Post-Quantum Authenticated Encryption Against Chosen-Ciphertext Side-Channel Attacks

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SECURE CONNECTIONS
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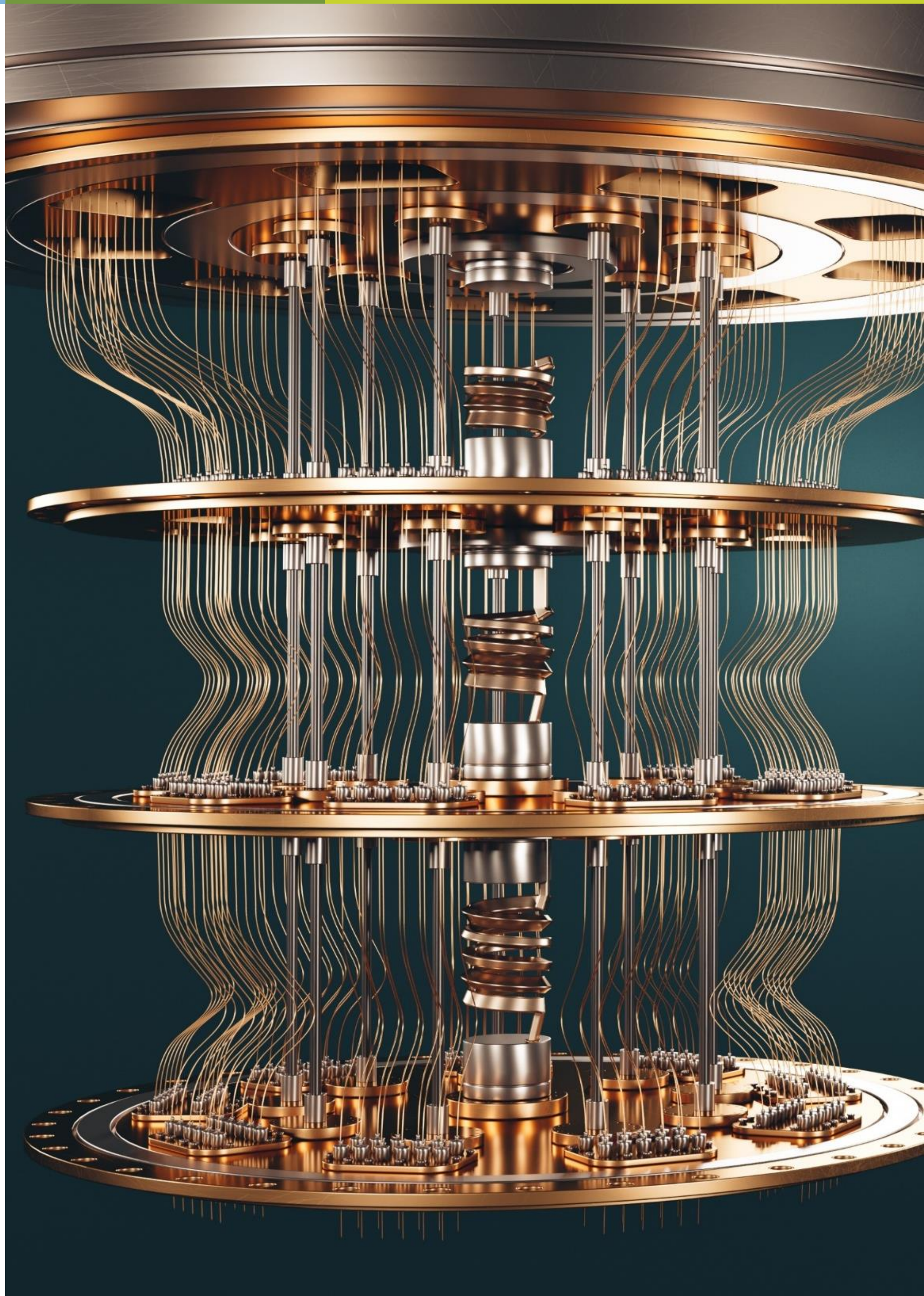
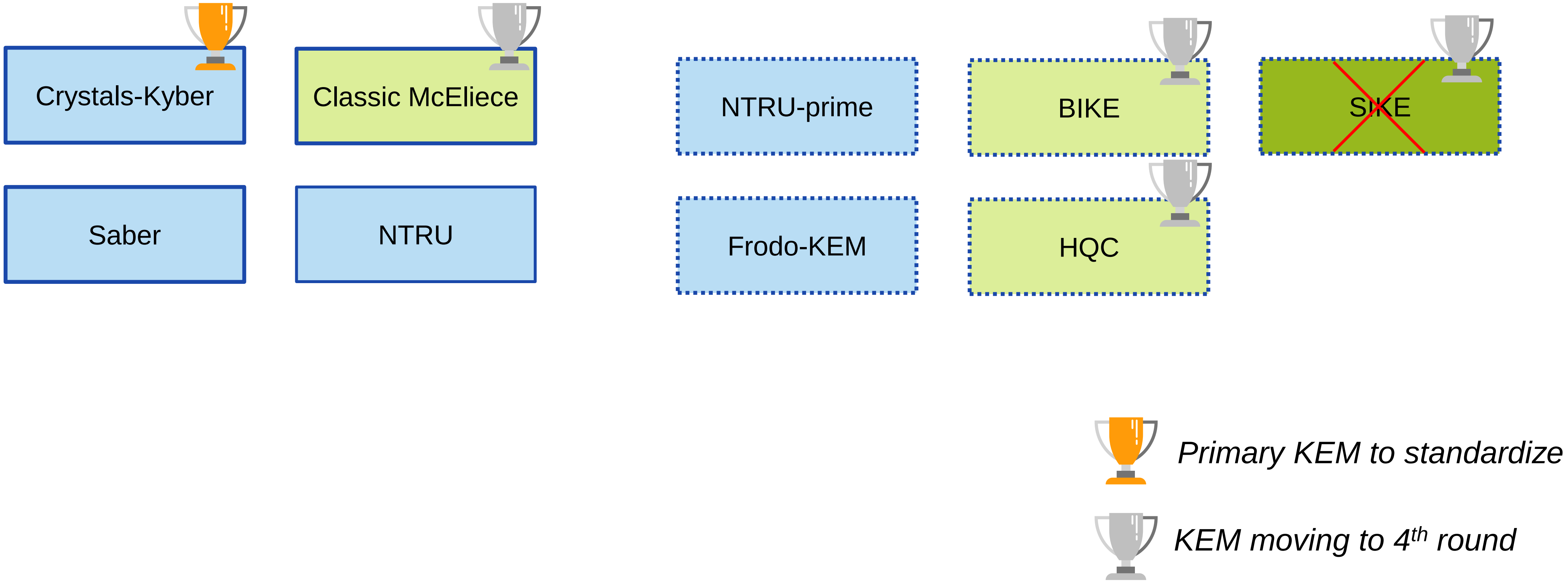
PUBLIC



