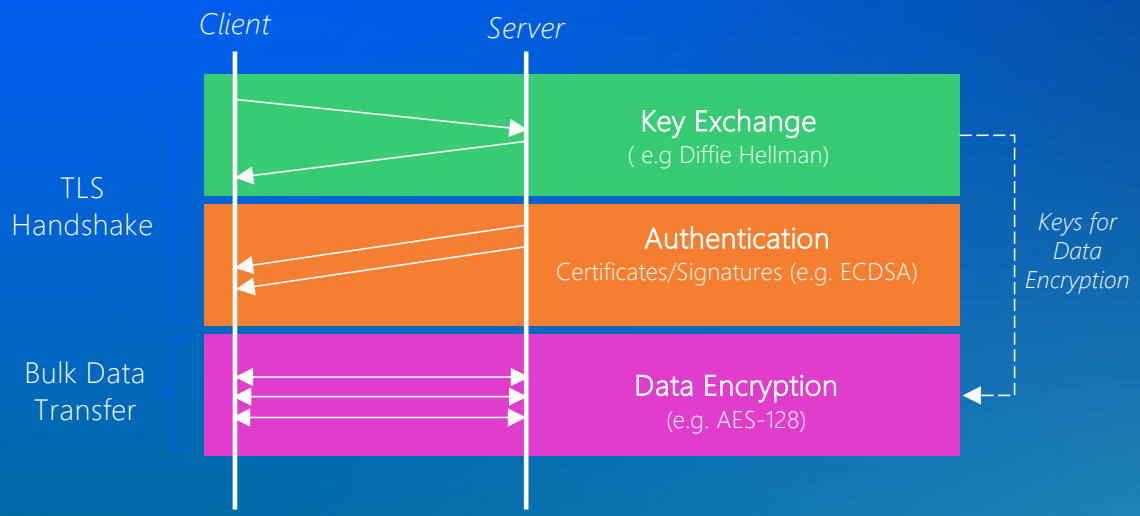
Impacts
SSL/TLS
SSH
IPsec
Digital signatures

Vulnerabilities

Harvest now and decrypt later (**HNDL**)

Zero-day vulnerability

Harvest Now Decrypt Later (HNDL) attack

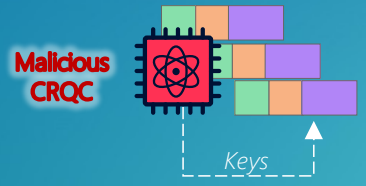


Key exchange algorithms vulnerable prior to & during existence of a CRQC e.g. Harvest Now Decrypt Later attack

