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Two-Tier Authenticated Encryption

Nonce Hiding in QUIC

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QUIC within the Network Stack

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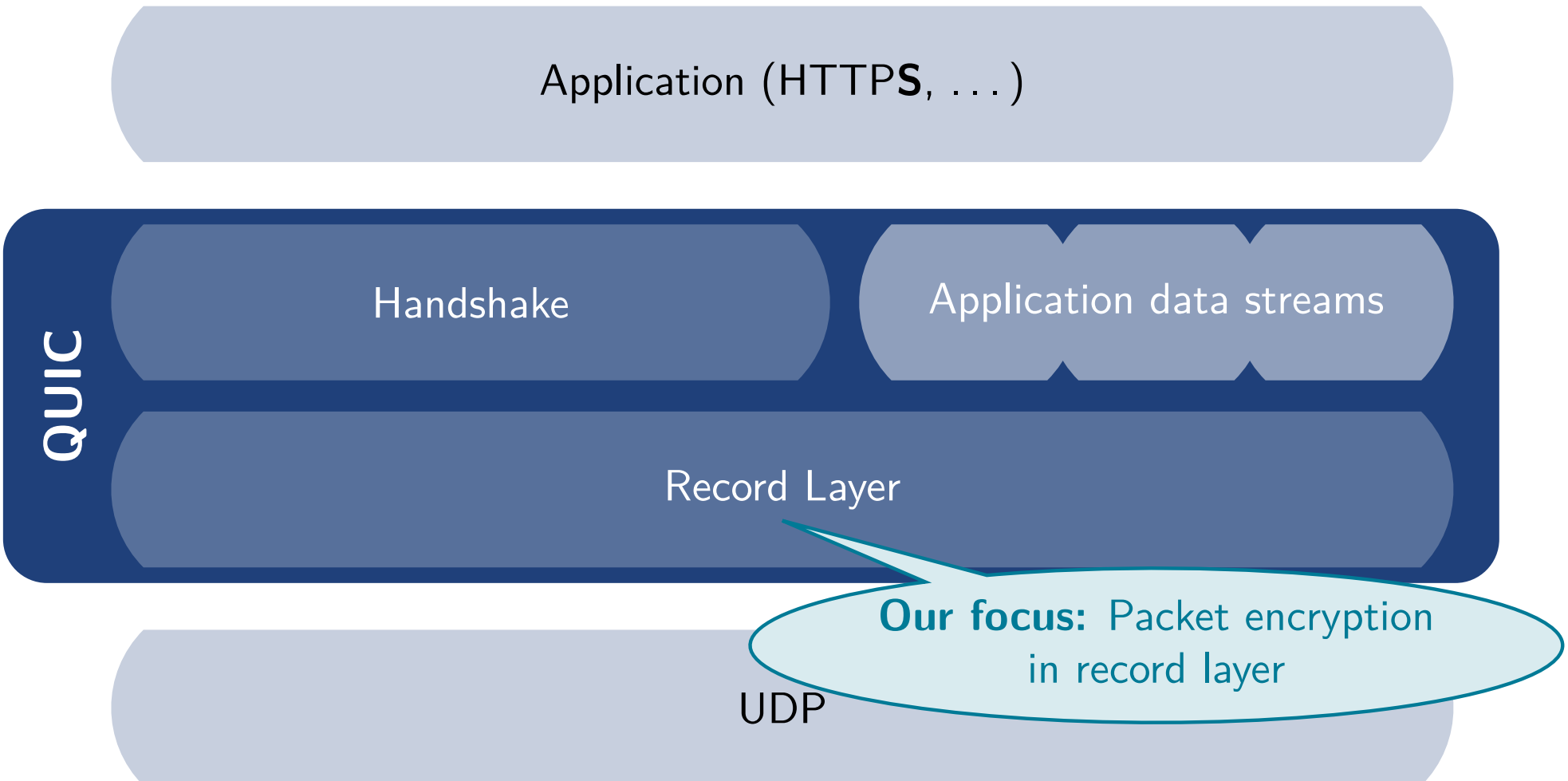

