On the Concrete Security of TLS 1.3 PSK Mode

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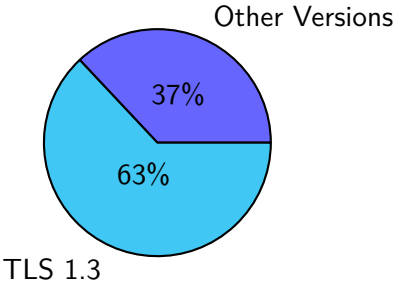
Transport Layer Security (TLS) 1.3

"TLS allows client/server applications to communicate over the Internet in a way that is designed to prevent eavesdropping, tampering, and message forgery."

— Abstract, RFC 8446

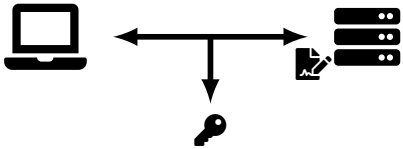


Preferred Version of the Top 1M Servers

— F5 Labs, Oct'21

Transport Layer Security (TLS) 1.3

Handshake Protocol



Application Data

Record Layer

Transport Layer Security (TLS) 1.3

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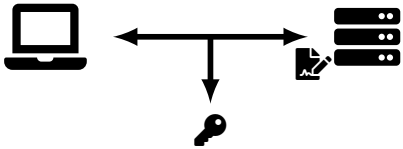

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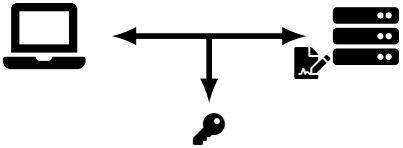
TLS 1.3 Handshake Protocol

TLS 1.3 Full Handshake



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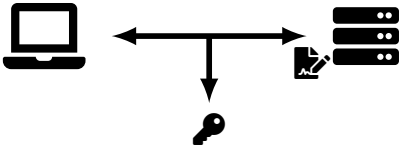
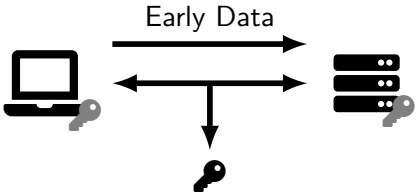


TLS 1.3 PSK-only Handshake



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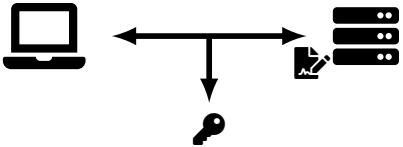

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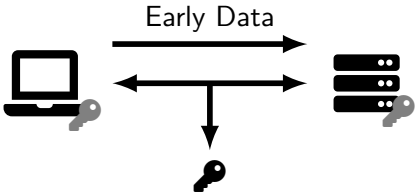
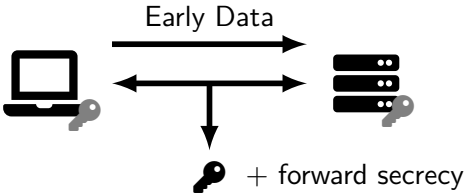


TLS 1.3 PSK-(EC)DHE Handshake



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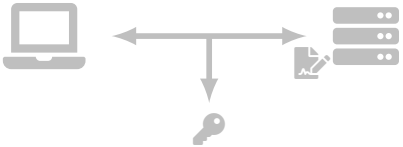

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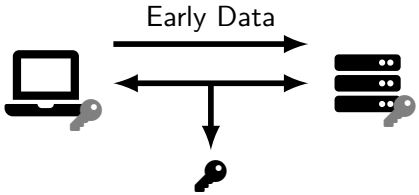

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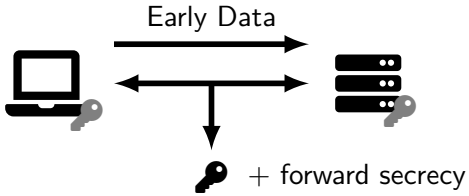
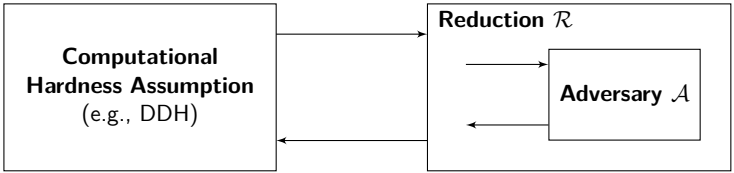


Concrete Security and Tightness



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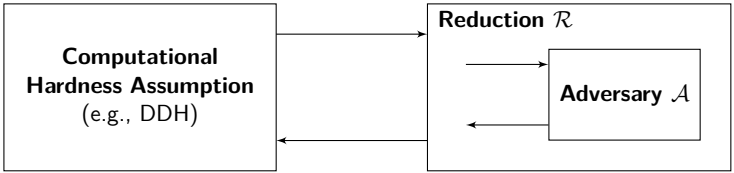

- Classically, security proofs considered asymptotically
  → Guarantee for the existence of "sufficiently" large parameters
- But: *no* guarantee that a real-world cryptosystem with standardized parameters achieves a certain expected security level
- Concrete security approach makes bounds explicit:

$$\mathsf{Adv}(\mathcal{A}) \leq \ell(\mathcal{A}) \cdot \mathsf{Adv}(\mathcal{R})$$

