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Secured and Adaptive Continuum:
Crypto Agility & Sustainable Security for Cyber-Physical Systems (or Physical AI)

‘Secure Digital Systems (SDS)‘ Research Group

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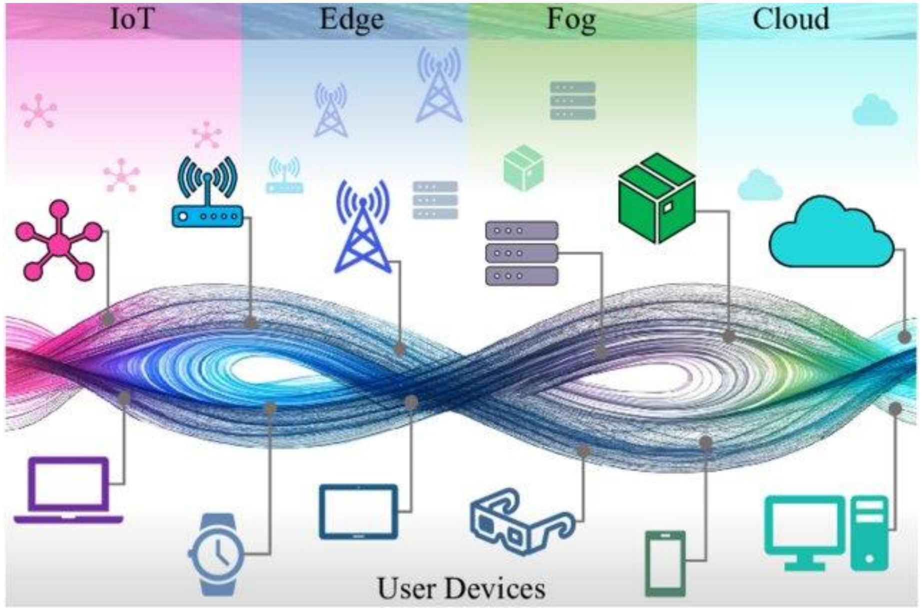
25.09.2025

What is “continuum“?

- In **computing & technology**

  - *Seamless integration* and *unified nature* of distributed computational resources, encompassing *devices from the cloud to the network edge**



[*] L. F. Bittencourt et al., The computing continuum: Past, Present, and Future, Computer Science Review, Volume 58, 2025, doi: 10.1016/j.cosrev.2025.100782
[Figure] V. Karagiannis, Data Sovereignty and Compliance in the Computing Continuum, 11th International Conference on Future Internet of Things and Cloud (FiCloud), pp. 123-130, 2024, doi: 10.1109/FiCloud62933.2024.00027

“Security“ in Computing Continuum

- Security in the computing continuum is essential!*
  - Vast, interconnected nature of cloud, edge, and IoT devices creates an expansive attack surface and complex vulnerabilities
  - Requires **end-to-end**, **agile**, and **proactive** protection
  - Demand for **smart, automated mechanisms** to **secure all layers and components** against threats, ensuring the **confidentiality, integrity, and availability of data** and systems **throughout their entire lifecycle**

[*] https://www.horizon-europe.gouv.fr/secure-computing-continuum-iot-edge-cloud-dataspaces-32305

Why Security is Crucial?

- **Interconnected Ecosystem**
  - Countless interacting devices and platforms, from resource-constrained IoT devices to high-performance cloud systems, broadens the attack surface

- **Complex Vulnerabilities**
  - System complexity creates numerous opportunities for attacks, ranging from industrial control systems to smart city infrastructure applications

- **Sensitive Data**
  - Vast amounts of sensitive user and business data is handled, which must be protected from breaches, tampering, and unauthorized access across different layers

- **Evolving Threats**
  - Conventional security methods are often inadequate for addressing the unique challenges of the continuum, requiring adaptable protection mechanisms

What Needs To Be Secured?

- **All Levels**
  - Security measures at every level of the architecture, from the smallest edge devices to complex cloud environments
- **Components**
  - Individual components; including software, cloud infrastructure, and IoT devices
- **System Lifecycle**
  - Security and privacy measures should be available for all components and systems throughout their entire lifecycle, from deployment to disposal

Key Security Concepts and Technologies [1, 2]

- **End-to-End Security**
  - Security must be integrated across the entire continuum, from the origin of data to its destination
- **Privacy-Enhancing Technologies**
  - Enabling data analysis without compromising sensitive information
- **Dynamic Intrusion Detection**
  - Systems are needed to detect and respond to malicious activities in real-time
- **Attribute-Based Access Control**
  - Used for managing access rights and authorizations, ensuring that users only have access to necessary resources

[1] https://www.horizon-europe.gouv.fr/secure-computing-continuum-iot-edge-cloud-dataspaces-32305
[2] M. Barbareschi, V. Casola and D. Lombardi, "Ensuring End-to-End Security in Computing Continuum Exploiting Physical Unclonable Functions," 2023 IEEE International Conference on Cloud Computing Technology and Science (CloudCom), pp. 273-278, 2023, doi: 10.1109/CloudCom59040.2023.00051

Key Security Concepts and Technologies [1, 2]

- **Physical Unclonable Functions (PUFs)**
  - Such unique hardware identifiers / hardware security anchors derived from physical/manufacturing variability can be used to enhance security, especially for resource-constrained devices, at low-cost

- **Data Encryption**
  - Encrypting sensitive data before it is uploaded to the cloud or transmitted over networks is fundamental

- **Identity and Access Management**
  - Regular review and updating of policies are critical to ensure proper user access

[1] https://www.horizon-europe.gouv.fr/secure-computing-continuum-iot-edge-cloud-dataspaces-32305
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All calling for cryptographic solutions such as encryption algorithms and protocols!

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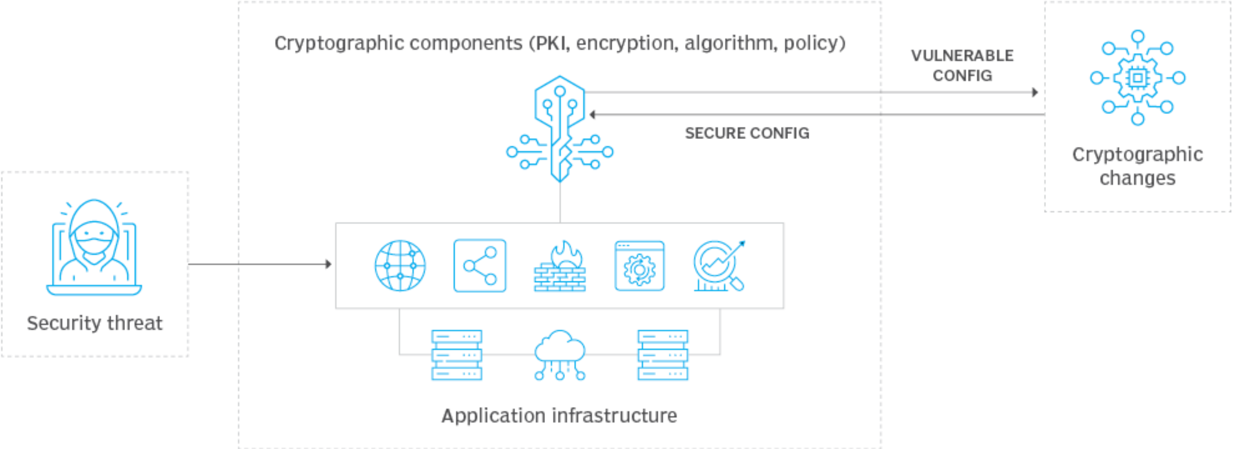
What is Crypto Agility?