Harvest Now, Decrypt Later Attack Overview

Step 1(Harvest Data) → Step 2(CRQC Available, Decrypt) → *time*

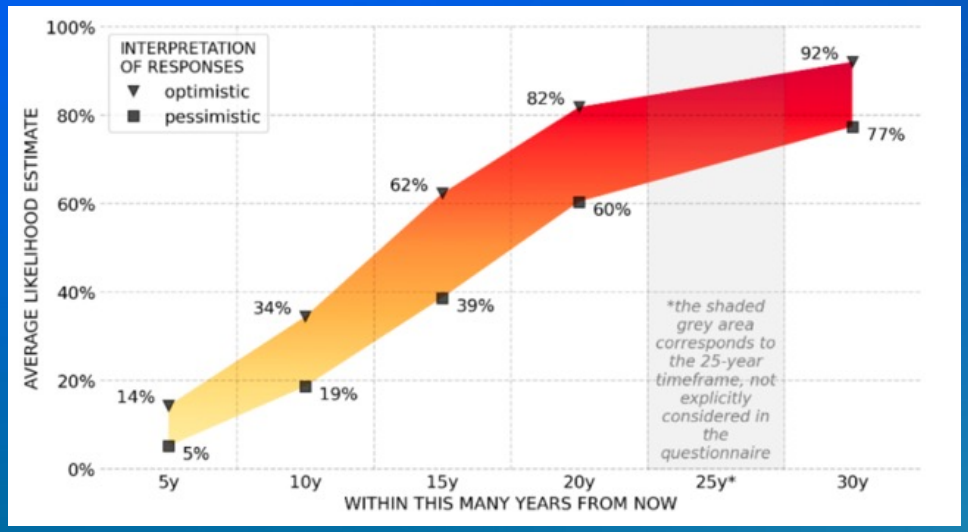
TLS Sessions Recorded & Saved



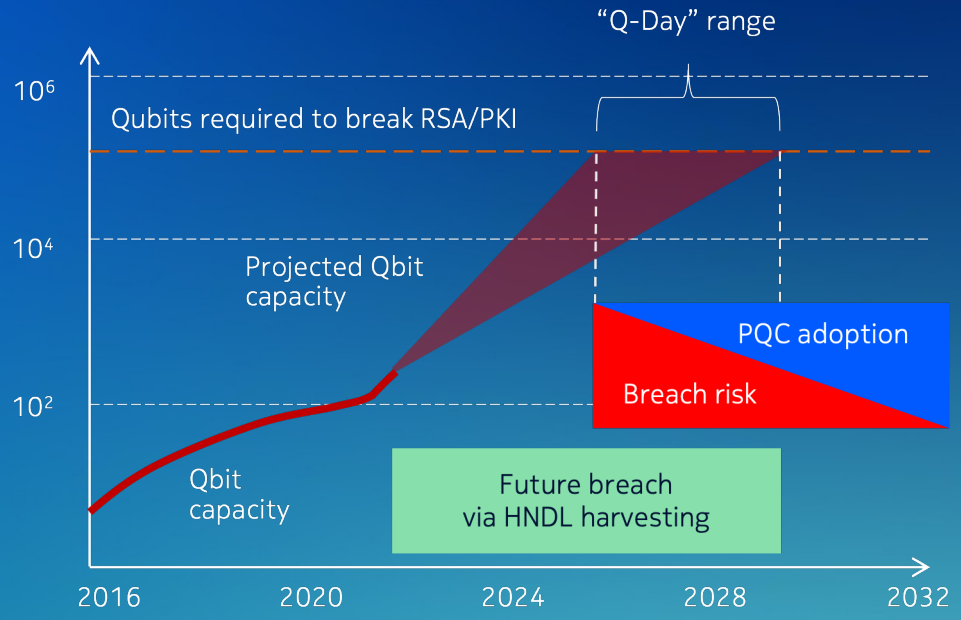
When CRQC available, replay recorded TLS handshake, break Key Exchange algorithm, reveal keys and decrypt recorded data

Quantum threat timeline

Likelihood of a Quantum Computer breaking RSA-2048 in 24h (2024)



Expert Survey Source: Global Risk Institute, Quantum Threat Timeline Report 2024



The key question: when is Q-Day?
Estimates vary … some predictions of as early as 2030!

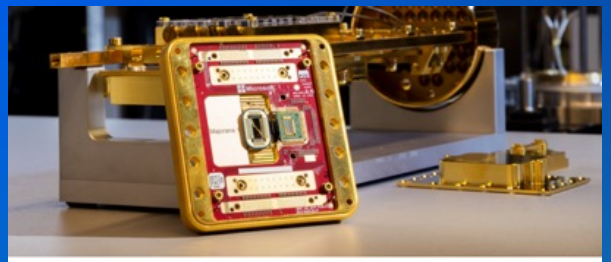
Quantum computers

Where we are today …

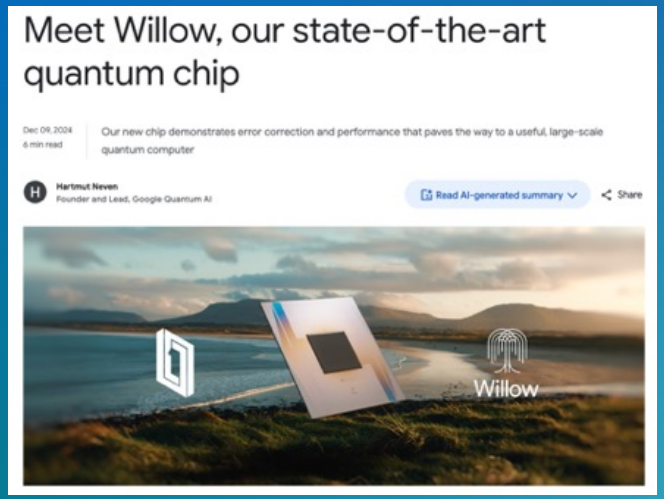
Comparison Table: Leading Quantum Computers (2025)

Source: https://makb183.com/top-10-most-powerful-quantum-computers-in-the-world/

Rank	Company	System Name	Qubits
1	IBM	Condor	1,121
2	D-Wave	Advantage 2	7,000+
3	Google	Quantum AI	100+
4	Xanadu	X-Series	216
5	IonQ	Aria	32
6	Intel	Tunnel Falls	12
7	Rigetti	Aspen-M-3	80
8	Amazon	Braket	Various
9	Microsoft	Azure Quantum	Various
10	Baidu	Quantum Leaf	10



Microsoft's Majorana 1 chip carves new path for quantum computing



We should not expect to be publicly informed about the existence of the first cryptographically relevant quantum computers (CRQCs)!