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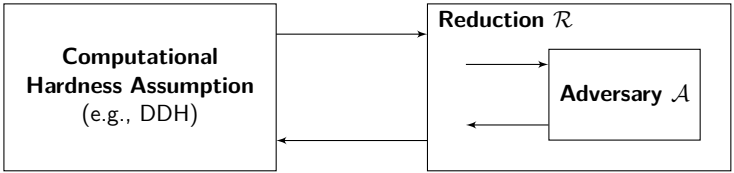

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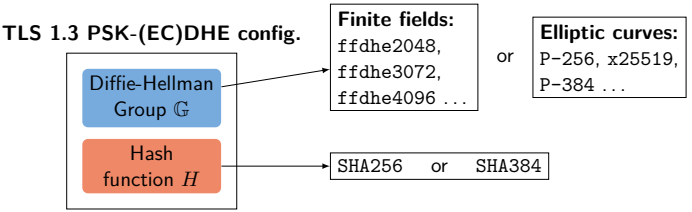
$$\mathsf{Adv}(\mathcal{A}) \leq \ell(\mathcal{A}) \cdot \mathsf{Adv}(\mathcal{R})$$

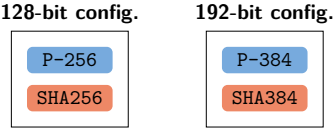
→ Tight security proof if ℓ is a small constant independent of $\mathcal{A}$

Previous Analyses of TLS 1.3

- TLS 1.3 developed in close collaboration between academia and industry
- Many draft revisions & final TLS 1.3 standard RFC 8446 were analyzed
- Dowling, Fischlin, Günther, and Stebila [DFGS21] gave bounds for
  - TLS 1.3 full
  - TLS 1.3 PSK-only
  - TLS 1.3 PSK-(EC)DHE

Security Bound for TLS 1.3 PSK-(EC)DHE by [DFGS21]





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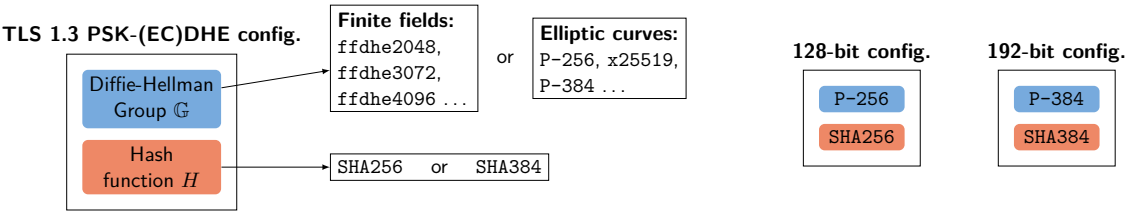

Theorem ([DFGS21], very simplified)

$$\mathsf{Adv}(\mathcal{A}, \text{TLS-PSK-(EC)DHE}) \leq 8S^2 \cdot \mathsf{Adv}(\mathcal{B}_1, \mathbb{G}) + 8S \cdot \mathsf{Adv}(\mathcal{B}_2, H) + \cdots$$

$\#$ sessions

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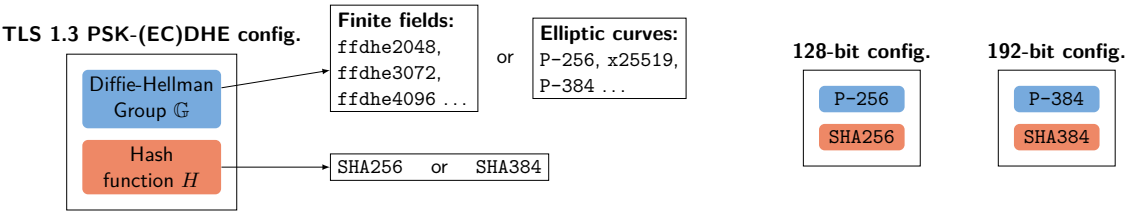

Highly non-tight!

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Concrete Evaluation of [DFGS21]'s Bound

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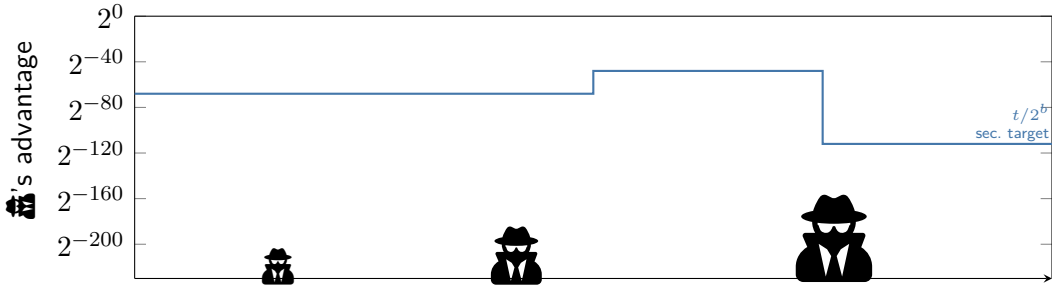