- Ability of an organization to **swiftly and easily switch between different cryptographic algorithms, protocols, and keys** to **adapt to evolving threats and new standards** [1, 2]

- An inherent **flexibility minimizes risk by preventing significant infrastructure disruption** when **vulnerabilities are discovered or when new encryption technologies become necessary**



[1] https://www.cyber.gc.ca/en/guidance/guidance-becoming-cryptographically-agile-itsap40018
[2] https://www.capgemini.com/ch-en/insights/expert-perspectives/crypto-agility-the-unsung-hero-in-the-quantum-security-race
[Figure] https://www.techtarget.com/searchenterpriseai/definition/crypto-agility

More exactly…

- **Adaptability**
  - Capability to replace or update cryptographic components without needing to change/replan the entire IT infrastructure
- **Response to threats**
  - Allows organizations to quickly respond to new cryptographic vulnerabilities or the emergence of more powerful computing capabilities
- **Proactive approach**
  - Instead of a one-time fix, a continuous, proactive process of building the flexibility to respond to threats and standards over time

Why important?

- **Long-term security**
  - Ensures that systems remain secure and trustworthy as technology and threats evolve
- **Minimizes risk and outages**
  - Enabling rapid adaptation helps preventing events like certificate outages and minimizes risk exposure for businesses and users
- **Future-proofing**
  - Prepares organizations for the challenges of new algorithms which may need to be adopted

How To Achieve?

- **Maintain a comprehensive inventory**
  - Track all cryptographic keys, certificates, and algorithms in use
- **Adopt flexible frameworks**
  - Use modern development frameworks and service software that allow cryptographic algorithms to be updated via configuration files or databases
- **Implement robust Public Key Infrastructure (PKI)**
  - For managing digital certificates, essential for authentication and encryption
- **Plan for transitions**
  - Develop detailed plans for migrating from older algorithms to new ones

An (Old) Example*

- **X.509 Public Key Certificate**
  - A public key certificate has cryptographic parameters including key type, key length, and a hash algorithm
  - X.509 version v.3, with key type RSA, a 1024-bit key length, and the SHA-1 hash algorithm were found by NIST to have a key length that made it vulnerable to attacks
  - Prompting the transition to SHA-2 (at least)

[*] https://www.csoonline.com/article/550478/all-you-need-to-know-about-the-move-from-sha1-to-sha2-encryption.html

A New Reason…

- **Quantum Threat! [1, 2]**
  - Quantum computers, while beneficial for various fields, have the potential to break current cryptographic algorithms
  - Rendering existing secrets vulnerable within 5-10 years, or even sooner

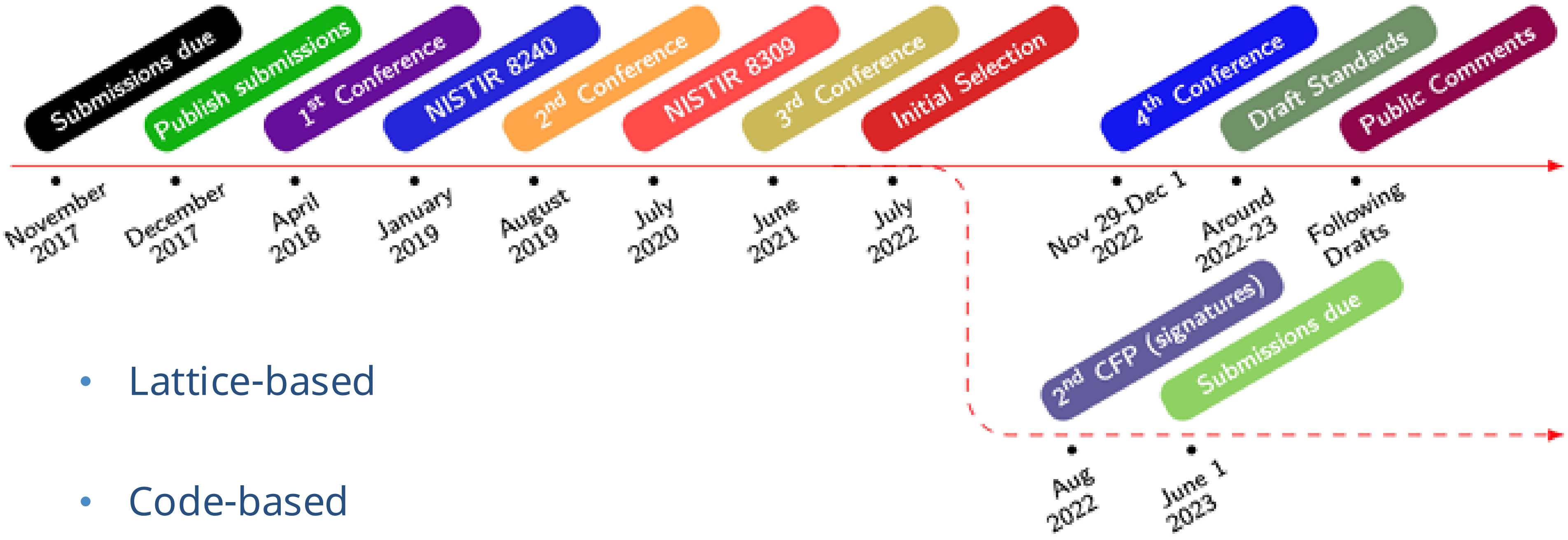
[1] https://csrc.nist.gov/projects/crypto-agility
[2] https://www.ibm.com/quantum/blog/crypto-agility
[Figure] https://quantumai.google/quantumcomputer

How?