The QUIC Record Layer

(highly simplified)

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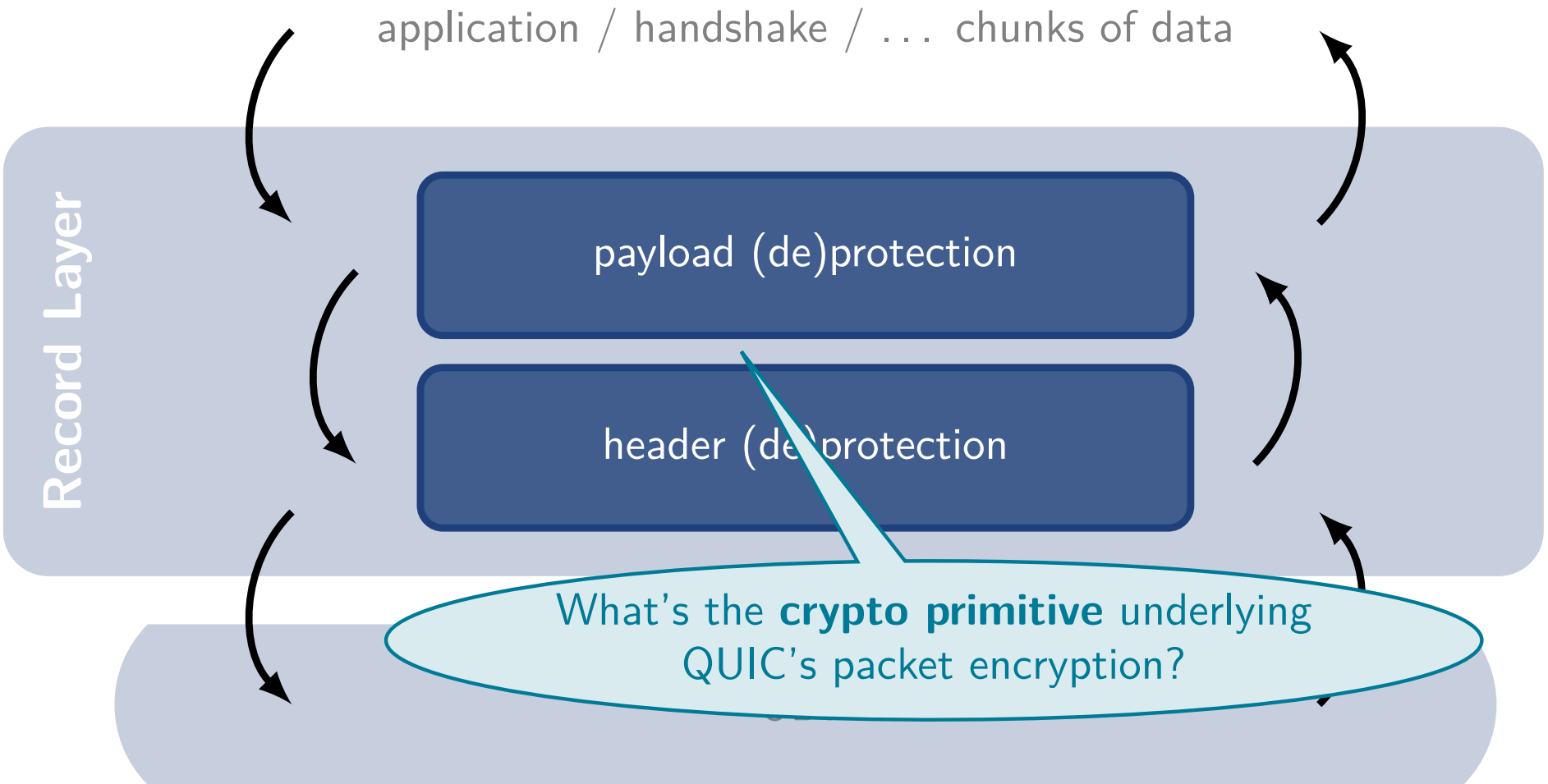