t: attacker time
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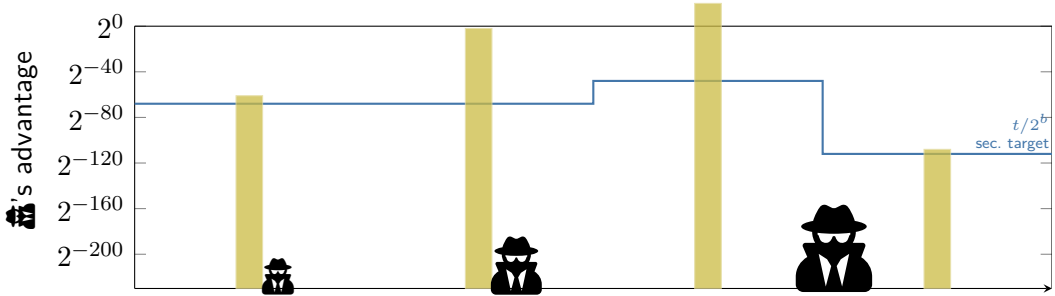

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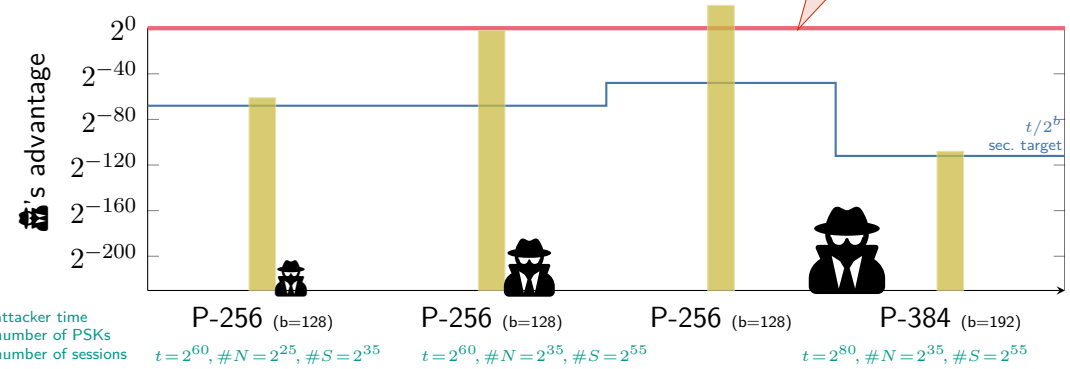

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Tighter Bounds for TLS 1.3

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- Davis and Günther [DG21] and Diemert and Jager [DJ21] independently gave tighter bounds for full handshake
- Limitations:
  - Both made assumptions about the key schedule (next)
  - Signatures need to be multi-user-secure with adaptive corruptions
    → none of the standardized signatures satisfies this tightly (implicit linear loss)

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Tight Bounds for TLS 1.3 PSK mode

- In this work, we give fully tight bounds for
  - TLS 1.3 PSK-only and TLS 1.3 PSK-(EC)DHE
- Exception: PSK-only with `SHA384`

Tight Bounds for TLS 1.3 PSK-(EC)DHE

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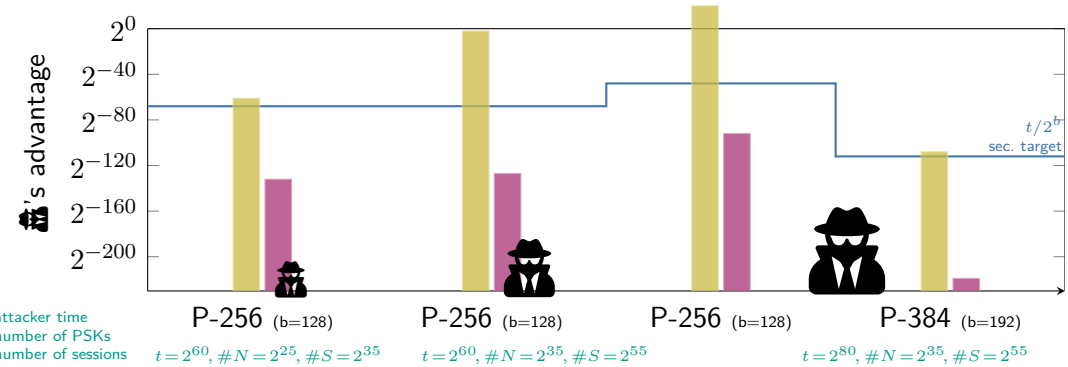
- **Us**: $\mathsf{Adv}(\mathcal{A}, \text{TLS-PSK-(EC)DHE}) \leq \mathsf{Adv}(\mathcal{B}_1, \mathbb{G}) + \mathsf{Adv}(\mathcal{B}_2, H) + \cdots$



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Tight Bounds for TLS 1.3 PSK-(EC)DHE