2033+

Deliver quantum-centric supercomputers with 1,000's of logical qubits.

Beyond 2033, quantum-centric supercomputers will include thousands of qubits capable of running 1 billion gates, unlocking the full power of quantum computing.

IBM

NOKIA

Agenda

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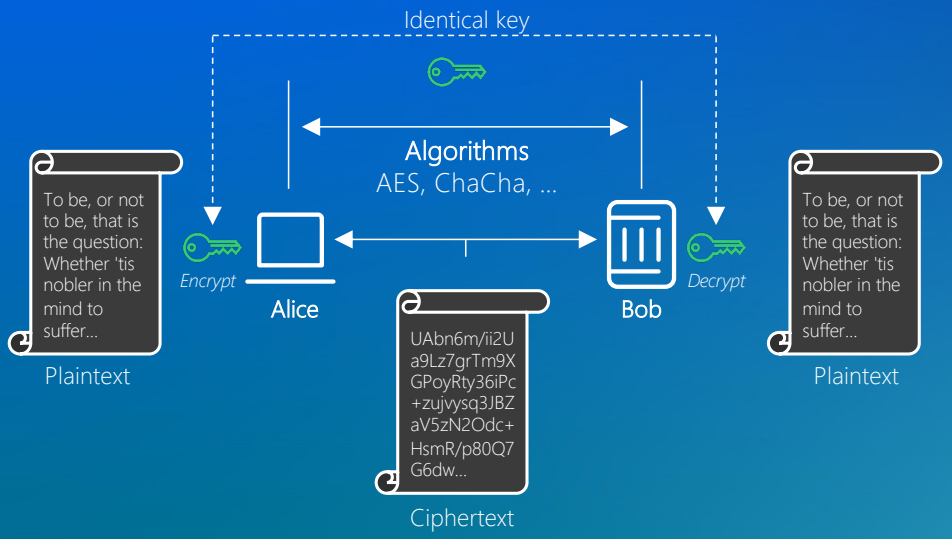
2. Impact of quantum computing on cryptography
3. The post-quantum future

Symmetric cryptography
Overview of operation

Main application: bulk data encryption



Static applications
suitable for manual or controlled configuration

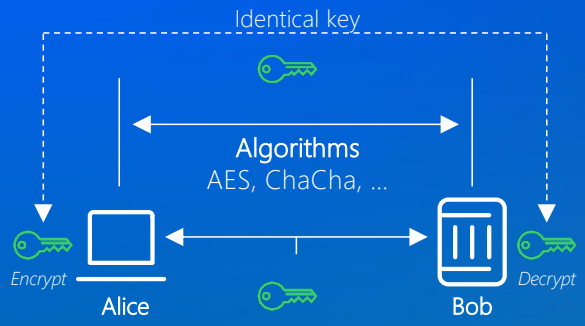
Lower scale of endpoints
limited by the need for explicit configuration

Large traffic volumes
fast encryption able to handle large amounts of data

Key distribution challenge
secure key distribution is a major challenge

Symmetric cryptography

Key distribution, strength and cipher

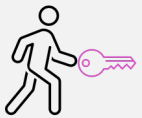


Single biggest challenge

How to ensure that both of the communicating parties can securely exchange or agree on the encryption key

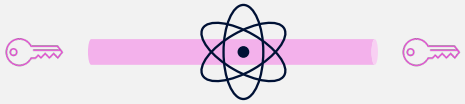
Key distribution

Pre-shared Keys (PSK)



"**Manual**" key distribution

Quantum-Key Distribution (QKD)