PQC KEY ENCAPSULATION MECHANISM

3rd round of the NIST PQC standardization



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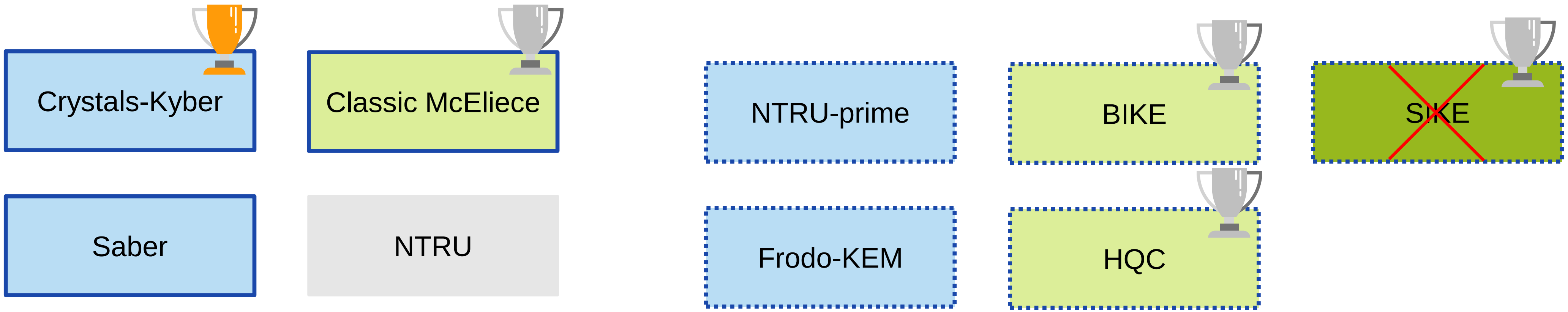
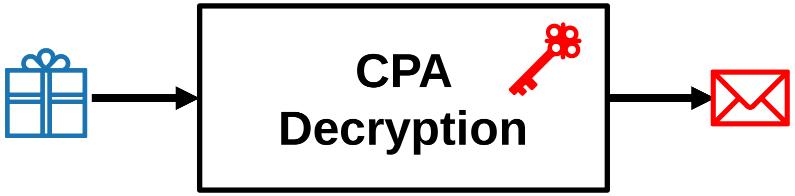


$$\text{IND-CPA-secure PKE} \xrightarrow{\text{FO}} \text{IND-CCA-secure KEM}$$

FO = Fujisaki-Okamoto Transform

FUJISAKI OKAMOTO TRANSFORM



- CCA KEM Decapsulation -

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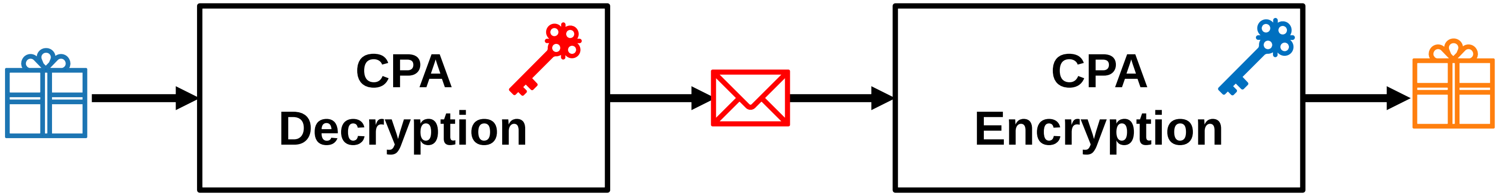

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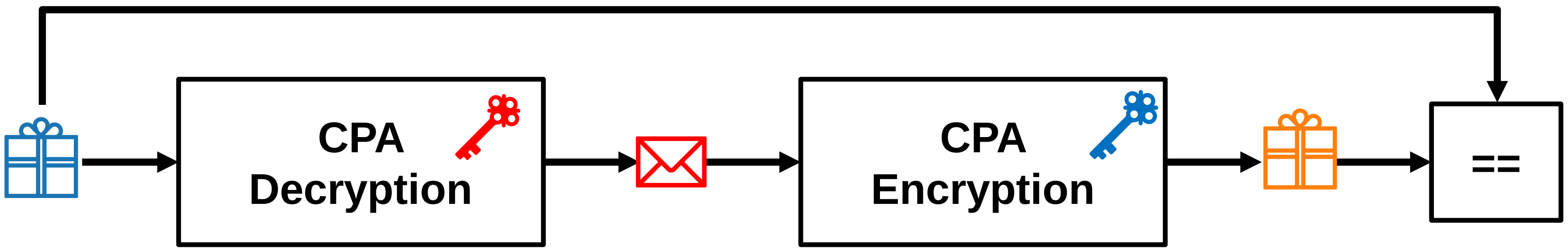

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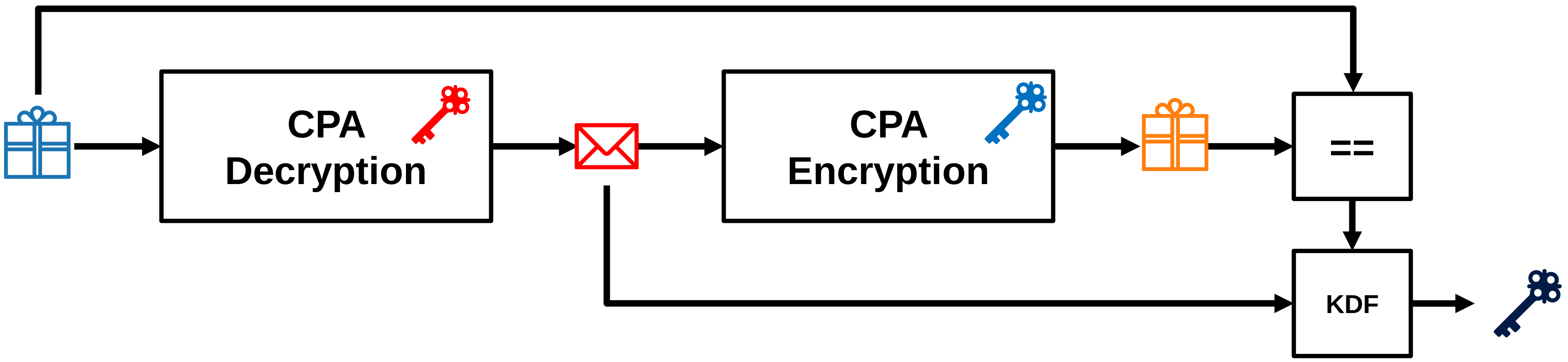

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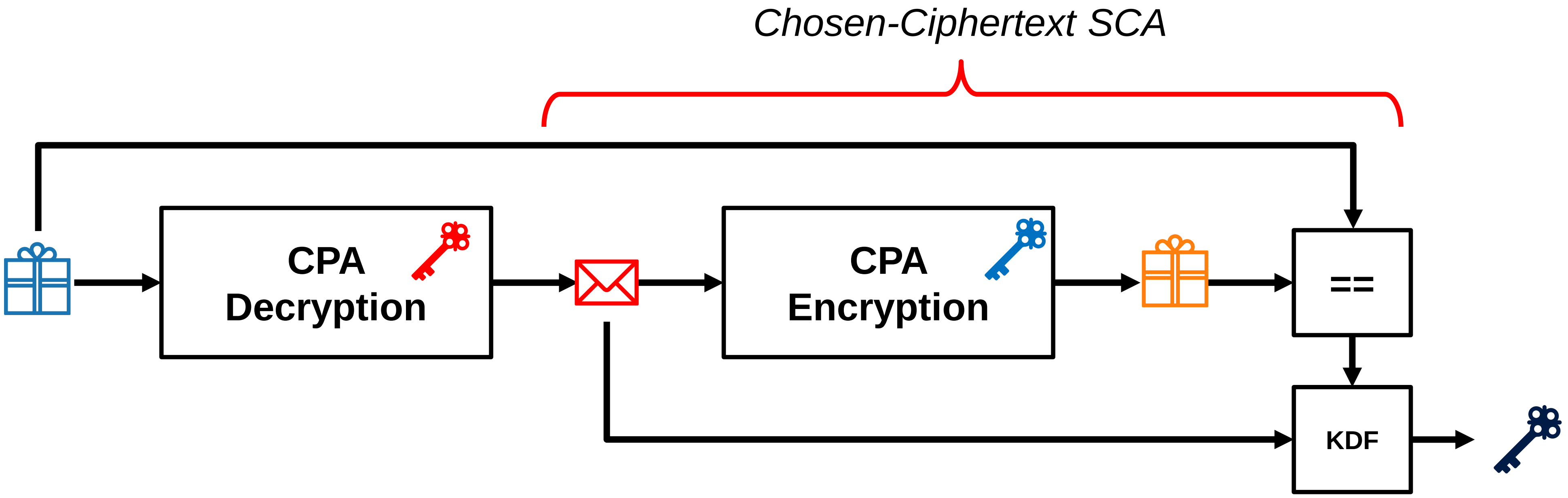
SIDE-CHANNEL ATTACKS ON THE FO-TRANSFORM