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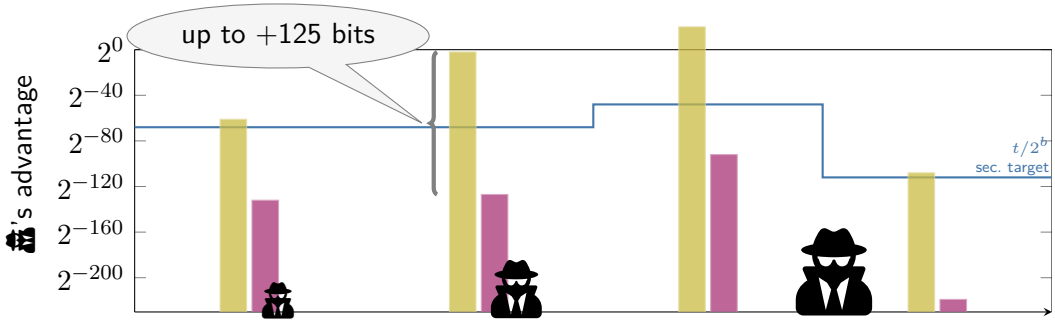

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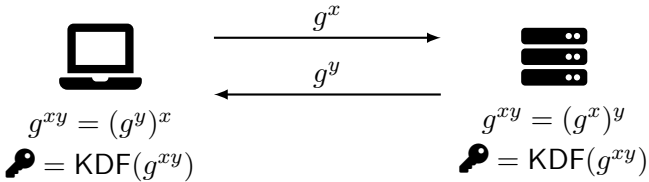
Why are the results not inherently tight?



KDF: Key Derivation Function

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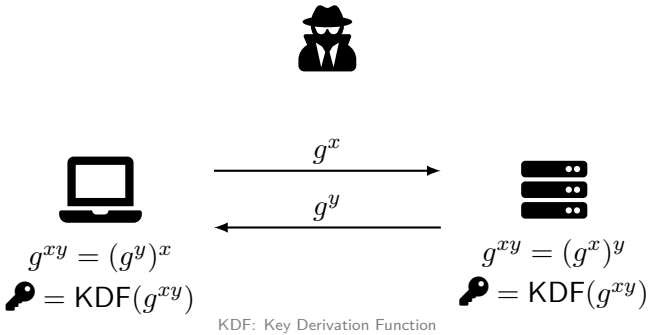

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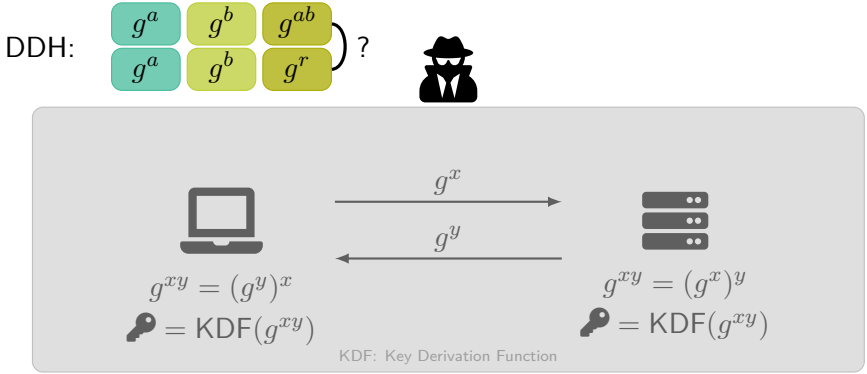

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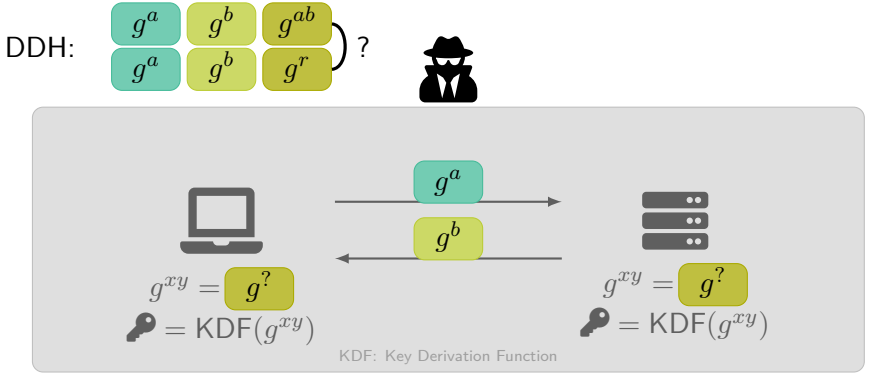

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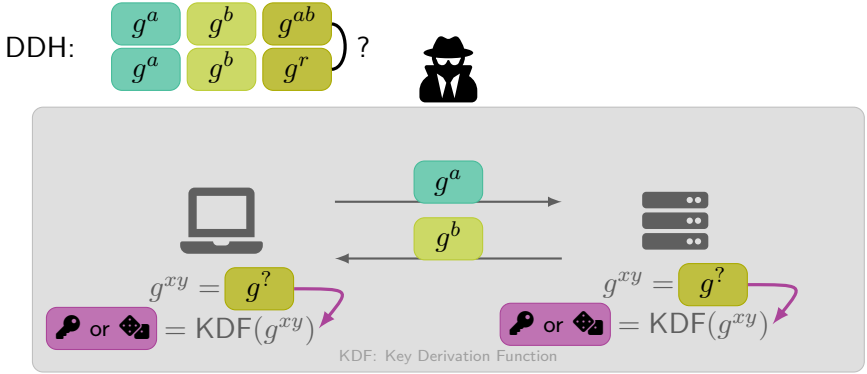