- **"Harvest now, decrypt later!" [1]**
  - Encrypted data harvested today could be decrypted in the future by quantum computers
  - **Impact of Decryption:** If quantum computers break current encryption, sensitive information, digital signatures, electronic records, payment systems, and critical infrastructure could be compromised
  - Poses a significant threat to sensitive information like intellectual property and personal data

[1] https://www.ibm.com/quantum/blog/crypto-agility
[Figure] https://quantumai.google/quantumcomputer

NIST Competition: Post-Quantum Cryptography (PQC)



- Lattice-based
- Code-based
- Hash-based
- Isogenies …

[Figure] https://www.nccoe.nist.gov/sites/default/files/2023-08/pqc-light-at-the-end-of-the-tunnel-presentation.pdf

NIST Competition: Post-Quantum Cryptography

- NIST outlines the following timeline [*]
  - **From now until 2030**, existing encryption methods should be phased out
  - **By 2030**, algorithms relying on 112-bit security will be deprecated
  - **By 2035**, all systems will need to be transitioned, as traditional cryptographic algorithms will be disallowed

[*] https://pqshield.com/nist-recommends-timelines-for-transitioning-cryptographic-algorithms/

NIST Competition: Post-Quantum Cryptography

- Digital Signature Algorithms [*]

Algorthims	Parameters	Deprecated	Disallowed
ECDSA, EdDSA, RSA	112 bits of security strength	2030	2035
ECDSA, EdDSA, RSA	≥ 128 bits of security strength	-	2035

[*] https://pqshield.com/nist-recommends-timelines-for-transitioning-cryptographic-algorithms/

NIST Competition: Post-Quantum Cryptography

- Key Establishment Schemes [*]

Algorthims	Parameters	Deprecated	Disallowed
FInite Field DH and MVQ	112 bits of security strength	2030	2035
FInite Field DH and MVQ	≥ 128 bits of security strength	-	2035
Elliptic Curve DH and MQC	112 bits of security strength	2030	2035
Elliptic Curve DH and MQC	≥ 128 bits of security strength	-	2035
RSA	112 bits of security strength	2030	2035
RSA	≥ 128 bits of security strength	-	2035

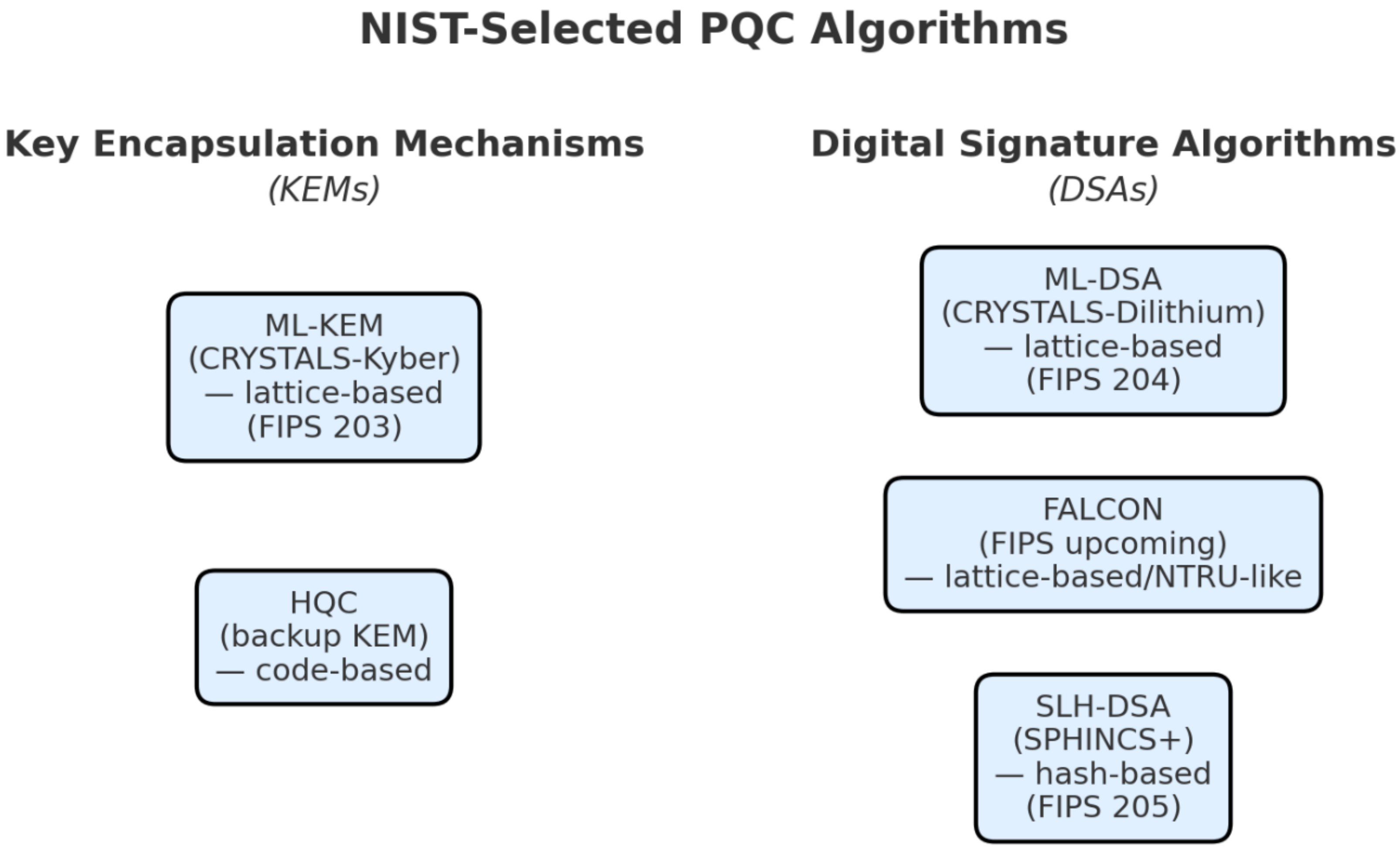
[*] https://pqshield.com/nist-recommends-timelines-for-transitioning-cryptographic-algorithms/

NIST Competition: Post-Quantum Cryptography

- Symmetric Cryptography [*]
  - Symmetric cryptography standards are less vulnerable to quantum attack
  - Currently not included in PQC transition recommendations
  - **However**, standards at the 112-bit security level will be disallowed from 2030
  - Applications should move away from these when transitioning to PQC

[*] https://pqshield.com/nist-recommends-timelines-for-transitioning-cryptographic-algorithms/

Post-Quantum Cryptography



Post-Quantum Cryptography

Federal Office
for Information Security

BSI – Technical Guideline

Designation: Cryptographic Mechanisms: Recommendations and Key Lengths

FrodoKEM-976 and FrodoKEM-1344, see [3, Section 2.5].

Table 2.5: Recommended parameters for FrodoKEM.