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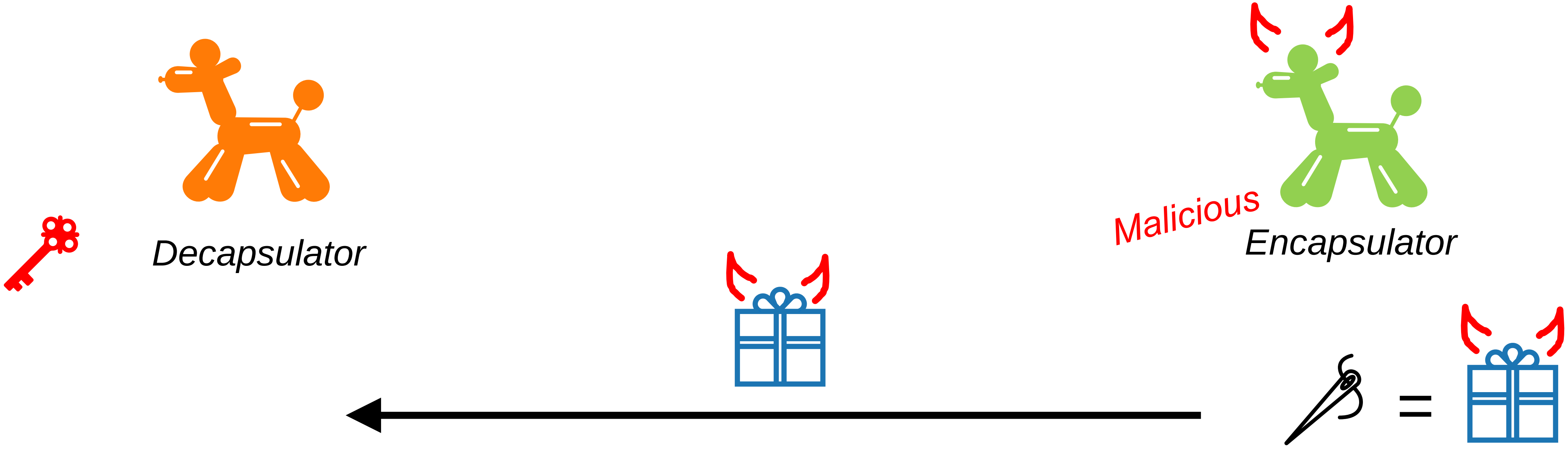
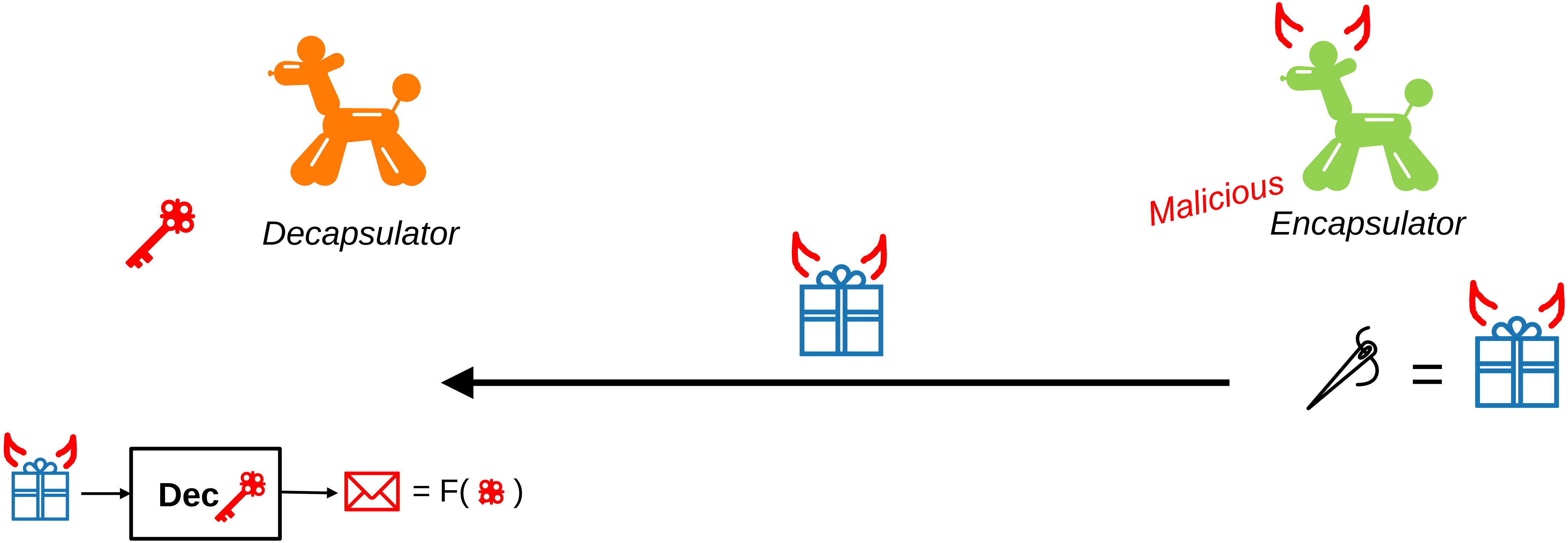


When maliciously crafted ciphertexts are decrypted, they depend on a small/enumerable part of the secret key