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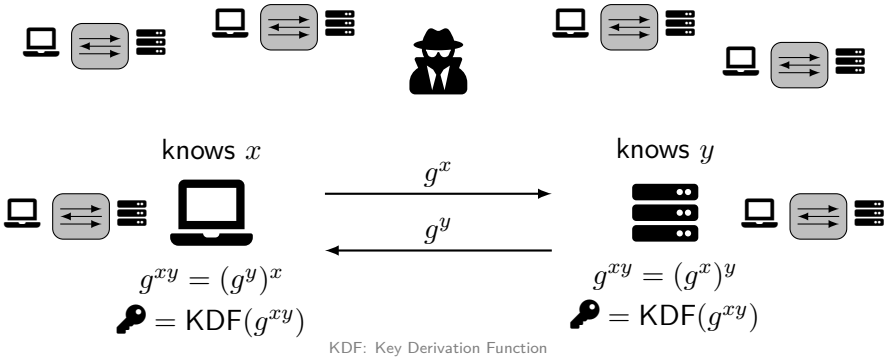

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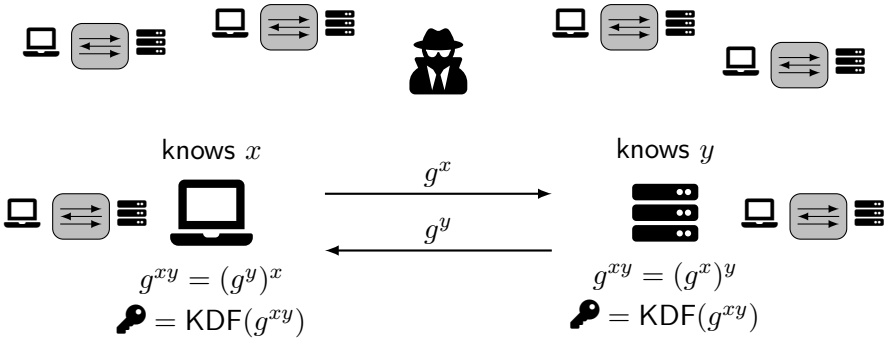

- key secrecy: given only g^x and g^y, key 🔑 remains secret (indist. from 🎲)
- Problem: many sessions in parallel... Where to embed?
  - Solution: guess 💻 and 🖴 $\implies$ loss of $(\#\text{ session})^2$

Tighter Proof for "simple DH" by [Coh+19]

Reduction idea

1. Embed rerandomized g^a in all and rerandomized g^b in all
2. The key derivation of must be modeled as random oracle RO.
   - Crucial: KDF gets as input $(g^x, g^y, g^{xy}, ...)$
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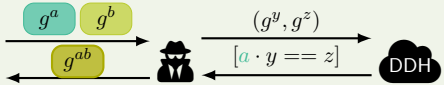
StrongDH ("Solve CDH with DDH oracle"):



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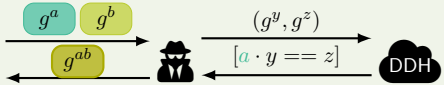
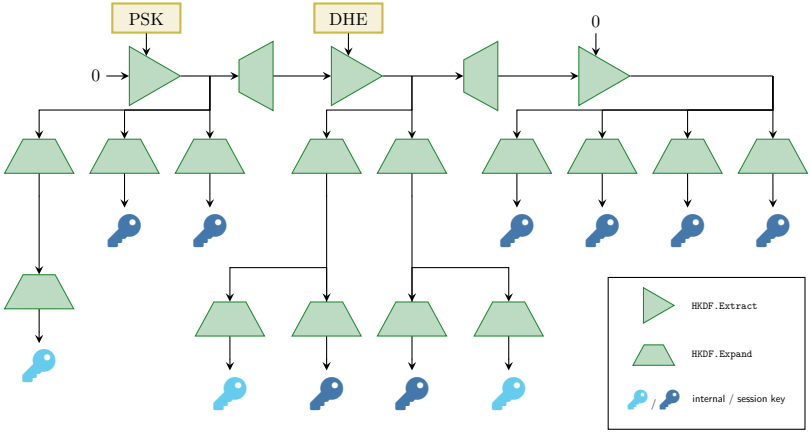


Is this reduction idea a template for a tight(er) proof for TLS 1.3?

TLS 1.3 Key Schedule



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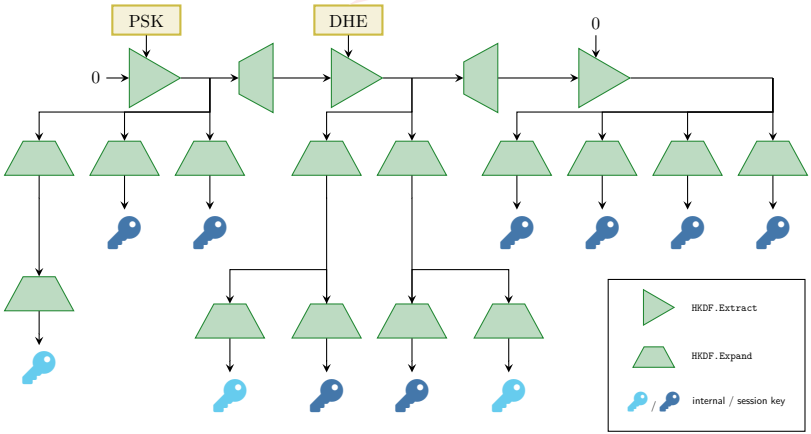

