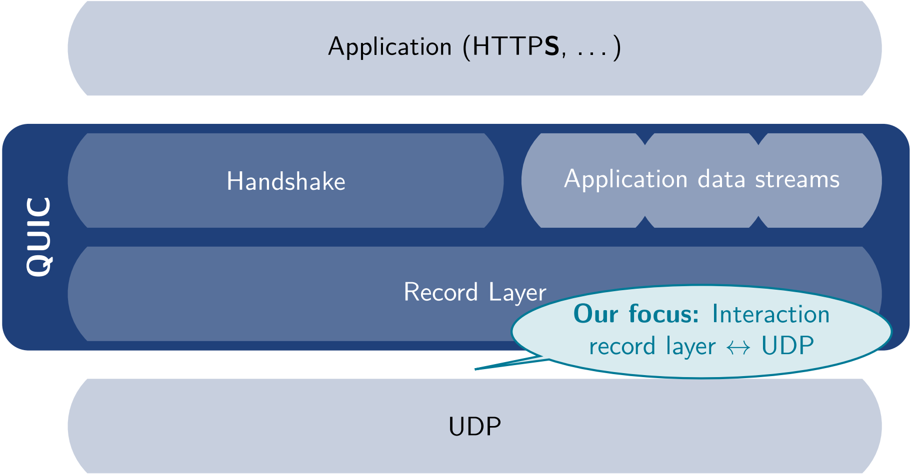
Robust Channels

Handling Unreliable Network Messages in QUIC's Record Layer

Marc Fischlin, **Felix Günther**, Christian Janson

QUIC within the Network Stack



The QUIC Record Layer

(highly simplified)

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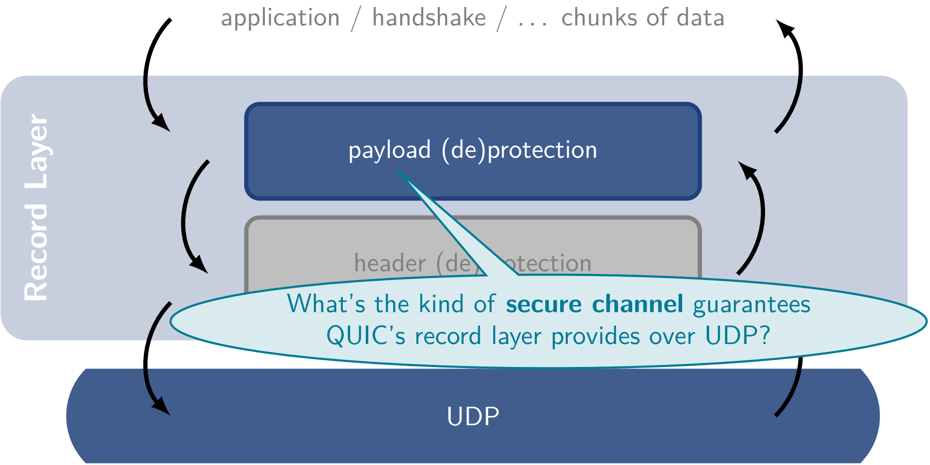

Recap: Secure Channels over TCP

... think: TLS

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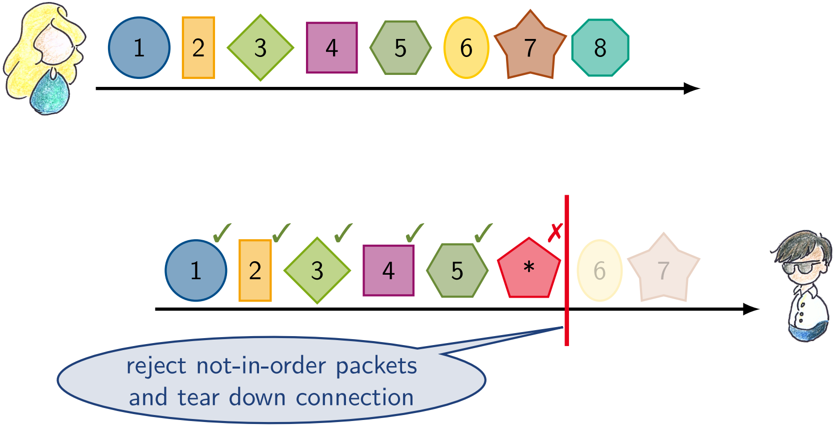
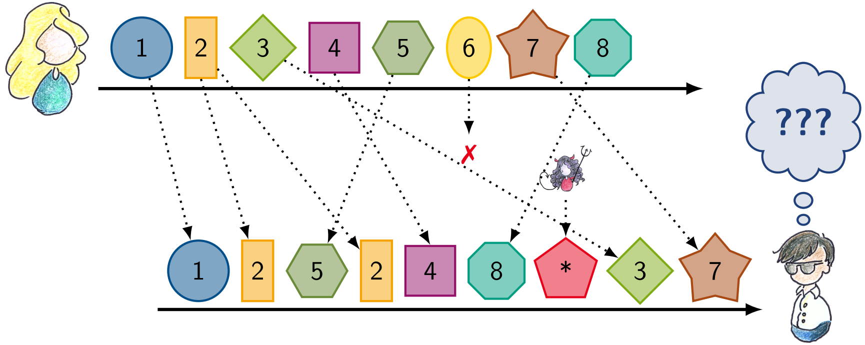