- mceliece460896, mceliece6688128 and mceliece8192128, see [2, Section 7],
- mceliece460896f, mceliece6688128f and mceliece8192128f (faster variants), see [2, Section 7].

Table 2.6: Recommended parameters for ClassicMcEliece-KEM.

- Quantum-safe signature algorithms
  - ML-DSA in the "hedged"-variant, see [104],
  - SLH-DSA in the "hedged"-variant, see [105], and
  - Stateful hash-based signatures[2](LMS/HSS and XMSS/XMSS^{MT}), see [98].

Table 5.3: Recommended signature algorithms.

Post-Quantum Cryptography

Asymmetric (All scenarios)	*Public-Key Encryption/KEMs*	CRYSTALS-KYBER	Classic McEliece, FrodoKEM	Any classical PKC
Asymmetric (Scenario 1 with Stateful Hash-based Signatures)	*Digital Signatures*	XMSS, $XMSS^{MT}$ LMS, HSS	Any NIST (Draft) Standards	Any classical PKC
Asymmetric (Scenario 1 without Stateful Hash-based Signatures)	*Digital Signatures*	Any NIST (Draft) Standards	-	Any classical PKC
Asymmetric (Scenario 2)	*Digital Signatures*	Any NIST (Draft) Standards	XMSS, $XMSS^{MT}$ LMS, HSS	Any classical PKC

Post-Quantum Cryptography

NIST-Selected PQC Algorithms

Key Encapsulation Mechanisms
(KEMs)

ML-KEM
(CRYSTALS-Kyber)
— lattice-based
(FIPS 203)

HQC
(backup KEM)
— code-based

Digital Signature Algorithms
(DSAs)

ML-DSA
(CRYSTALS-Dilithium)
— lattice-based
(FIPS 204)

FALCON
(FIPS upcoming)
— lattice-based/NTRU-like

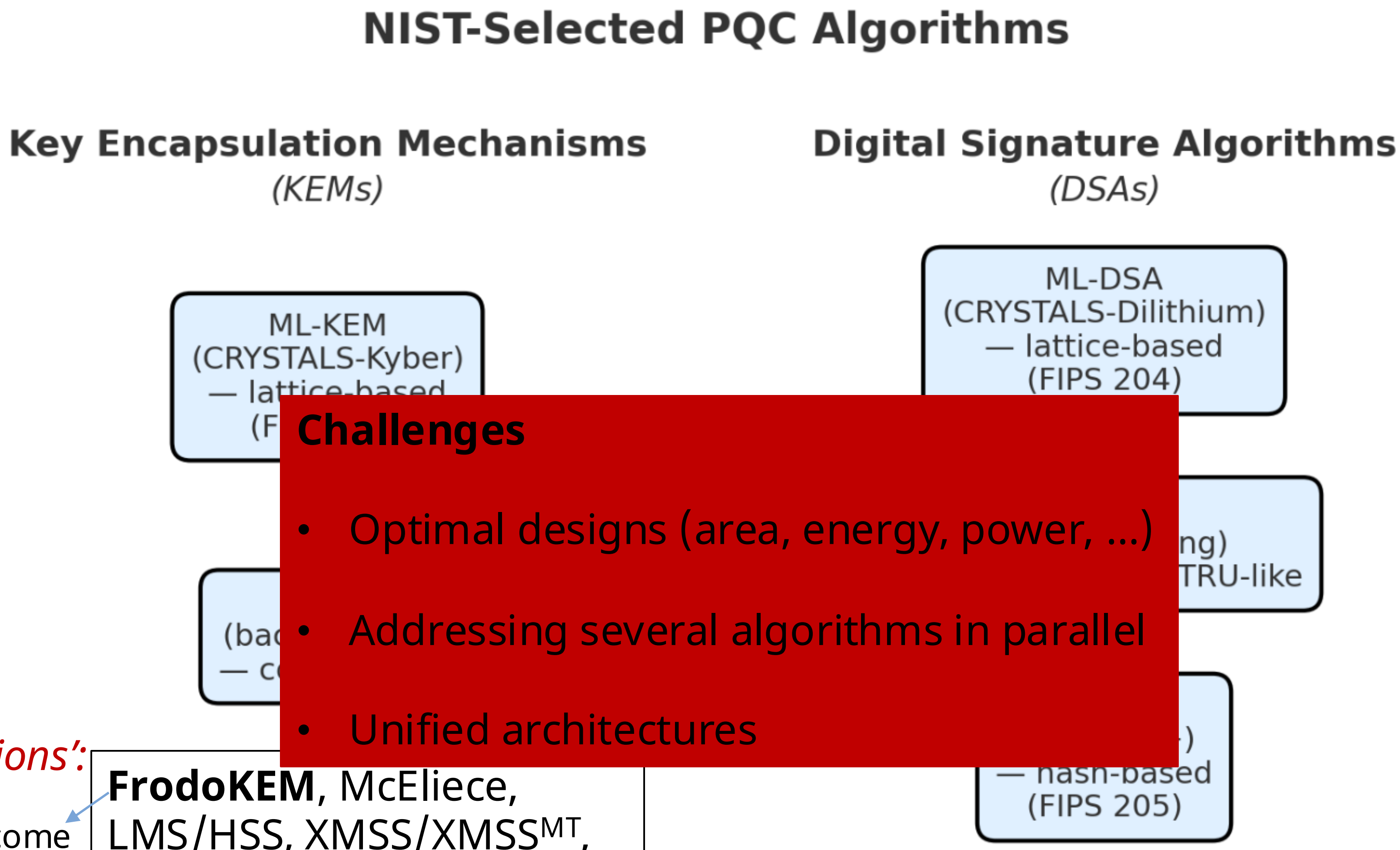
SLH-DSA
(SPHINCS+)
— hash-based
(FIPS 205)

Other ‘Recommendations’:

FrodoKEM, McEliece, LMS/HSS, XMSS/XMSS^{MT}, etc.