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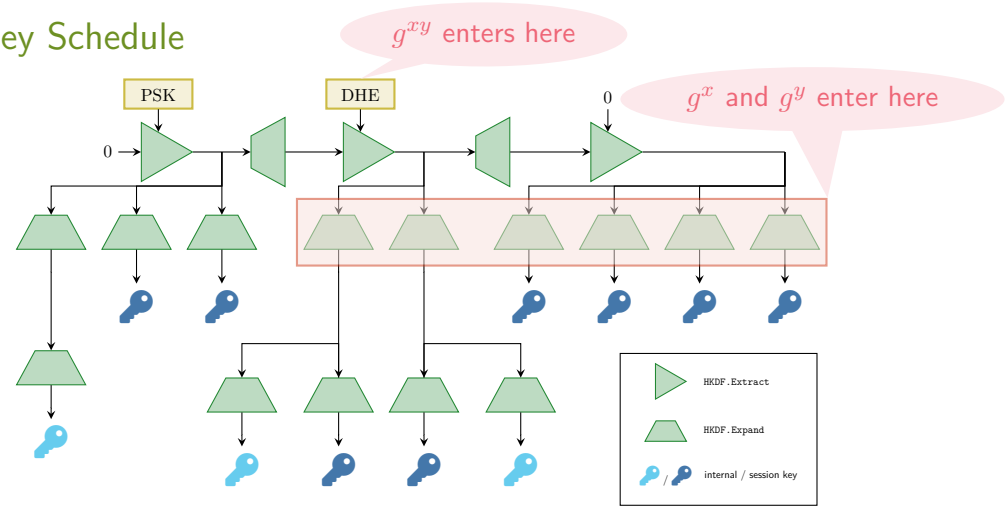

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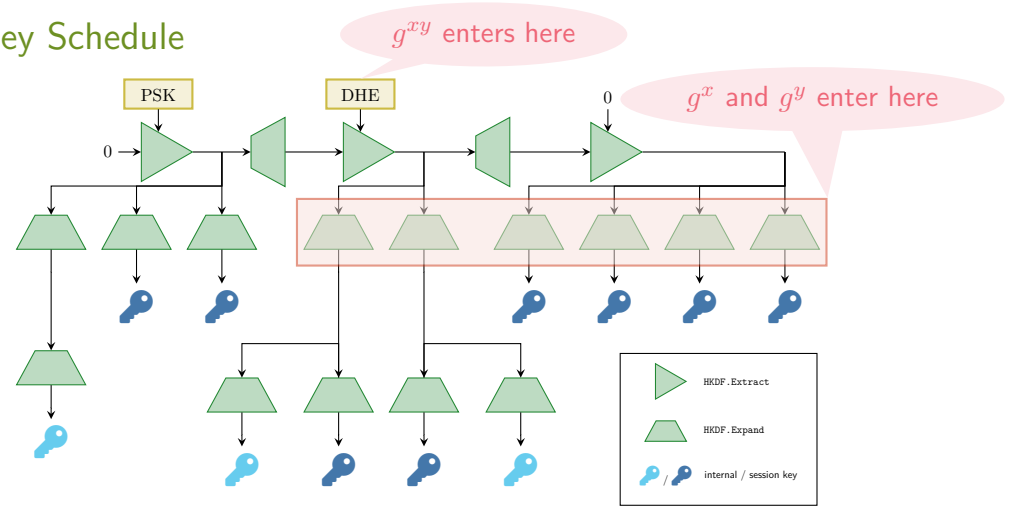
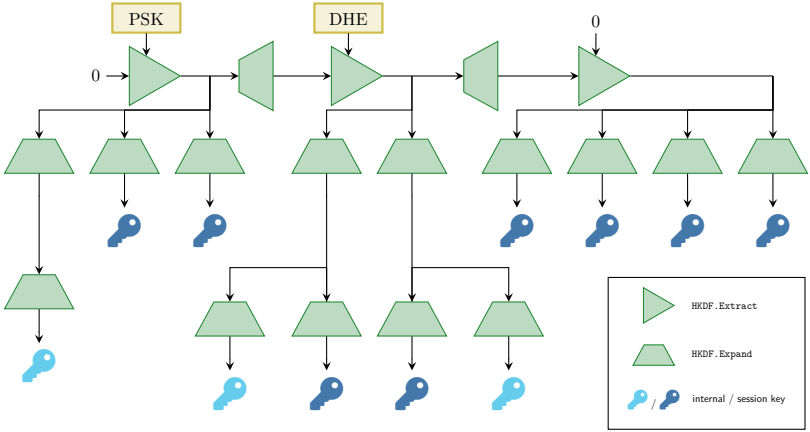


[Coh+19] technique not directly applicable!