drawings by *Giorgia Azzurra Marson*

Handling Unreliable Transport

QUIC, DTLS, ... over UDP



Handling Unreliable Transport

Many choices...

- **Replays / Duplicates**
  - prevent them? — **QUIC**: MUST prevent
  - check how far back? — **QUIC**: e.g., replay-check window (IPsec)
- **Reordering**
  - permitted? — **QUIC**: well, yes—it's UDP
  - by how far max.? — **QUIC**: dynamic sliding window
- **Adversarial interaction**
  - Integrity: always want to reject non-genuine packets — **QUIC**: use AEAD
  - But how do you (formally) guarantee that replayed / reordered / adversarial packets don't affect others?

Our Contributions

- **Generic channel model** capturing handling of unreliable transport
- New notion: **Robustness**
  — *"malicious packets cannot disturb expected channel behavior"*
- Assess **QUIC**'s packet encryption as [robust + secure?] channel
  - we also analyze the similar **DTLS 1.3** record layer

We're not the first to look at channels. . .

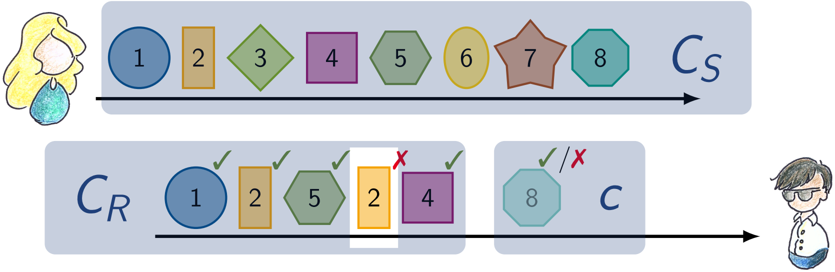
- initial (game-based security) formalization by [BKN02]
  - (stateful) confidentiality (IND-CCA) and integrity (INT-CTXT)
  - assuming reliable transport $\rightarrow$ reject upon/after first deviation
  - most cryptographic channel models follow this approach

- approaches towards a hierarchy of channels [KPB03,BHMS16,RZ18]
  - different levels of permissible reordering & replays
  - yet, these don't capture QUIC's sliding-window approach

- prior work on QUIC
  - don't consider the fine-grained reordering/replay protection [LJBN15,CJJ+19]
  - or remain on the AEAD-primitive level [DLFP+20,BGT20]

Generalizing Channel Correctness

- parameterize what packet (ciphertexts) reordering a channel **supports**
- predicate $\mathrm{supp}(C_S, C_R, c) = ✓ \,/\, ✗$
  - C_S: sequence of sent ciphertexts
  - C_R: sequence of *supported* ciphertexts received prior
  - c: next ciphertext to receive
- correctness requires (only) genuine, supported ctxts be correctly decrypted

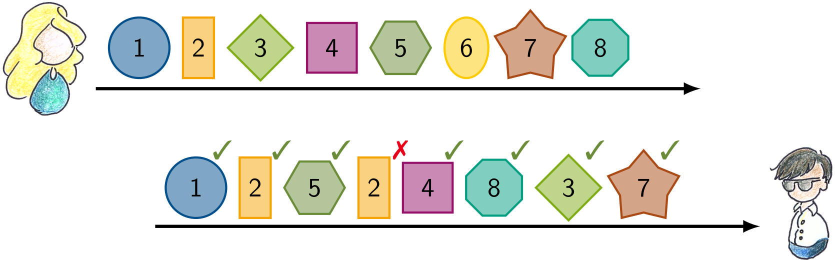


Generalizing Channel Correctness

Example support class: $\mathsf{supp}_{no\text{-}r}$ (no order, global anti-replay)

$$\mathsf{supp}_{no\text{-}r}(C_S, C_R, c) := \left[c \in C_S \wedge c \notin C_R\right]$$