Key-distribution channel secured by **quantum-physics**

Key agreement/exchange

Key-distribution channel secured by **asymmetric crypto**

Key strength

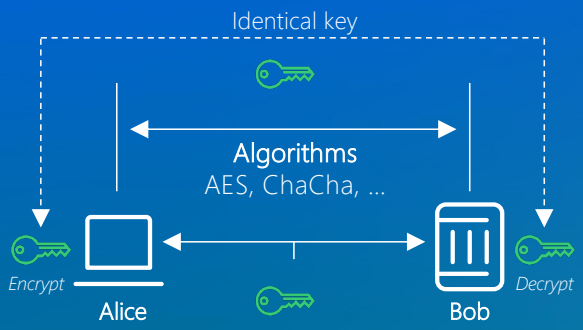
Function of:

- Size of the key
- Method of key generation and resulting entropy
- Process of key exchange
- Key management

Advanced Encryption Standard (AES)

- A symmetric encryption algorithm used for securing sensitive data
- Symmetric encryption means the same secret key is used for both encryption and decryption
- AES is computationally efficient, making it suitable for a wide range of applications

Symmetric cryptography
Impact of quantum computing



The Quantum Threat

Grover's algorithm

- Devised by Luv Grover in 1996
- Also known as the quantum search algorithm
- Finds with high probability the unique input to a black box function that produces a particular output value, using sqrt(N) evaluations. In other words, it reduces time to brute-force a key from $O(N) \rightarrow O(\sqrt{N})$ i.e. provides *quadratic speedup*
- Classical computers cannot solve this in fewer than O(N) as one has to check half of the domain to get a 50% chance of finding the right input

The Solution

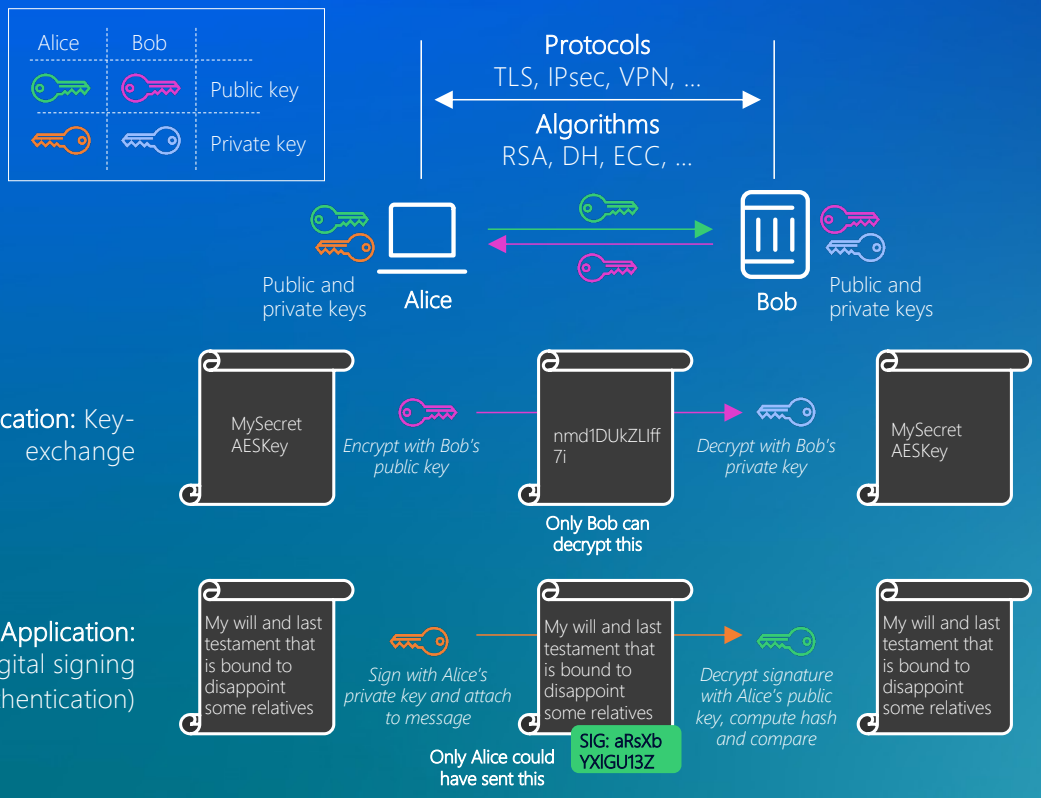
Double the key size just to be safe!

AES128→ AES256
SHA256 → SHA512

However, even this is not required since in real environments it is quite likely that Grover's algorithm will provide little or no advantage in attacking AES and AES-128 will be secure for years to come.