SIDE-CHANNEL ATTACKS ON THE FO-TRANSFORM



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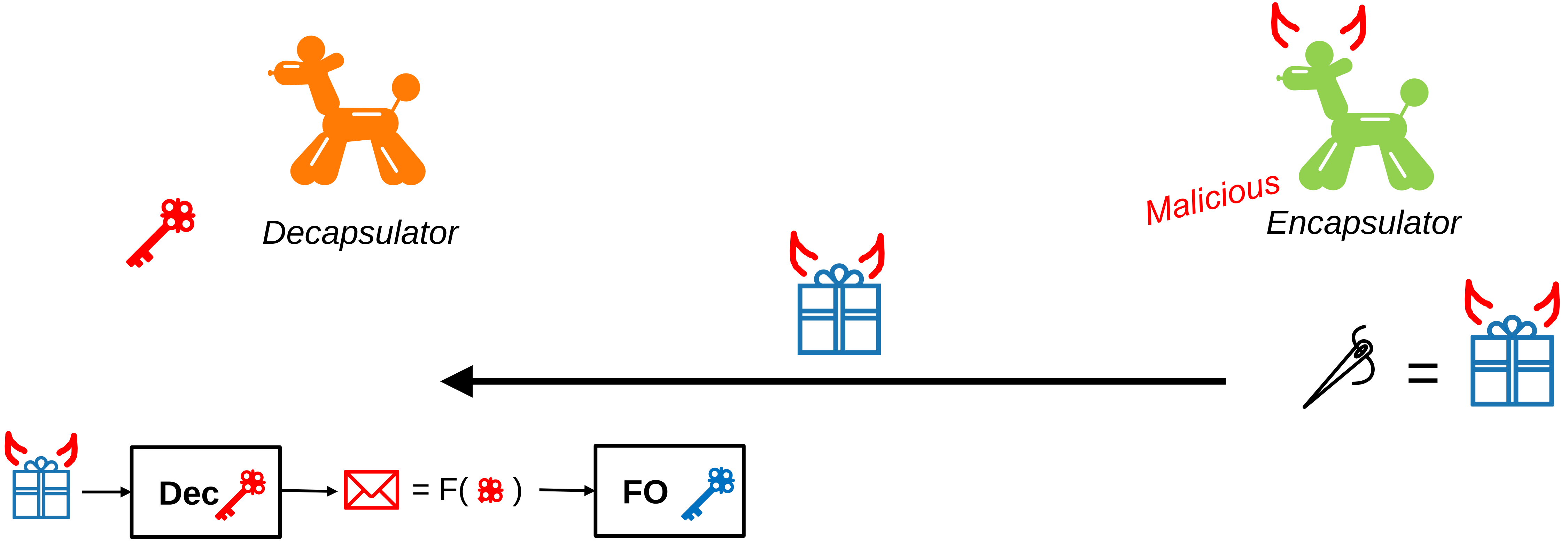

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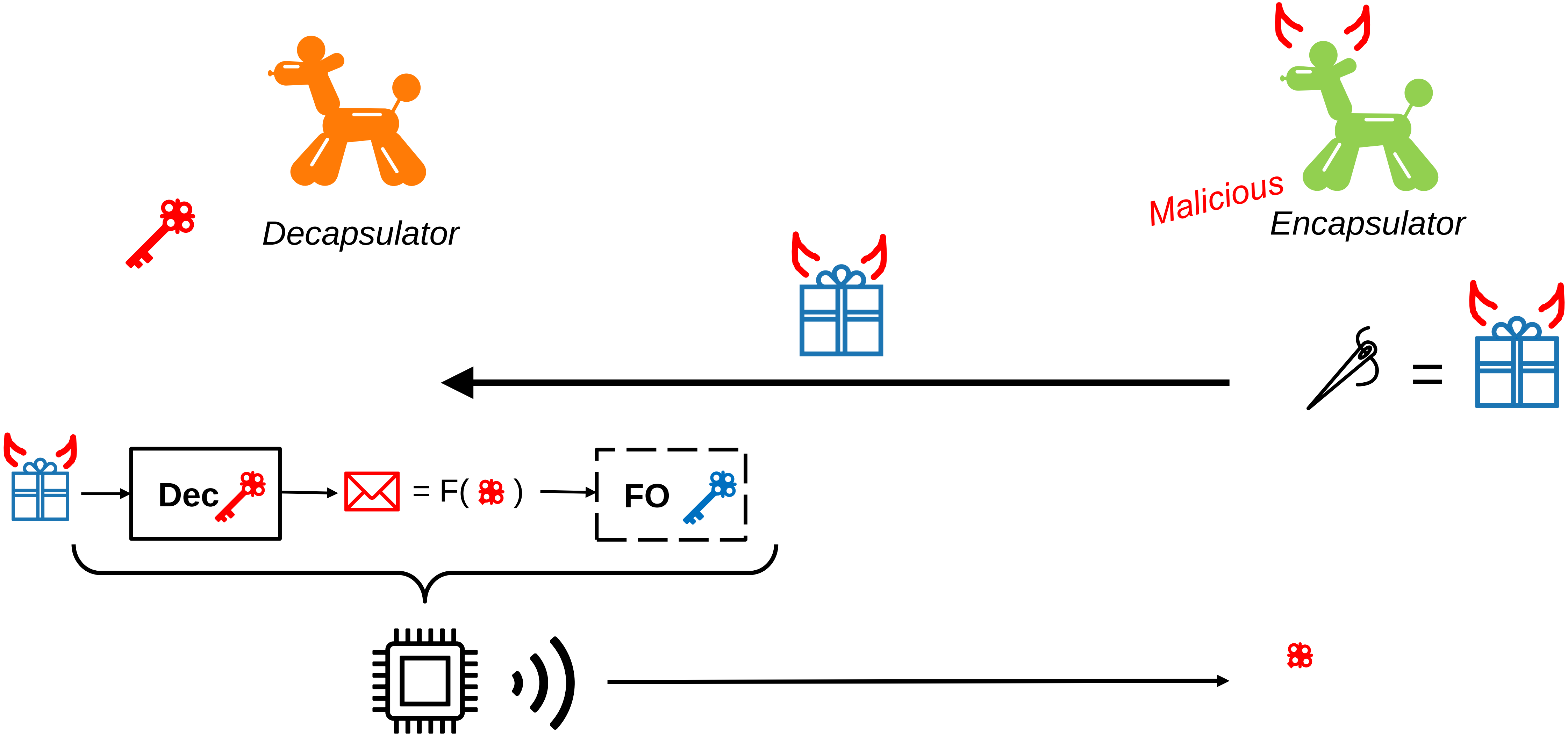

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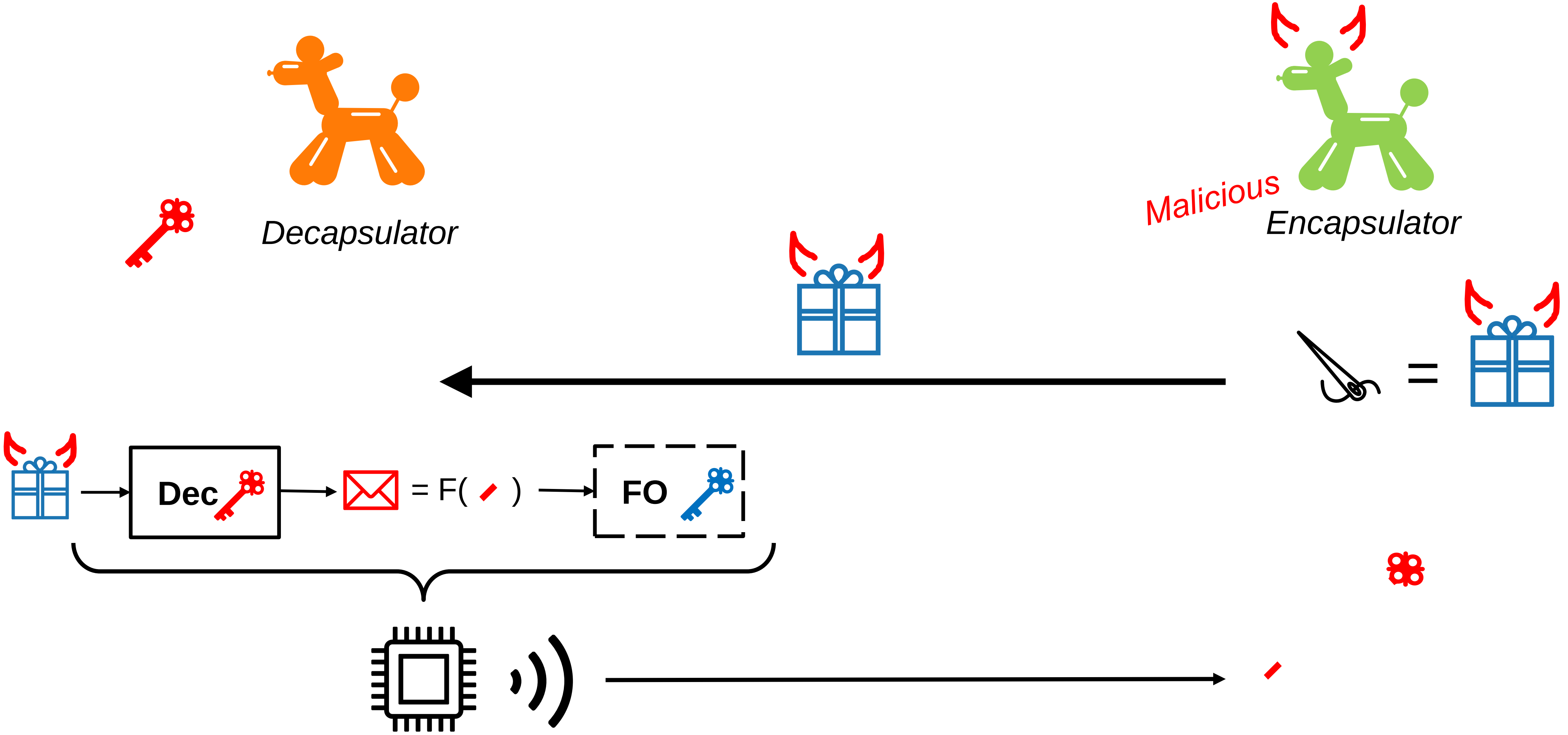