- corresponds to level 2 of [BHMS16] $\neq$ DTLS (1.2)



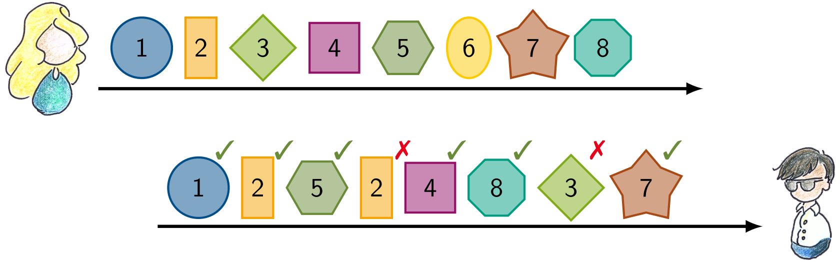
Generalizing Channel Correctness

Example support class: $\text{supp}_{\textit{no-r}[w_r]}$ (no order, anti-replay window)

$$\text{supp}_{\textit{no-r}[w_r]}(C_S, C_R, c) := \left[c \in C_S \wedge c \notin C_R \wedge \underline{\text{index}(c, C_S) \geq \text{m} - w_r} \right]$$

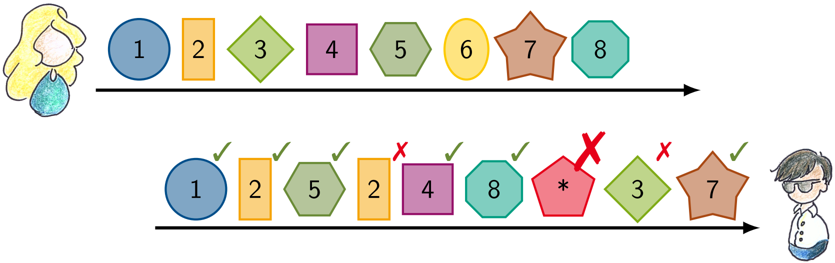
m: highest received index / packet number

- this is DTLS 1.2
- example below: $w_r = 4$



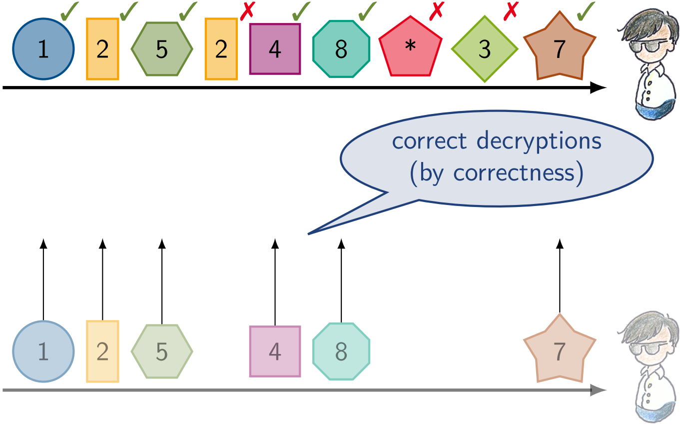
Defining Robustness (ROB)

"malicious packets cannot disturb expected channel behavior"



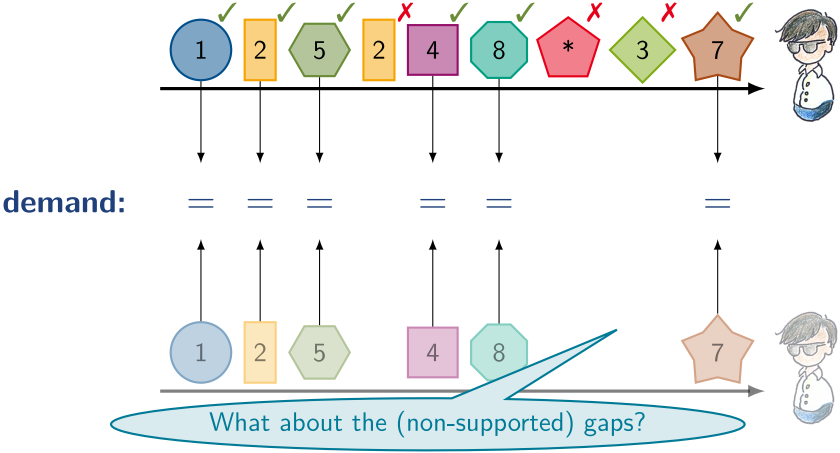
Defining Robustness (ROB)