On track to become an ISO standard

Post-Quantum Cryptography



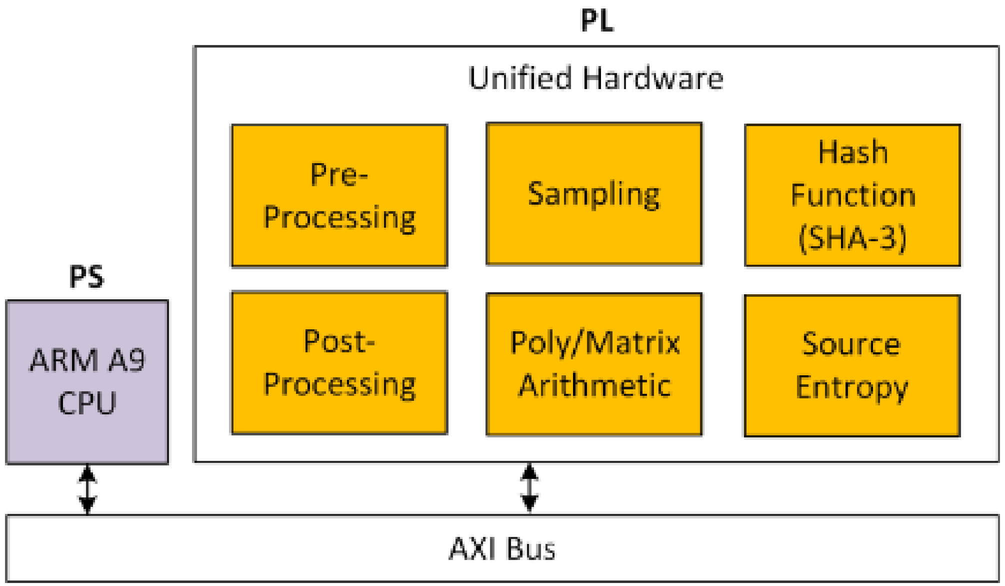
Challenges

- Optimal designs (area, energy, power, …)
- Addressing several algorithms in parallel
- Unified architectures

Other 'Recommendations': **FrodoKEM**, McEliece, LMS/HSS, XMSS/XMSS^{MT}, etc.

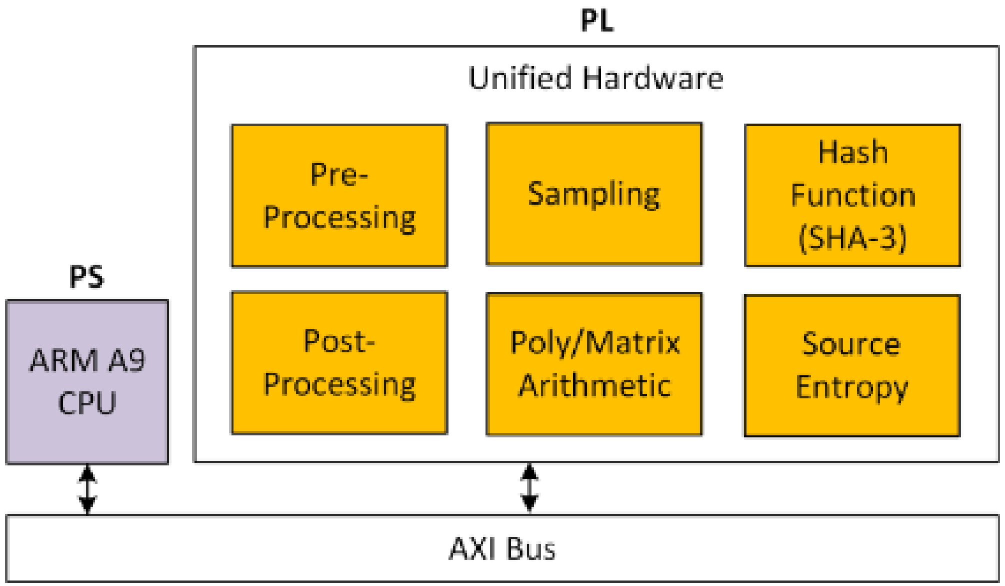
On track to become an ISO standard

Post-Quantum Cryptography
Bottlenecks



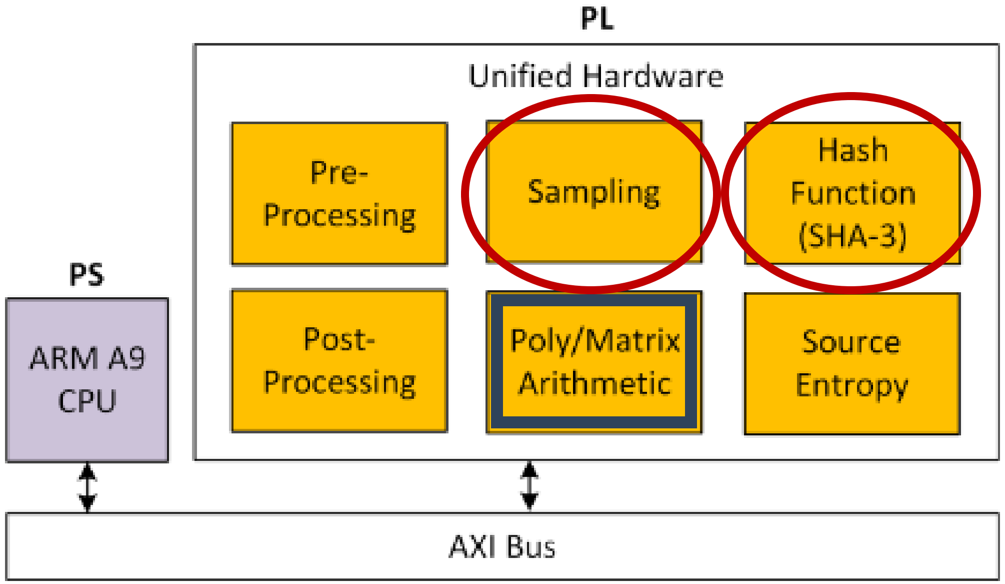
[*] Figure credit (next ten slides): Joint Project NSF (Award No. 2350142) - DFG (Project No. 543352068) with Dr. A. Aysu (NCSU, US)

Post-Quantum Cryptography
Bottlenecks



	Kyber KEM		FrodoKEM	
	Encaps	Decaps	Encaps	Decaps
Pre-processing	51.310	152.673	310.602	711
Post-processing	142.819	160.227	268.571	602.954
Matrix/Poly. Arith.	2.850.446	3.821.137	270.613.307	270.832.087
Sampling	497.525	496.469	436.428	458.370
Hashing	1.136.218	590.496	4.381.389	3.287.054
Misc.	112.409	18.397	90.791	197.224
Total	4.790.727	5.239.401	276.101.088	275.378.400

Post-Quantum Cryptography
Bottlenecks



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AI for Optimizing PQC?

- Deus Ex LLMs: AI vs Humans in Post-Quantum Cryptographic Hardware Code Generation
  - To be presented at **2025 IFIP/IEEE 33rd International Conference on Very Large Scale Integration (VLSI-SoC)**

The Challenge: Post-Quantum Crypto Hardware

FALCON Signature Scheme

A lattice-based digital signature scheme designed to resist quantum computer attacks.

SamplerZ Bottleneck

This subroutine consumes over **65%** of signature generation cycles.

Complex Implementation

Involves discrete Gaussian sampling with intricate control flow and complex arithmetic.