QUIC Packet Encryption (QPE)

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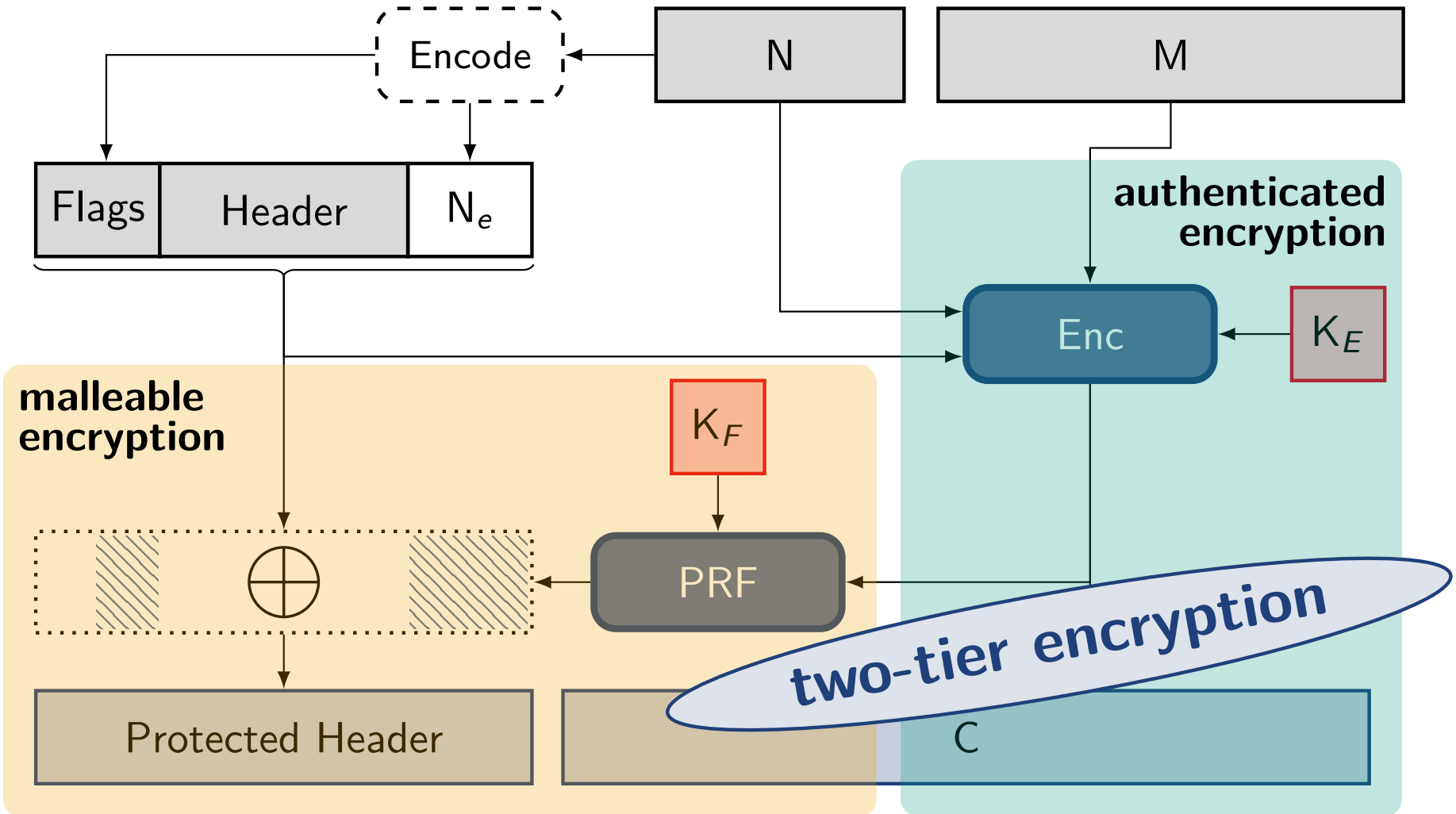

Why a dedicated primitive?