Idea: Compare with the supported, correct sub-trace



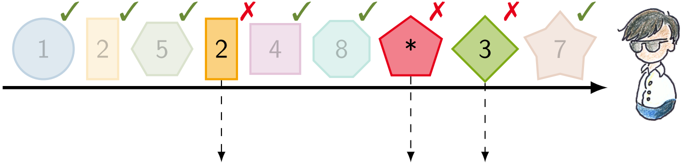
Defining Robustness (ROB)

Idea: Compare with the supported, correct sub-trace



Integrity (INT)

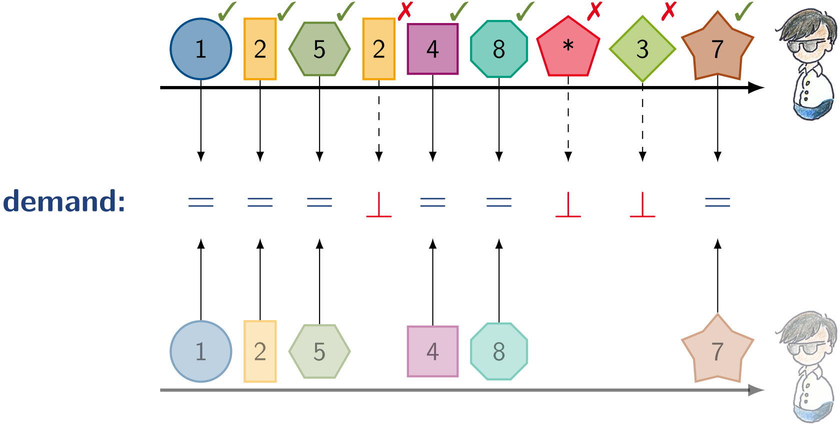
. . . wrt. supp predicate



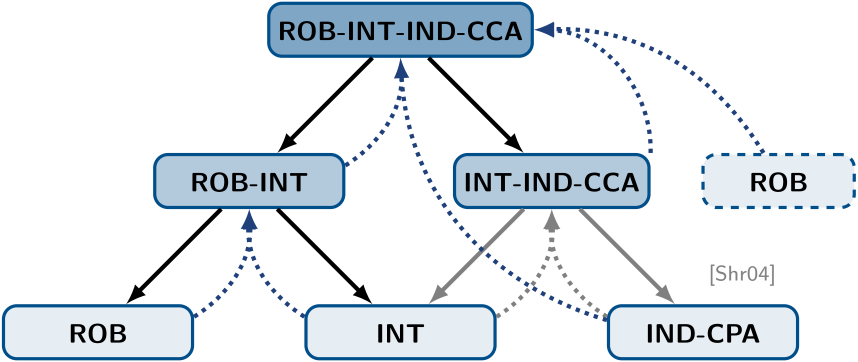
demand: $\perp$ $\perp$ $\perp$

Robust Integrity (ROB-INT)

- join **robustness** and **integrity** for desired property over unreliable transport



A Robust Hierarchy



all notions parameterized by same supp predicate

QUIC Payload Encryption

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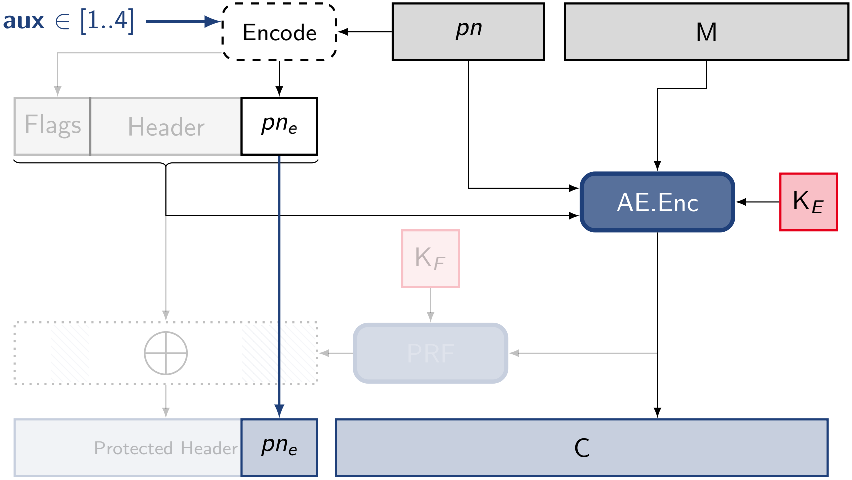