No Available RTL Code

Allows testing the true creative capability of LLMs

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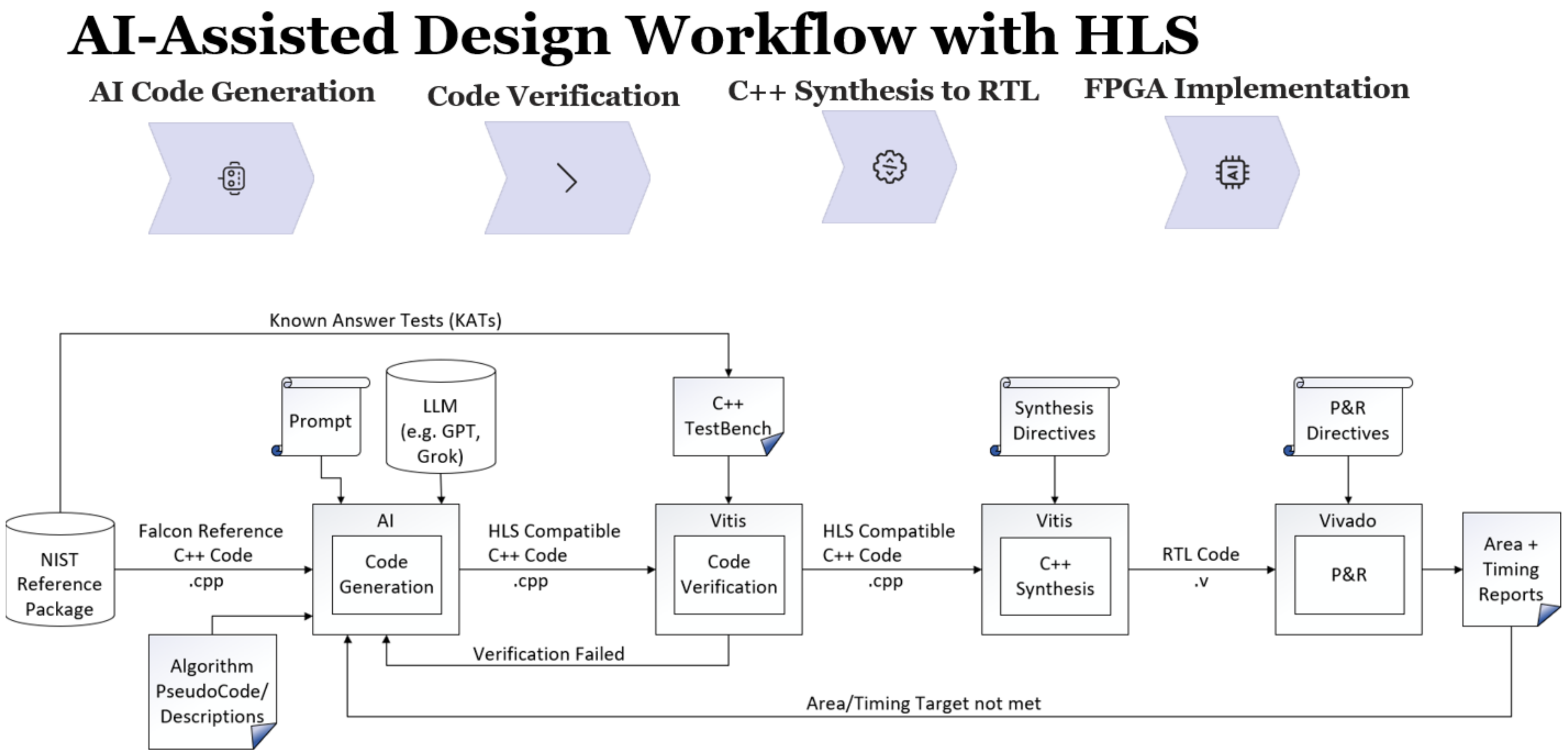

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The Prompt

```
Goal: Generate HLS-compatible C++ code for four
functions ApproxExp, BerExp, BaseSampler,
SamplerZ optimized equally for latency and
area-delay product.

Return: For each function, provide .cpp and .h
files using exact prototypes:
• uint64_t ApproxExp(double x, double ccs);
• int BerExp(uint8_t random_byte, double x,
  double ccs);
• int BaseSampler(ap_uint<72> random_bits);
• int SamplerZ(double mu, double sigma_prime,
  fpr sigma_min, ap_uint<72> BaseSampler_rand,
  uint8_t b_rand, uint8_t BerExp_rand);
```

```
Requirements:
• Distribute the random 88 bits in SamplerZ:
  First 9 bytes for BaseSampler, next byte for
  variable b in SamplerZ, and the last byte for
  BerExp using little-endian format.
• Make sure to use the exact function prototypes
  as listed above.
• Make sure to use MAXIMUM precision for all
  calculations to get the correct functionality
• Make sure that each function can be called
  correctly by the function in the level above
  it in the hierarchy.
• Make sure that all functions are HLS compatible
  with Vitis.

Context:
• I will attach the following  files for Context
 SamplerZ.c (source code) and images of all of
 the algorithms broken into steps for easier
 optimization of each step.
• I will also include a file that defines the
 function headers that should be implemented.
```

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Key AI Optimization

Algorithm 13 ApproxExp(x, ccs)

Require: Floating-point values $x \in [0, \ln(2)]$ and $ccs \in [0, 1]$

Ensure: An integral approximation of $2^{63} \cdot ccs \cdot \exp(-x)$

Implementing e^x directly with Xilinx IPs is more efficient than computing approximation

1: C = `[0x00000004741183A3,0x00000036548CFC06,0x0000024FDCBF140A,0x0000171D939DE045, 0x0000D00CF58F6F84, 0x000680681CF796E3, 0x002D82D8305B0FEA, 0x011111110E066FD0, 0x0555555555070F00, 0x155555555581FF00, 0x400000000002B400, 0x7FFFFFFFFFFF4800, 0x8000000000000000]`

2: $y \leftarrow C[0]$ ▷ y and z remain in $\{0, ..., 2^{63} - 1\}$ the whole algorithm.