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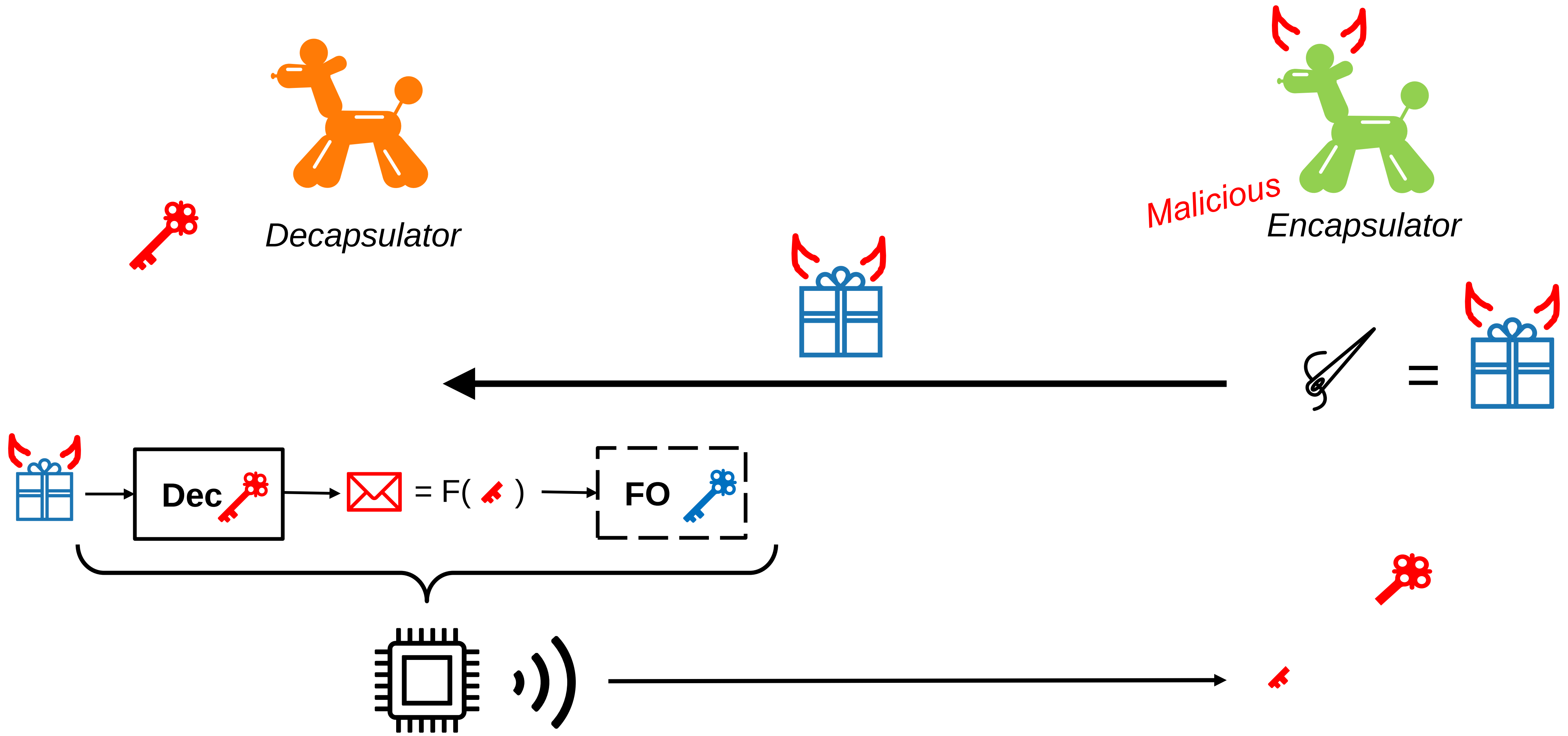

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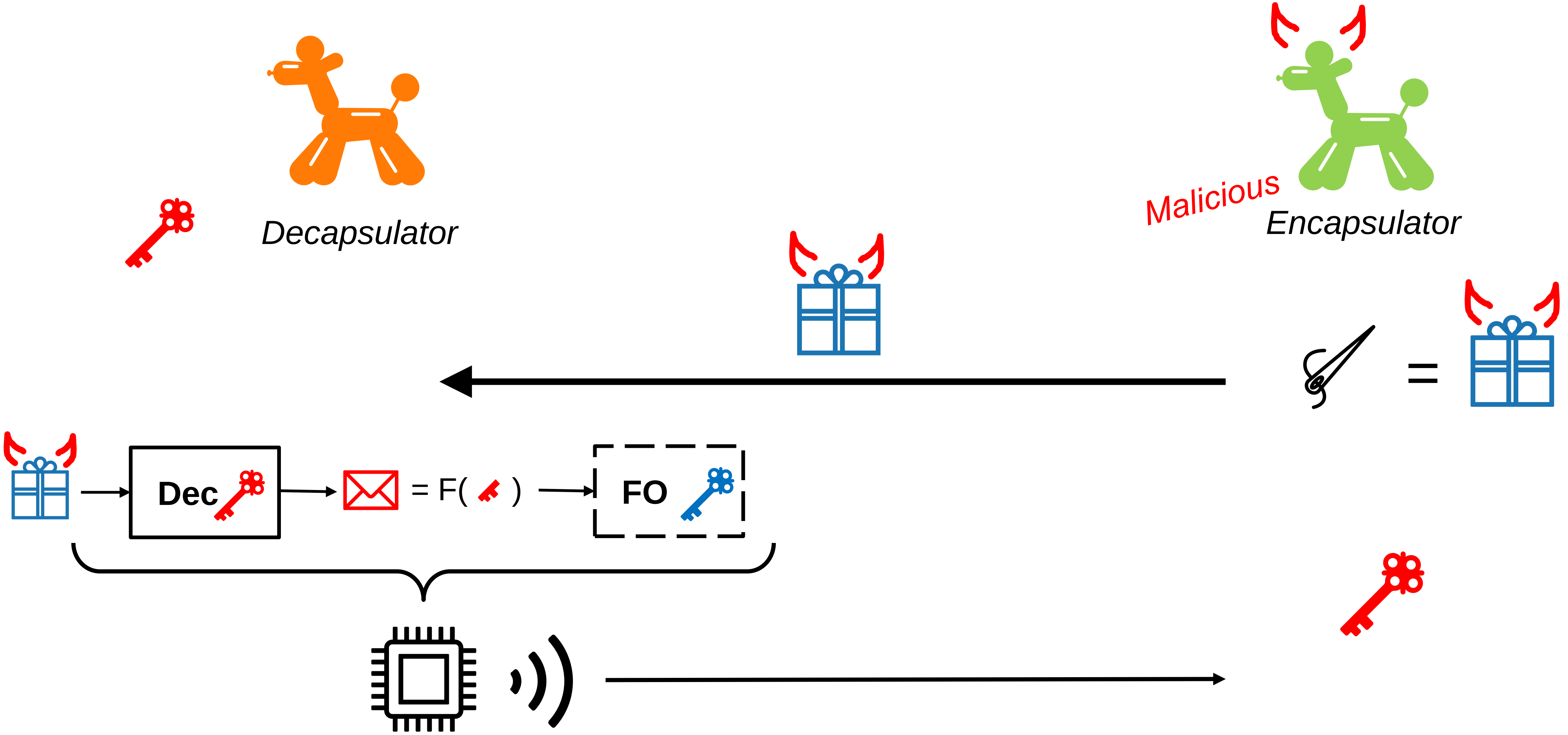