QUIC Channel

Dynamic Sliding Window

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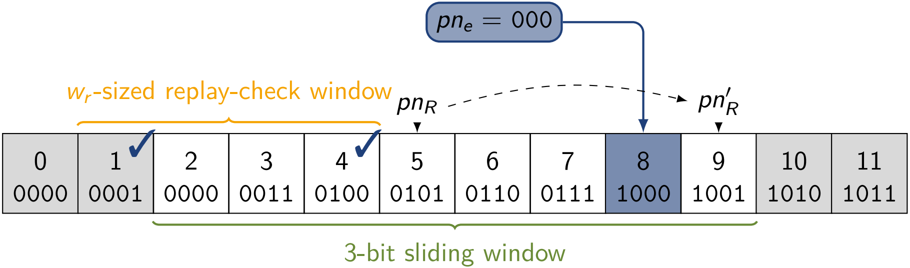
- interpret pn_e in $|pn_e|$ **bit dynamic window** around next expected (pn_R)
- check for **replays in w_r sized window** back from pn_R

- **(toy) example:** 3-bit sliding window, replay window $w_r = 4$, $pn_R = 5$



QUIC Channel

Correctness

$$\mathsf{supp}_{dw\text{-}r[w_r]}(AC_S, C_R, c) :=$$

$$\Big[c \in C_S \wedge c \notin C_R \wedge \mathsf{index}(c, C_S) \in [\mathsf{n} - \min(w_b^c, w_r + 1), \mathsf{n} + w_f^c]\Big]$$

supported if in sliding window
(dynamic for c) **and** replay window

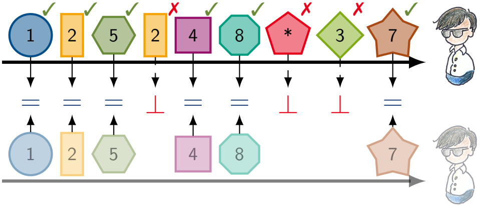
- **QUIC** matches this
  - based on correct decoding property when interpreting pn_e

QUIC Channel

Robust Integrity (ROB-INT)

Intuition:

- non-supported ctxts are rejected as AEAD error (or replays)
  - reordered out-of-window: pn_e decodes to different pn
  - or: actual adversarial forgery
- either would require **AEAD authenticity break** (via game-based reduction)
  - but:  can try multiple times
  - factor q_R (#received ciphertexts) loss in security reduction



QUIC Channel: Overall Security

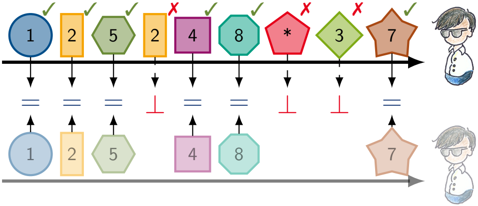
Robust Confidentiality and Integrity (ROB-INT-IND-CCA)

- use hierarchy: **ROB-INT** + **IND-CPA** = **ROB-INT-IND-CCA**

$$\mathrm{Adv}^{\mathrm{ROB-INT-IND-CCA}}_{\mathrm{QUIC}} \leq \mathrm{Adv}^{\mathrm{priv}}_{\mathrm{AEAD}} + q_R^{*} \cdot \mathrm{Adv}^{\mathrm{auth}}_{\mathrm{AEAD}}$$

* for technical reasons (uniqueness of ciphertexts) there's an additional q_S^2 factor

- q_r loss matches that attacks become easier over unreliable transports [AP13]



Summary

- QUIC's channel construction ensures **robustness** over unreliable transport

- We establish this in a **generic channel model**
  - parameterized in what reordering / replay / ... is supported
  - introducing robustness as a first-class security property

- Our model captures **QUIC's dynamic sliding-window & replay-checking**
  - ... but also other settings like DTLS 1.2, DTLS 1.3, etc.
  - confirm QUIC achieves intended robust confidentiality and integrity

- Preliminary preprint for QUIPS 2020:
  `felixguenther.info/Q20_RC.pdf`

Thank You!

mail@**felixguenther.info**

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