Asymmetric (public key) cryptography
Overview of operation

Main applications: Key-agreement, authentication



Dynamic environments
suitable for client-server applications

Larger scale of endpoints
suits dynamic, on-demand requirements

Small traffic volumes
fast encryption able to handle large amounts of data

Solves the challenge of key distribution
public/private key pair derived mathematically

Asymmetric (public key) cryptography

How it works

Entropy Sources → A measure (in bits) of the amount of randomness or unpredictability → A full random binary string has maximal entropy → Informational Entropy

Informational Entropy: a function of deterministic algorithms and seed value(s) used to generate sequences of numbers that appear random

RSA → **prime factorization** is given by;

From two large prime numbers p and q, calculate $N = p \cdot q$
Then the totient T is calculated $T = (p-1) \cdot (q-1)$
Alice's Public key E_a is calculated by $T \pmod{E_a} \neq 0$
Alice's Private Key D_a is calculated by $(D_a \cdot E_a) \pmod{T} = 1$

*It's easy to work out N = p*q. However, given N, it is extremely difficult to determine p and q (the problem of integer factorization), provided they are sufficiently large.*

DH, ECDSA or ECDH → **Discrete logarithm** is given by;

From a large prime number p, g, a generator of p and a random number X_a (Alice's private key),
Alice's Public key E_a is calculated by $E_a = g^x \pmod{p}$
Using Bob Public key E_b, the Shared Secret Session key S is calculated by $S = E_b^{Xa} \pmod{p}$

Key exchange

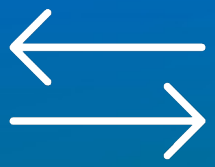
Asymmetric (public key) cryptography

Random Secret Keys

Used to encrypt and decrypt messages, and ensure the security of the system

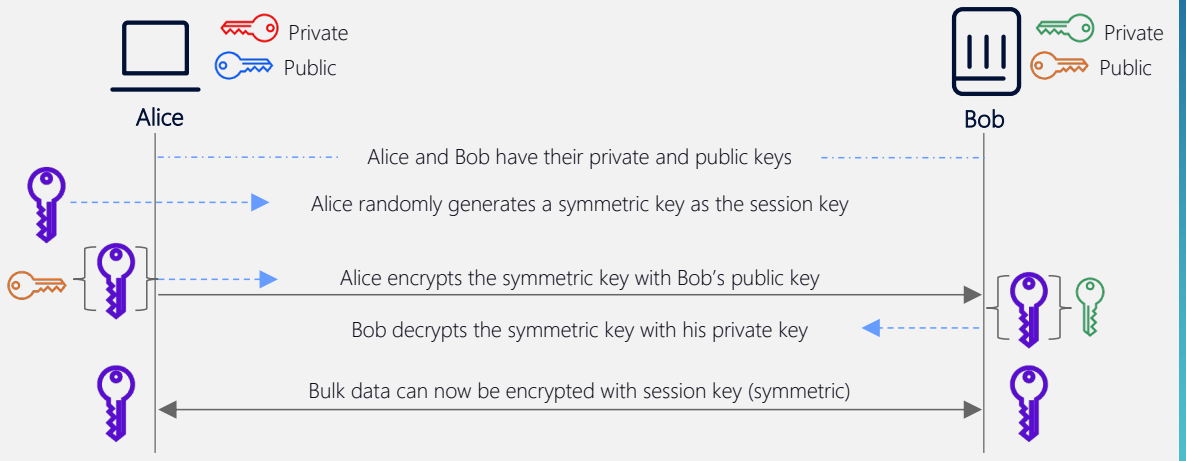
Key exchange

- Public Key Cryptography (Factorization)
- Pre-Shared Keys
- Quantum-Key Distribution