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- *Ravi et al. "Generic Side-channel attacks on CCA-secure lattice-based PKE and KEMs" TCHES 2020*
- *Xu et al. "Magnifying Side-Channel Leakage of Lattice-Based Cryptosystems with Chosen Ciphertexts: The Case Study of Kyber" IEEE Transactions on Computers, 2021*
- *Qin et al. "A Systematic Approach and Analysis of Key Mismatch Attacks on Lattice-Based NIST Candidate KEMs" ASIACRYPT 2021*
- *Ngo et al. "A Side-Channel Attack on a Masked IND-CCA Secure Saber KEM Implementation" TCHES 2021*
- *Ravi et al. "Will You Cross the Threshold for Me? - Generic Side-Channel Assisted Chosen-Ciphertext Attacks on NTRU-based KEMs" TCHES 2022*
- *Ueno et al. "Curse of Re-encryption: A Generic Power/EM Analysis on Post-Quantum KEMs" TCHES 2022*
- *Shen et al. "Find the Bad Apples: An efficient method for perfect key recovery under imperfect SCA oracles – A case study of Kyber" IACR ePrint archive 2022*
- *Ngo et al. "Side-Channel Attacks on Lattice-Based KEMs Are Not Prevented by Higher-Order Masking" IACR ePring archive 2022*
- *Rajedran et al. "Pushing the Limits of Generic Side-Channel Attacks on LWE-based KEMs - Parallel PC Oracle Attacks on Kyber KEM and Beyond" IACR ePrint archive 2022*
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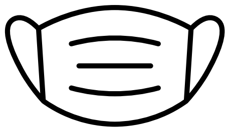
MASKING THE FO : THE CASE STUDY OF KYBER



High order masking is the main countermeasure against SCA

- The leakage of the FO implies an increase of 1 to 2 masking shares to achieve a target security *[ABF+22]*
- Implies slowdown factors ranging from $\times$ 1.2 to $\times$ 3

[ABH+21] Azouaoui, M., Bronchain, O., Hoffmann, C., Kuzovkova, Y., Schneider, T., Standaert, FX. "Systematic Study of Decryption and Re-encryption Leakage: The Case of Kyber". COSADE 2022.

A CLOSER LOOK AT THE COST OF DECAPSULATION

Table 4: STM32F4 ARM Cortex-M4 MCU Performance numbers for masked Kyber.CCAKEM.Dec and its subroutines in kCycles.

Operation	Number of shares					
	2	*3*	*4*	*5*	*6*	*7*
Kyber.CCAKEM.Decaps	3 178	57 141	97 294	174 220	258 437	350 529
Kyber.CPAPKE.Dec	200	4 203	7 047	13 542	20 323	27 230
Kyber.CPAPKE.Enc	2 024	18 879	32 594	53 298	75 692	104 191
comparison ($c = c'$)	693	32 293	54 725	102 922	156 075	210 518
$\mathcal{G}$	98	1 639	2 801	4 489	6 456	8 794
$\mathcal{H}$	113	113	113	113	113	113
$\mathcal{H}'$	13	13	13	13	13	13

- *Masked decryption is <8% of the cost of masked decapsulation*
- *Cost of masked decapsulation is dominated by the masked FO*

A VERY SIMPLE IDEA

Replace expensive FO by a signature verification of the ciphertext.
Signature verification only uses public data and does not require SCA protection.

Never decrypt untrusted ciphertexts.

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Signature verification only uses public data and does not require SCA protection.

→ Never decrypt untrusted ciphertexts.

- Based on the *Encrypt-then-Sign* ($\mathcal{E}t\mathcal{S}$) paradigm
- CCA security shown in *[ADR02]*

Theorem 2. *If* $\mathcal{E}$ *is* IND-CPA-*secure, and* $\mathcal{S}$ *is* UF-CMA-*secure, then* $\mathcal{E}t\mathcal{S}$ *is* IND-gCCA2-*secure in the Outsider- and* UF-CMA-*secure in the Insider-security models.*

- Post-quantum CCA security shown in *[CPPS20]*

[ADR02] An, JH., Dodis, Y., Rabin, R. "On the Security of Joint Signature and Encryption". EUROCRYPT 2002.

[CPPS20] Chatterjee, S., Pandit, T., Puria, SKP., Shah, A. "Signcryption in a Quantum World". IACR ePrint Arch., 2020.

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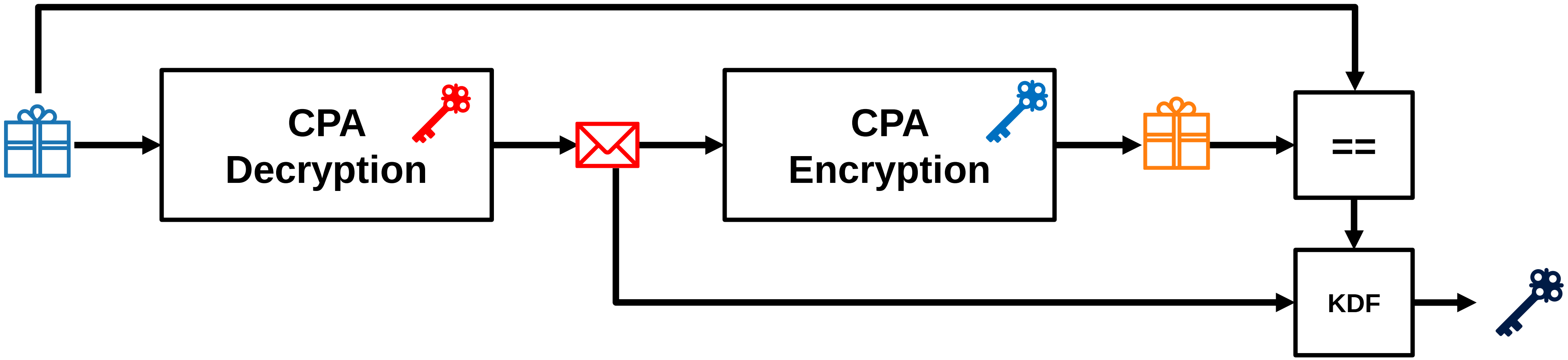
THE $\mathcal{E}t\mathcal{S}$ KEM VS. THE FO KEM