Solution 1 – [DG21]



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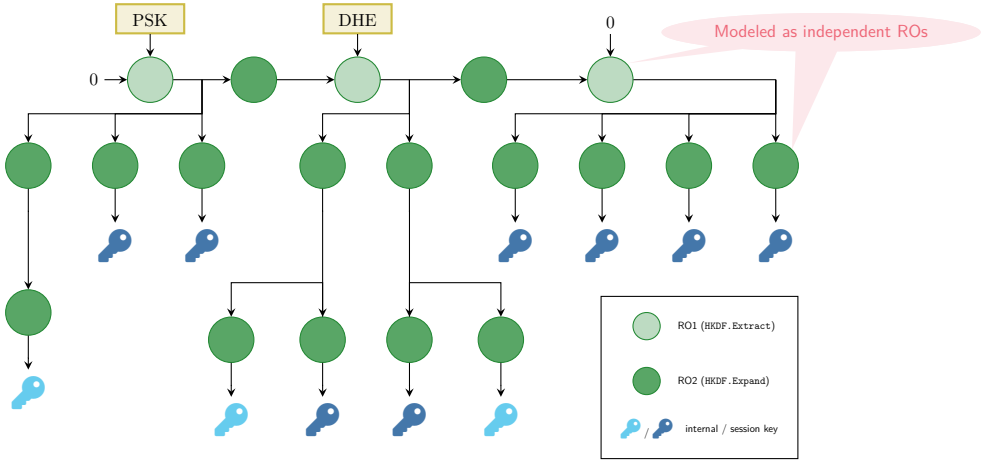

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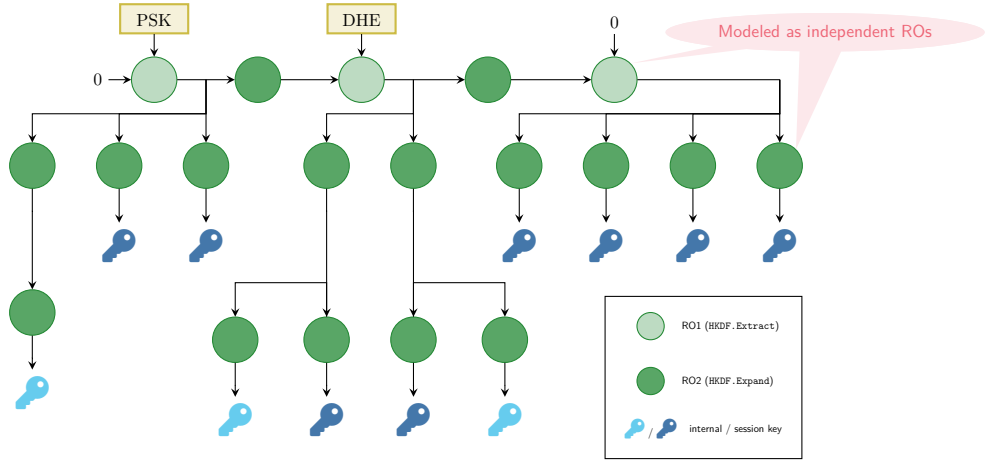
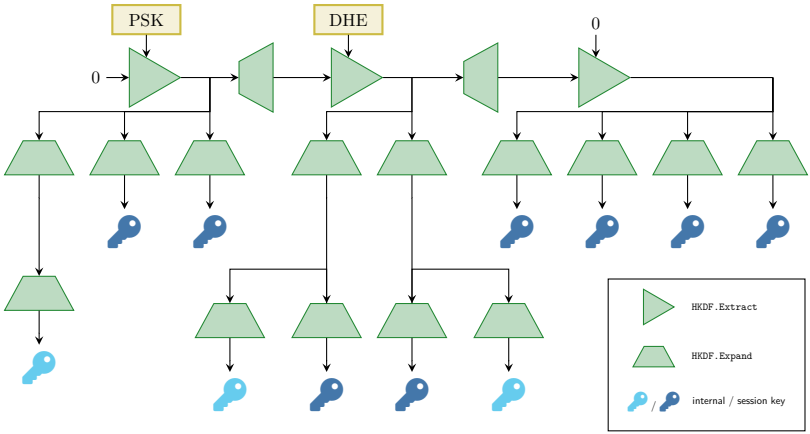


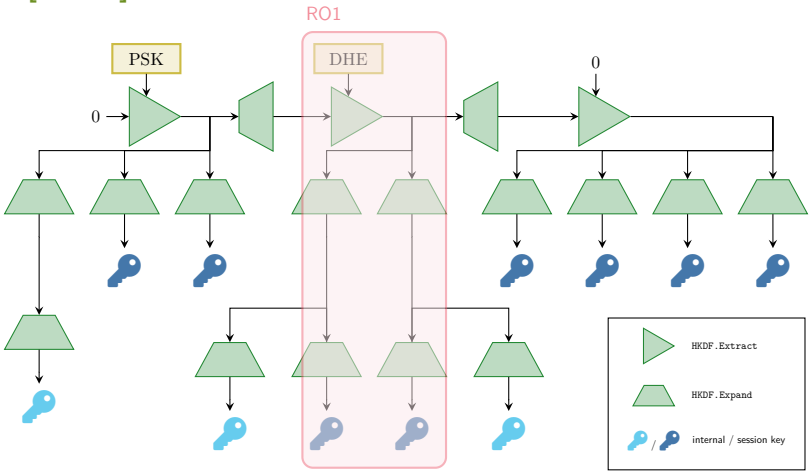
HKDF.Extract and HKDF.Expand unfortunately are not independent!