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- formalize statements about expected properties of QPE
  - nonce-hiding [BNT19]
  - header-hiding *(new)*
  - forward secrecy through key updates (adopted from TLS 1.3 [GM17])
- explore variant constructions
  - potential for stronger security?
- establish a primitive that can be used elsewhere

Recap: Classical Nonce-based AE (NBE1)

[Rog02]

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$$C \leftarrow \mathsf{SE}_1.\mathsf{Enc}(K, N, M, H)$$
$$M \leftarrow \mathsf{SE}_1.\mathsf{Dec}(K, N, C, H)$$

- Enc **and** Dec get nonce N as input
- ... nonce has to travel with the ciphertext, somehow

- **What if you (QUIC) want to hide the nonce?**

Nonce-hiding AE (NBE2)

[BNT19]

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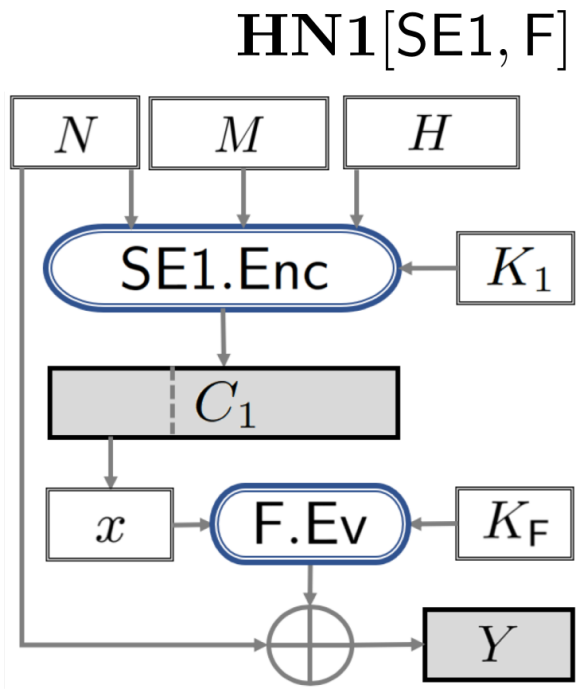
$$C \leftarrow \mathsf{SE}_2.\mathsf{Enc}(K, N, M, H)$$
$$M \leftarrow \mathsf{SE}_2.\mathsf{Dec}(K, C, H)$$

- Dec no longer gets the nonce N
- Nonce needs to travel as part of (extended/full) ciphertext
- **HN1** transform: mask nonce via PRF
- **Still not quite what QUIC does...**
  - only partial nonce N_e gets transmitted
  - partial nonce length varies
  - further header bits masked



[BNT19]

Two-tier Authenticated Encryption

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$$(C_1, C_2) \leftarrow \mathsf{SE}_{\mathsf{tt}}.\mathsf{Enc}(K = (K_1, K_2), N, M = (M_1, M_2), H)$$

$$(M_1, st) \leftarrow \mathsf{SE}_{\mathsf{tt}}.\mathsf{Dec}_1(K_1, C_1)$$
$$M_2 \leftarrow \mathsf{SE}_{\mathsf{tt}}.\mathsf{Dec}_2(K_2, N, C_2, H, st)$$

- Encryption takes two keys and messages, produces two-part ciphertext
- Decryption in two steps/tiers:
  - Dec_1 recovers M_1 from C_1 (only)
  - Dec_2 recovers M_2 from C_2 **and** N, H (some of which may be derived from M_2)
- Idea (for QUIC): M_1 carries (partial) nonce / (to-be-)protected header

Two-tier Authenticated Encryption

Security

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$$(C_1, C_2) \approx (\$^{cl_1}, \$^{cl_2})$$