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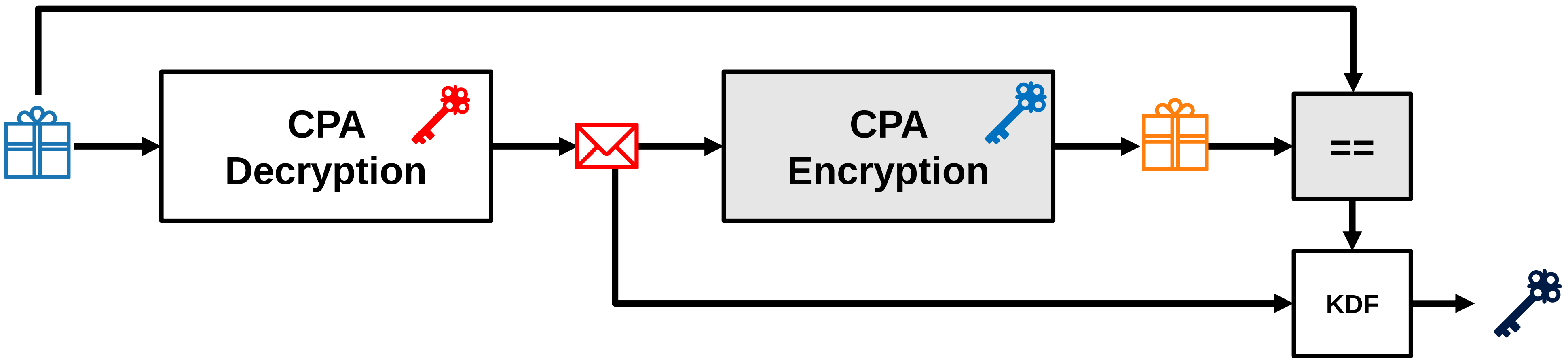

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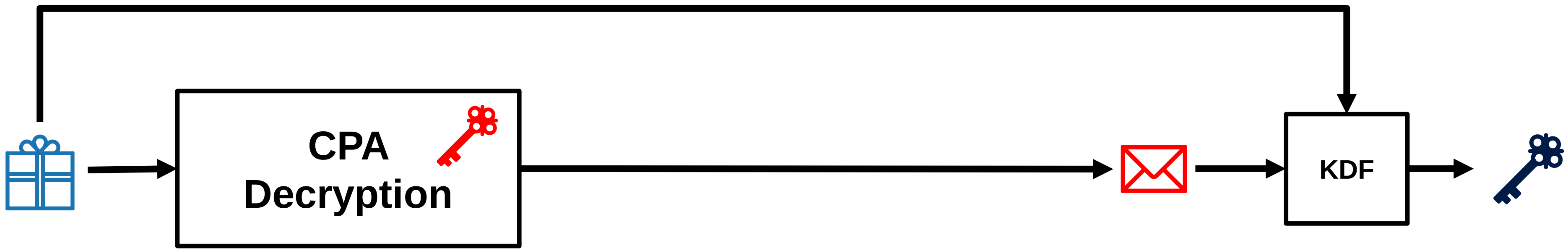

- CPA PKE Decryption -

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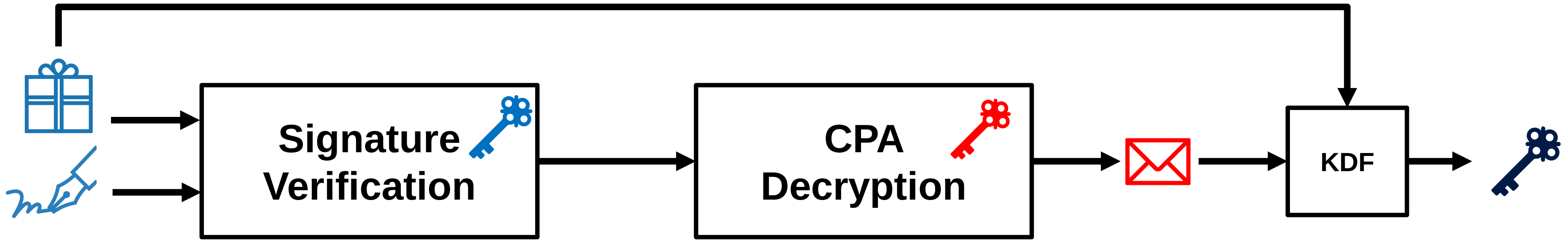

- CCA $\mathcal{E}t\mathcal{S}$ KEM Decapsulation -

Outsider vs. Insider security models

Outsider security

– Adversary is not a legitimate user of the system.

– Adversary does not have a trusted signature key pair and cannot sign ciphertexts.

Insider security

– Adversary can be the sender.

– Adversary can sign ciphertexts and receiver verifies these signatures.

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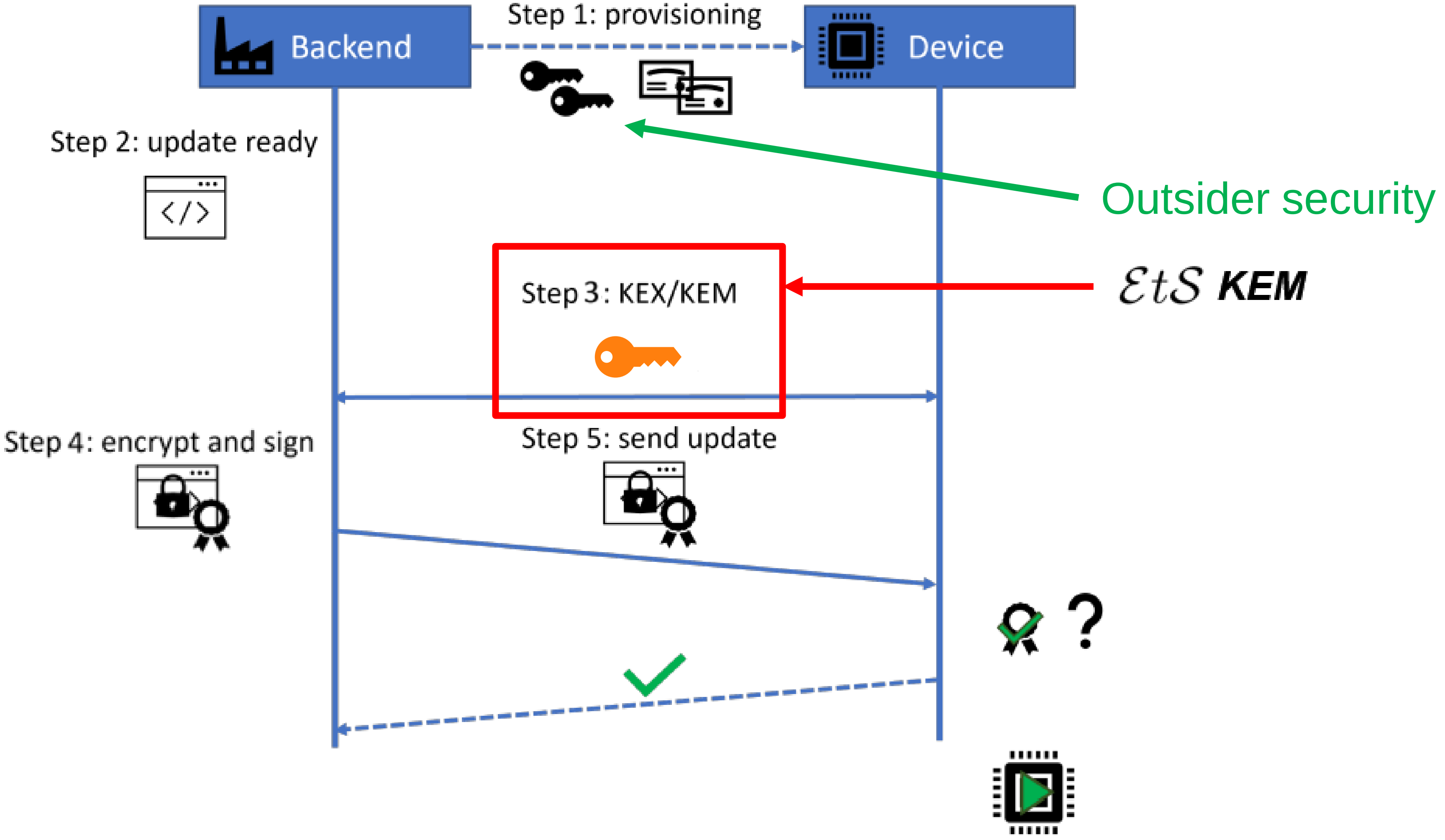
THE $\mathcal{E}t\mathcal{S}$ KEM FOR SECURE ENCRYPTED UPDATE MECHANISM