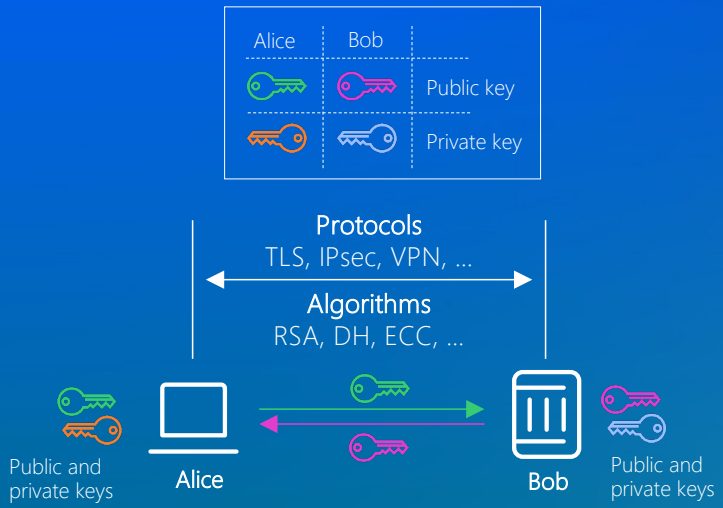
Key exchange permits the information exchange with asymmetric encryption to enable two parties with a symmetric key as session key to cipher in-flight bulk information.

Simplified example with RSA (confidentiality)



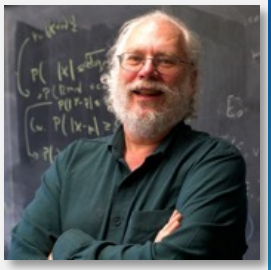
Asymmetric (public key) cryptography

Impact of quantum computing



The Quantum Threat

Shor's algorithm



- Developed in 1994 by the American mathematician Peter Shor
- Quantum algorithm for finding the prime factors of an integer.
- RSA → prime factorization
- DH, ECDSA or ECDH → Discrete logarithm
- Estimate: to break RSA 2048, in an ideal world, one needs about 4,000 logical qubits and 100 million gates *(today: 100s of qubits and 1000s of gates).*

Breaks classical public key cryptography

The Solution

Design new quantum-resistant algorithms!

=> Post-Quantum Cryptography (PQC)

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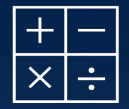
Quantum-safe cryptography - the post-quantum future

The way forward…

Symmetric key solutions

- Based on **EXISTING** technology
- Symmetric keys & symmetric crypto
- Key distribution approach
  - Pre-shared keys (PSK)
  - Quantum Key-Distribution (QKD)
- Only encryption

Asymmetric key solutions (**PQC**)



- Based on **NEW** mathematics (**Post Quantum Cryptography = PQC**)
- Public Key Cryptography
- Key agreement approach (protocols)
- Authentication and encryption

QKD and PQC are seen as complementary and will co-exist in the post-quantum cryptography toolkit

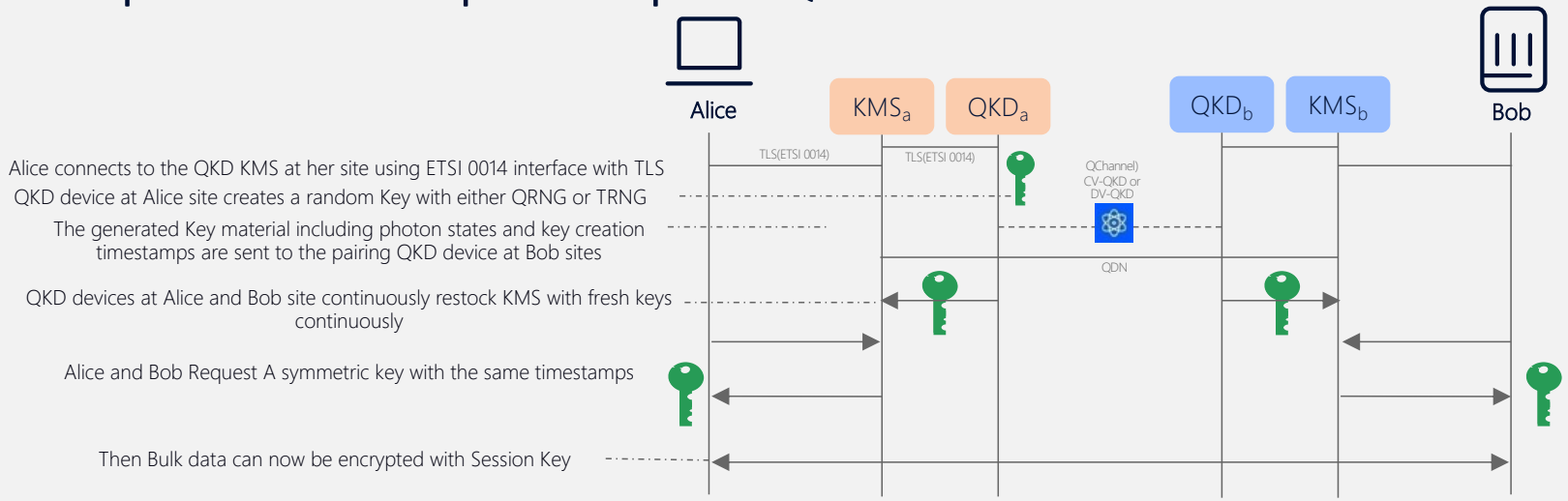
Quantum Key Distribution (QKD)