- Ciphertexts (both parts) look like random strings (of appropriate length cl_1, cl_2)

and

- Hard to come up with C_1^* for $(C_1, C_2) \leftarrow \mathsf{SE}_{\mathsf{tt}}.\mathsf{Enc}(.., (M_1, M_2), ..)$ s.t.

$$M_1 = M_1^* \leftarrow \mathsf{SE}_{\mathsf{tt}}.\mathsf{Dec}_1(.., C_1^*)$$

and

QUIC: leaks if decryption with decoded nonce is successful

classical **AE security**

- Hard to forge C_2^* which decrypts to non-error message $M_2^* \neq \perp$

QPE's Core: AEX

(Two-tier) Authenticated Encryption with XOR

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- based on (NBE1) nonce-based AE scheme SE and PRF F
- Keys: K_1 for F, K_2 for SE
- Encryption: M_2 via SE, then masking M_1 with sample of C_2

$\underline{\mathsf{AEX.Enc}((K_1, K_2), N, (M_1, M_2), H)}$

$s \| C_2 \leftarrow \mathsf{SE.Enc}(K_2, N, M_2, H)$

$C_1' \leftarrow M_1 \oplus \mathsf{F}(K_1, s)$

Return $(C_1 = (C_1' \| s), C_2)$

- Decryption: unmask M_1, pass sample onto Dec_2 in state

$\underline{\mathsf{AEX.Dec}_1(K_1, C_1)}$

$C_1' \| s \leftarrow C_1$

$M_1 \leftarrow C_1' \oplus \mathsf{F}(K_1, s)$

Return $(M_1, st = s)$

$\underline{\mathsf{AEX.Dec}_2(K_2, N, C_2, H, st)}$

$M_2 \leftarrow \mathsf{SE.Dec}(K_2, N, st \| C_2, H)$

Return M_2

QPE Is (Partially) Nonce-Hiding

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$$C \leftarrow \text{QPE.Enc}(K, (N_i, N_e), M, H)$$
$$M \leftarrow \text{QPE.Dec}(K, N_i, C, H)$$

- Dec is given N_i (based on expected sequence number) but not N_e
  - similar to AE5 notion (for CAESAR competition) of Namprempre, Rogaway, Shrimpton [NRS13]
  - likewise captured by Delignat-Lavaud et al. [DLFP+20]
- Generalizes NBE1 (omit N_e) and NBE2 (omit N_i)
- AEX internally:
  - Encrypt explicit nonce N_e part of inner scheme with the outer scheme
  - Recover N_e (and unprotected header) in two-tier decryption operation