THE $\mathcal{E}t\mathcal{S}$ KEM VS. THE FO KEM

Num. of shares	Scheme		
	Kyber.Decaps	$\mathcal{E}t\mathcal{S}$ Kyber + Dilithium 3	$\mathcal{E}t\mathcal{S}$ Kyber + Falcon-1024
2	3 178	2 568 (80.8%)	1 316 (41.41%)
3	57 141	6 571 (11.5%)	5 319 (9.3%)
4	97 294	9 415 (9.7%)	8 163 (8.4%)
5	174 220	15 910 (9.1%)	14 658 (8,4%)
6	258 437	22 691 (8.9%)	21 439 (8.3%)
7	350 529	29 598 (8.4%)	28 346 (8.1%)

Kannwischer, MJ., Rijneveld, J., Schwabe, P., Stoffelen, K. "pqm4: Testing and Benchmarking NIST PQC on ARM Cortex-M4". 2019.

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Ciphertext size	1088 bytes	4381 bytes	2368 bytes

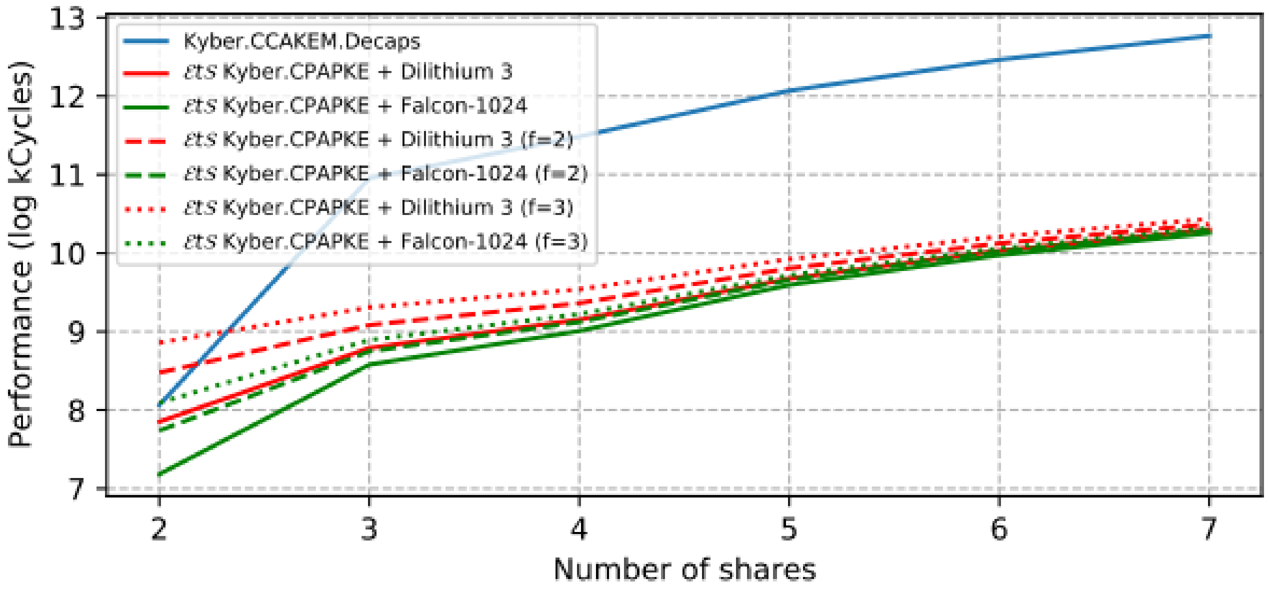
Kannwischer, MJ., Rijneveld, J., Schwabe, P., Stoffelen, K. "pqm4: Testing and Benchmarking NIST PQC on ARM Cortex-M4". 2019.

THE $\mathcal{E}t\mathcal{S}$ KEM VS. THE FO KEM

Pros	Cons
– More efficient ($\times 8$ to $\times 12$ depending on signature verification speed and number of masking shares) – We remove the FO SCA vector	– Larger ciphertext ($\times 2$ to $\times 4$ depending on choice of signature scheme) – We introduce the signature verification FIA vector

THE $\mathcal{E}t\mathcal{S}$ KEM VS. THE FO KEM

- ~~FO SCA vector~~ Signature verification FIA vector
- SCA protecting FO vs. FIA protecting signature verification
- Ad hoc countermeasure against FIA is re-computation (Recomputing m times protects against $m-1$ faults)



Impact of protecting the signature verification against fault injection is trivial compared to the cost of masking the FO at high order

THE $\mathcal{E}t\mathcal{S}$ KEM VS. THE FO KEM

Pros	Cons
– More efficient (×8 to ×12 depending on signature verification speed and number of masking shares)	– Larger ciphertext (×2 to ×4 depending on choice of signature scheme)
– We remove the FO SCA vector	– We introduce the signature verification FIA vector
– Fault protection of signature verification is less challenging and costly than SCA protection of the FO	

CONCLUSION

- The $\mathcal{E}t\mathcal{S}$ KEM is a simple solution to achieve improved leakage resilience for post-quantum KEMs for practical use cases in the outsider security model
- The $\mathcal{E}t\mathcal{S}$ KEM significantly speeds up and reduces the attack surface for post-quantum secure encrypted updates

OUTLOOK

- Find other applications that could benefit from the $\mathcal{E}t\mathcal{S}$ KEM (e.g., IoT edge communication, banking applications)
- Investigate lattice-based PQC schemes for encryption and signature (e.g., SETLA [GM18])

[GM18] Gérard. F., Merckx. K., "SETLA: Signature and Encryption from Lattices". CANS 2018.

THANK YOU.

QUESTIONS?

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CONTACT: PQC@NXP.COM | NXP.COM/PQC