QKD: theoretically (provably) secure *without making any assumptions about the computational capability to crack it*

Quantum Key Distribution

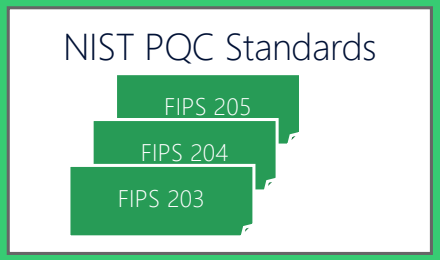
- Based on principles of quantum mechanics
- Used only to produce and distribute a key (not to encrypt data itself) [can take the place of an asymmetric key exchange protocol]
- Key can then be used with a symmetric cipher
- Attempts to eavesdrop can be detected

Example of standard point-to-point QKD



PQC standardisation

NIST PQC Standards



2016~2024

- NIST PQC Standardization Program launched in 2016 & first PQC standards published in Aug 2024:
  - ML-KEM (FIPS 203)- Key Encapsulation
  - ML-DSA (FIPS 204)- Signature
  - SLH-DSA (FIPS 205)- Signature(backup)
- NIST evaluating additional algorithms for both Key Encapsulation and Signatures
- NIST selects HQC as an alternative to ML-KEM

IETF PQC Stds Support

Protocol	Hybrid PQ/T Key Exchange	Hybrid PQ/T Signatures
TLS	Stable Document for Implementation	Draft discussed in WG
IKE/IPsec	Stable Document for Implementation	Draft discussed in WG
JWS	N/A	Draft adopted by WG
JWE	Draft discussed in WG	N/A
X.509/CMP under discussion, more studies required for PKI in general		

3GPP PQC Stds Support

- 3GPP expected to undertake first PQC studies in 6G Rel20 and define normative specifications in 6G Rel21
- Scope of work expected to include
  - Profiles of IETF PQC enabled protocols used in 3GPP e.g., TLS, IKE/IPsec, JWS, JWE…
  - SUPI protection w/ PQC

Policy makers are responding to the security impact

Is your cybersecurity ready to take the quantum leap?

EU urged to prepare for quantum cyberattacks with coordinated action plan

The US is worried that hackers are stealing data today so quantum computers can crack it in a decade*

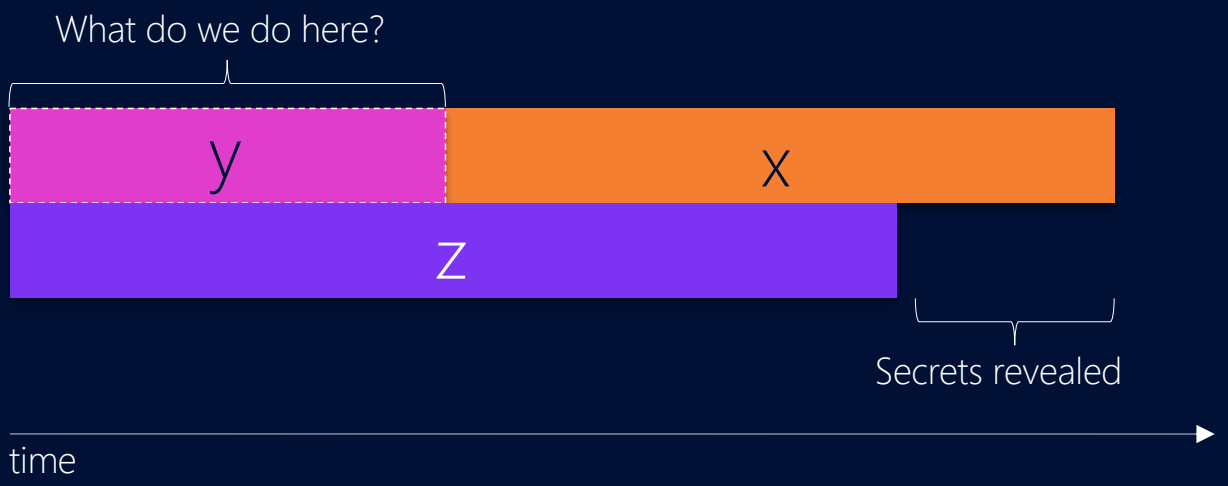
*The US government is starting a generation-long battle against the threat next-generation computers pose to encryption.