QPE Is (Partially) Nonce-Hiding

Mapping Two-tier AEX to QPE

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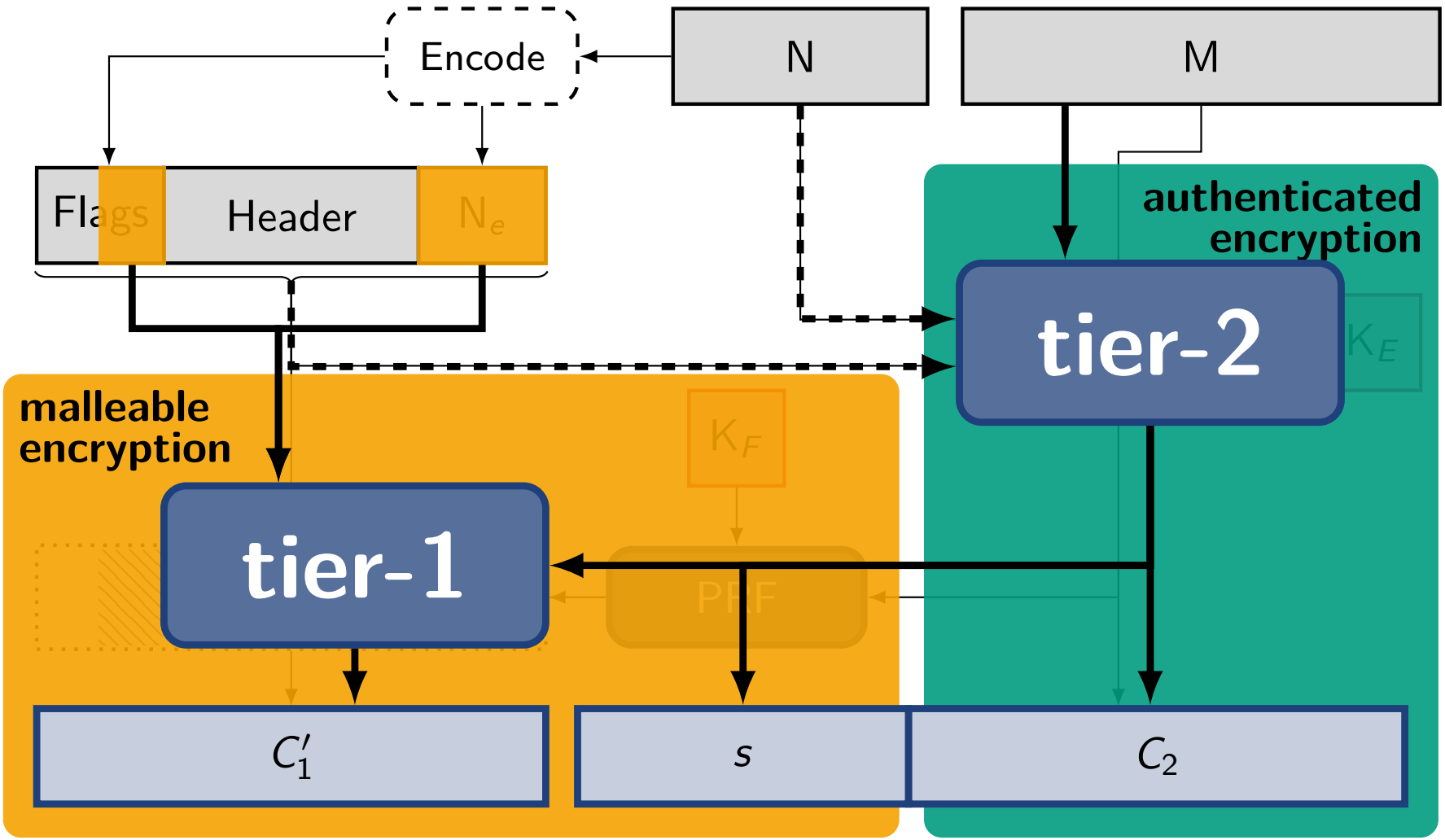

Ongoing & Future Work

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- **Forward secrecy** through rotating AE encryption keys
  - two-tier AE notion modularly separates AE and masking (PRF) keys
  - tier-1 hiding QUIC's key-phase bit $\rightarrow$ lets tier-2 decide on which K_2 to use
- **Further instantiations** of two-tier AE
  - other nonce-hiding transforms from [BNT19]
  - stronger authenticity for tier-1 — what are the trade-offs?
- Application in **other settings**
  - **DTLS 1.3** adopted QUIC's header encryption
  - **Message Layer Security** (MLS) considers metadata encryption
  - ...

Summary

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- QUIC's Packet Encryption aims to hide packet numbers & more header
- We model its core as **two-tier authenticated encryption**

$$(C_1, C_2) \leftarrow \mathsf{SE}_{\mathsf{tt}}.\mathsf{Enc}(K = (K_1, K_2), N, M = (M_1, M_2), H)$$

$$(M_1, st) \leftarrow \mathsf{SE}_{\mathsf{tt}}.\mathsf{Dec}_1(K_1, C_1)$$
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- We confirm that QPE is (partial) nonce-hiding via its core two-tier scheme AEX (AE-with-XOR)
- Two-tier AE as stepping stone:
  - forward security via key updates
  - variants with stronger security
  - applications beyond QUIC

Thank You!

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