3: $z \leftarrow \lfloor 2^{63} \cdot x \rfloor$

4: for $1 = 1, \ldots, 12$ do

5: $\quad y \leftarrow C[u] - (z \cdot y) >> 63$ ▷ $(z \cdot y)$ fits in 126 bits, but we only need the top 63 bits

6: $z \leftarrow \lfloor 2^{63} \cdot ccs \rfloor$

7: $y \leftarrow (z \cdot y) >> 63$

8: return y

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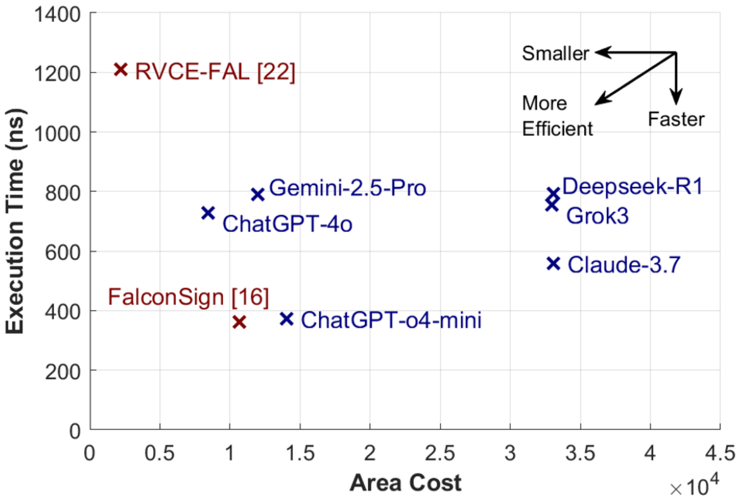
BLUF: AI is Surprisingly Good



SAMPLERZ: HLS SYNTHESIS RESULTS ACROSS LLM MODELS

Metric/Model	ChatGPT-4o	ChatGPT-o4-mini	Claude3.7	Deepseek-R1	Gemini-2.5-Pro	Grok3	[16][1]	[22]
LUTs	7299	7683	11438	14995	7524	14646	9368	4761
FFs	10096	8266	12538	17529	7959	17411	4527	692
DSPs	52	108	273	265	82	265	76	9
BRAMs	0	0	6	0	6	0	0	0
Area Cost[2]	**8412**	14013	33079	33076	11970	32974	10690	**2198**
Target Freq (MHz)	200	200	200	200	200	200	-	-
Max Freq (MHz)	231	**297**	243	222	185	233	**185**	86
Latency (Cycles)	168	111	136	176	146	176	67	104
Execution Time (ns)	727	**374**	560	793	789	775	**362**	1209
ADP ($\times 10^6$)	6.12	**5.24**	18.51	26.22	9.45	24.91	4.63	**2.66**
Design Iterations[3]	20	5	3	2	13	6	-	-

[1]: The utilization of the ChaCha20 PRNG block from [16] has been subtracted to enable a direct comparison.[2]: The Area Cost calculation is defined as Area Cost $=$ (LUTs $\div$ 4) $+$ (FFs $\div$ 8) $+$ (DSPs $\times$ 102.4) $+$ (BRAMs $\times$ 116.2), which is based on [35], [36], which provides the conversion of 1 LUT/FF/DSP/BRAM to an equivalent number of slices. [3]: Each iteration is equivalent to approximately 4 hours of design time.

[16] Y. Ouyang, Y. Zhu, W. Zhu, B. Yang, Z. Zhang, H. Wang, Q. Tao, M. Zhu, S. Wei, and L. Liu, "FalconSign: An Efficient and High-Throughput Hardware Architecture for Falcon Signature Generation," IACR Transactions on Cryptographic Hardware and Embedded Systems, vol. 2025, no. 1, p. 203–226, Dec. 2024.
[22] X. Yu, Y. Sun, Y. Zhao, H. Kuang, and J. Han, "RVCE-FAL: A RISC-V Scalar-Vector Custom Extension for Faster FALCON Digital Signature," in 2024 Design, Automation & Test in Europe Conference & Exhibition (DATE), Mar. 2024, pp. 1–6, iSSN: 1558-1101.

AI for Optimizing PQC?

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Novel AI-Discovered Optimizations

Floating-Point Replacement
ChatGPT-04-mini replaced complex integer-based exponentiation with standard exp() function.

Simplified Dataflow
Eliminated operations in the critical datapath while preserving functional correctness.

Leveraged Optimized IP
Used Xilinx's optimized floating-point IP to reduce area utilization.

Constant-Time Behavior
Maintained security guarantees with fixed-latency hardware implementation.

Challenges in AI-Assisted Design

Precision Issues
LLMs default to single-precision vs. required double-precision

Arithmetic Inconsistency
Mixing floating-point and fixed-point representations

Interface Mismatches
Incorrect function signatures causing synthesis failures

Testbench Overfitting
Limited test vectors leading to over-optimized designs

Mathematical Errors
Misinterpreting complex expressions affecting algorithm correctness

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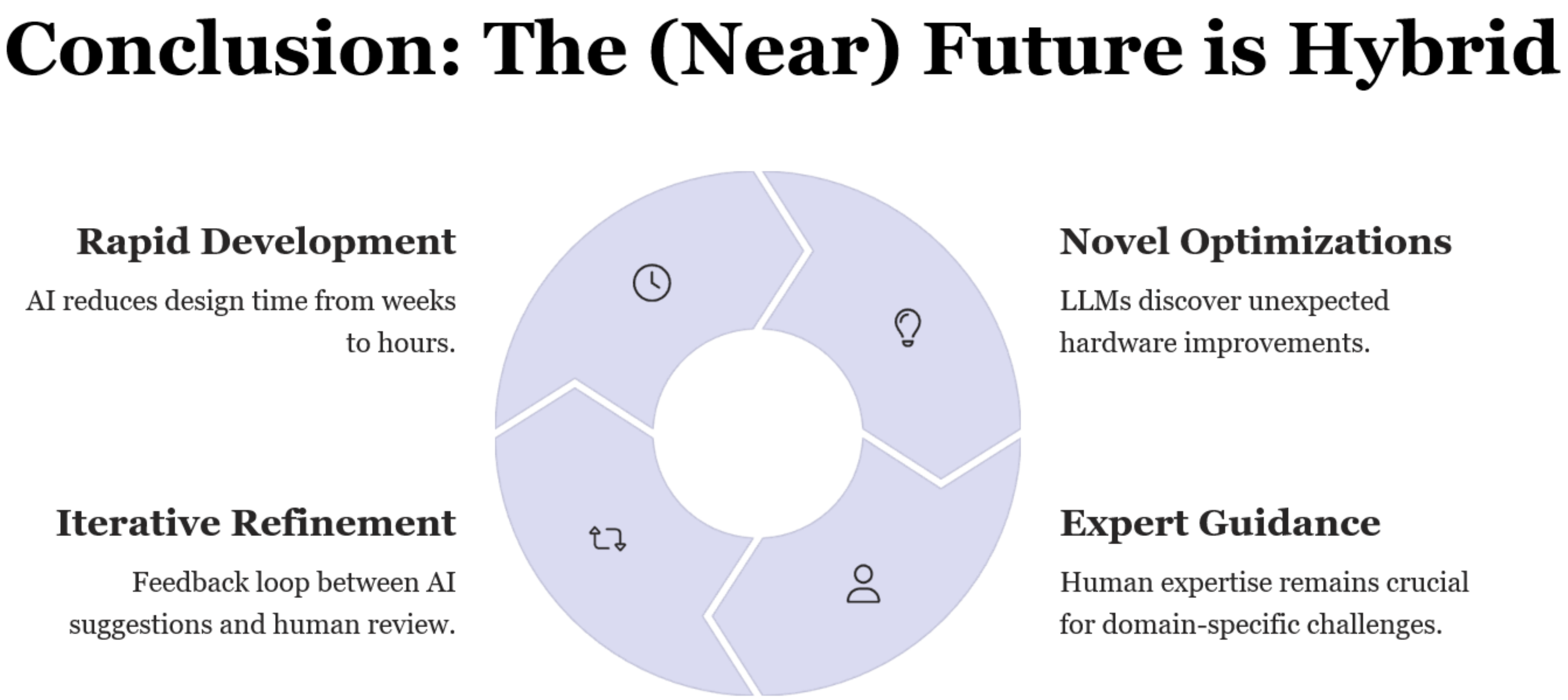