Singapore to build national quantum-safe network that provides robust cybersecurity for critical infrastructure

South Korea plans large scale quantum cryptography adoption

Assessing the threat

Mosca's theorem of cybersecurity in the quantum era[1]



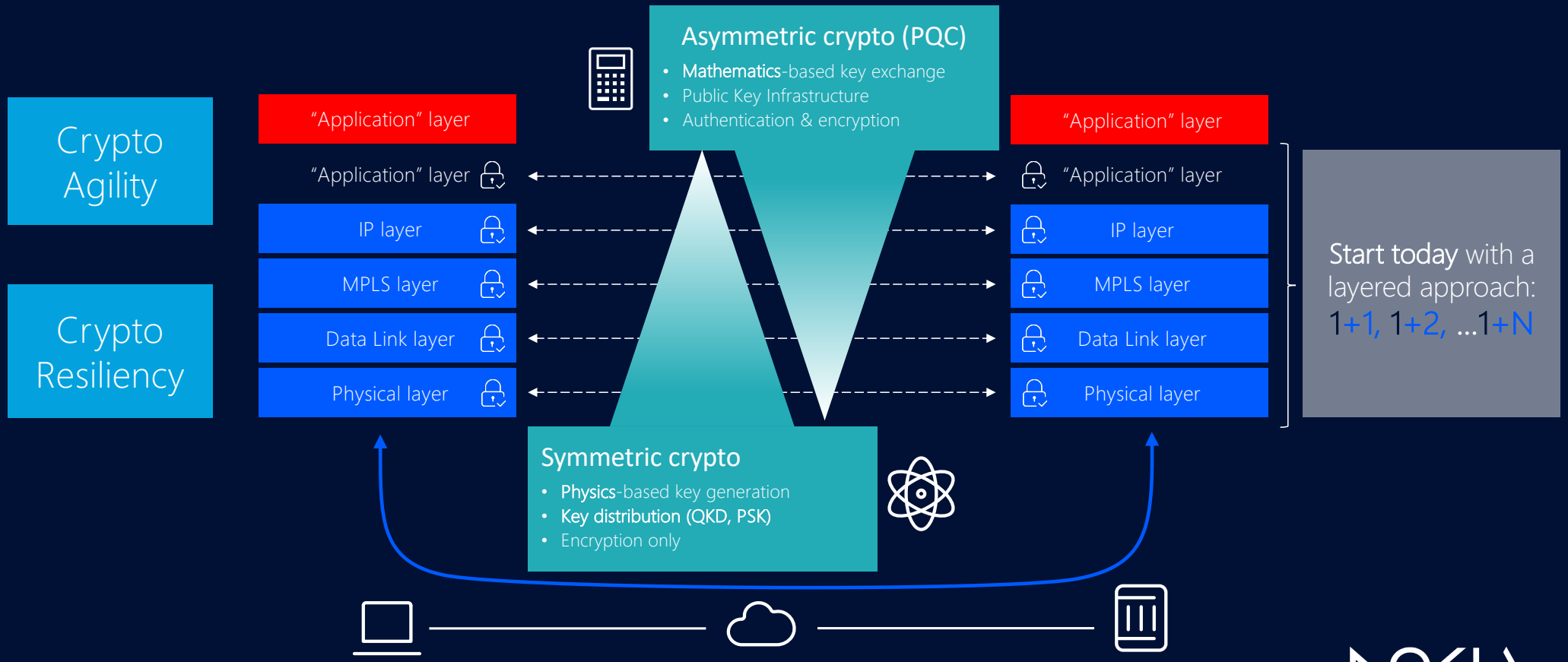
If x + y > z, then start worrying

x: time we want to keep our systems secure
y: time to deploy a quantum-safe migration plan
z: time to build a large-scale quantum computer (2030s?)

[1] https://eprint.iacr.org/2015/1075.pdf

Strategy for the way forward: defense-in-depth approach

Demands multi-layered approach using asymmetric and symmetric cryptography

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