Rolling Back To Crypto Agility: PQC View

- Future/Quantum-Proofing cryptographic implementations to allow for easy updates to new standards
  - NIST PQC Standards!

- Revisit **implementation steps** [*]
  - **Three main steps:** Discover, Manage, Remediate

[*] https://www.ibm.com/quantum/blog/crypto-agility

Rolling Back To Crypto Agility: PQC View

- Implementation Step 1: **Discover**
  - Create a cryptographic inventory to identify all cryptographic implementations within an organization
  - Requires automated scanning tools as manual methods are prone to errors
- Implementation Step 2: **Manage**
  - Define a crypto policy
  - Prioritize which systems to update first based on sensitivity
  - Track progress (likely multi-year project)
- Implementation Step 3: **Remediate**
  - Migrate from classical to quantum-safe cryptography
  - A crypto proxy can be used as a temporary solution to provide immediate protection during the migration phase
    - Converting PQC algorithms from the user's end to classical algorithms for legacy backend applications
  - Performance testing of these new algorithms is also crucial

Rolling Back To Crypto Agility: PQC View

- Hybrid Key Establishment Schemes

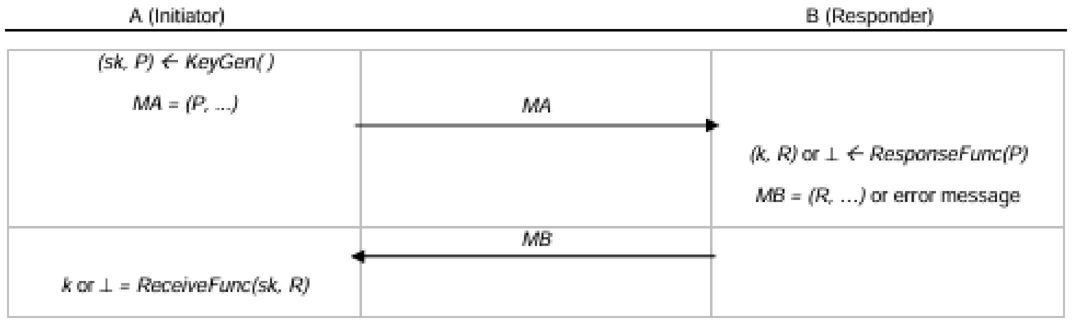

Figure 3: Key establishment abstraction

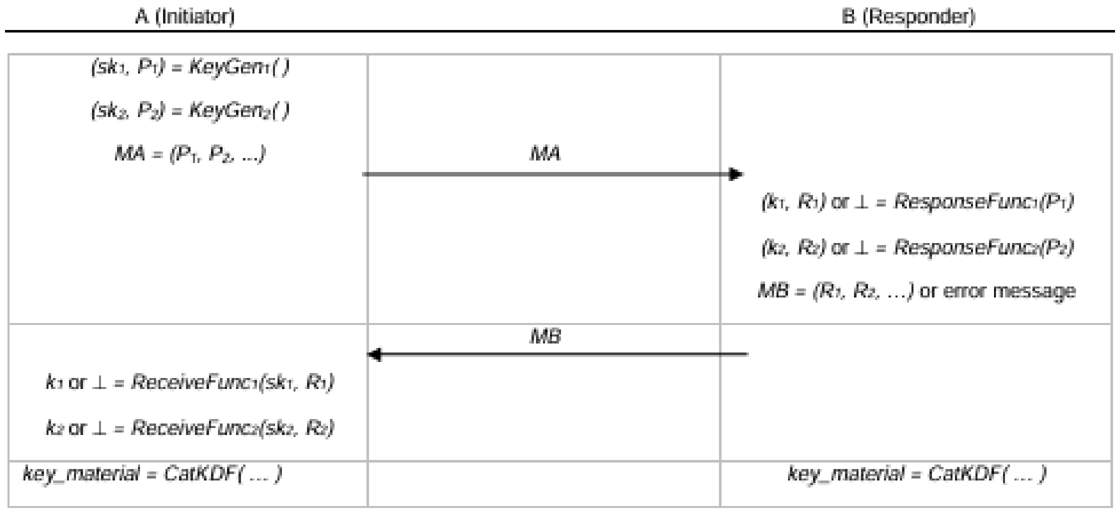

Figure 4: Concatenate hybrid key establishment - ephemeral

[Figures] https://www.etsi.org/deliver/etsi_ts/103700_103799/103744/01.02.01_60/ts_103744v010201p.pdf

Lessons Learned: Best Practices

- All business applications involving any sort of cryptographic technology should incorporate the latest algorithms and techniques
- Crypto agility requirements must be disseminated to all hardware, software, and service suppliers, who must comply on a timely basis
  - Suppliers who cannot address these requirements must be replaced
- Suppliers must provide timely updates and identify the crypto technology they employ
- Quantum-resistant solutions (PQC) should be kept in mind [*]

[*] Chen, Lily; Jordan, Stephen; Liu, Yi-Kai; Moody, Dustin; Peralta, Rene; Perlner, Ray; Smith-Tone, Daniel. "Report on Post-Quantum Cryptography (NISTIR 8105)". National Institute of Standards and Technology (NIST)

Lessons Learned: Best Practices

- Symmetric-key algorithms should be flexible in their key lengths
- Hash algorithms should support different lengths of outputs
- Digital certificate and private key rotations must be automated [*]
- Standards and regulations must be complied with [**]
- Used algorithms should be communicated; not assumed or defaulted

[*] “Digital certificate and private key rotations must be automated”. www.appviewx.com
[**] Macaulay, Tyson. “Cryptographic Agility in Practice”. InfoSec Global.

Thanks for listening!

Any questions?

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