$\texttt{HKDF.Extract}(K, M) = \text{HMAC}(K, M)$ $\texttt{HKDF.Expand}(\text{K,M}) = \text{HMAC}(K, M \parallel \texttt{0x01})$

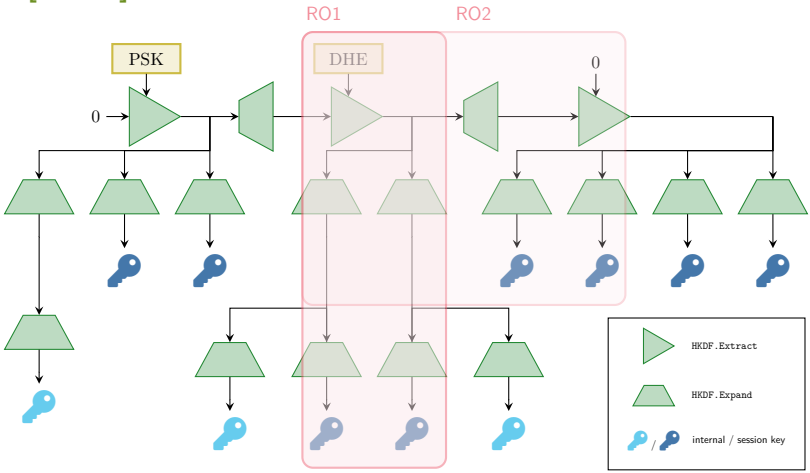
Solution 2 – [DJ21]



Solution 2 – [DJ21]



Solution 2 – [DJ21]



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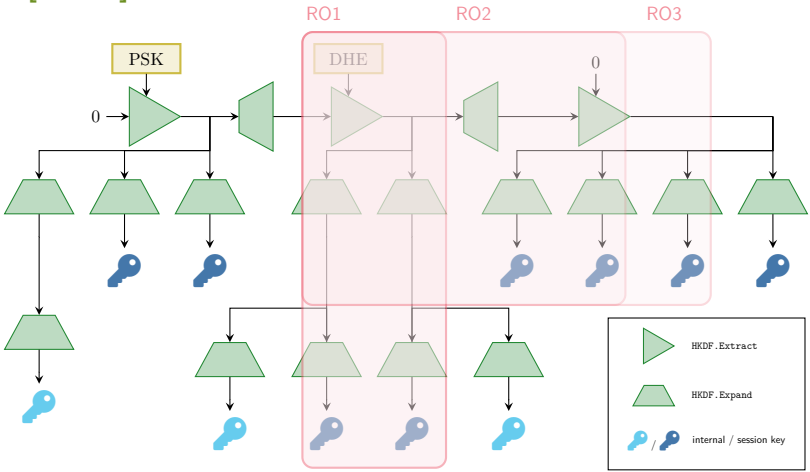

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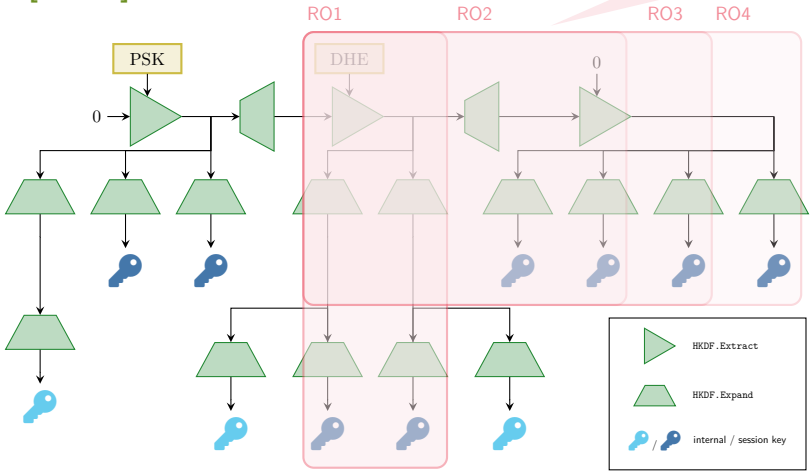

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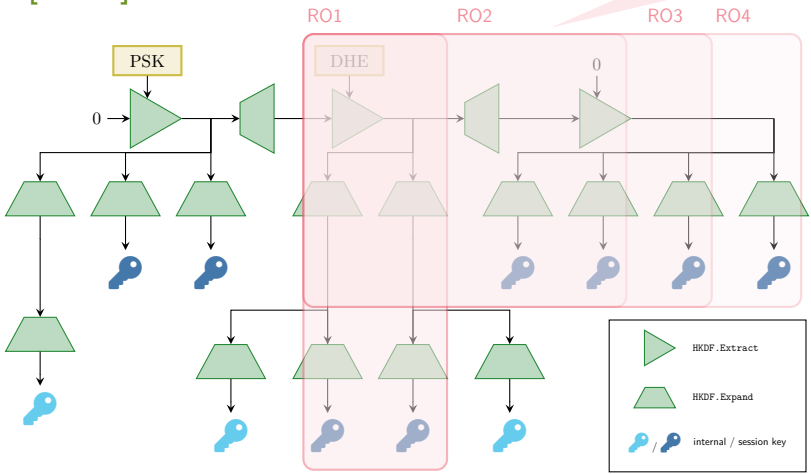
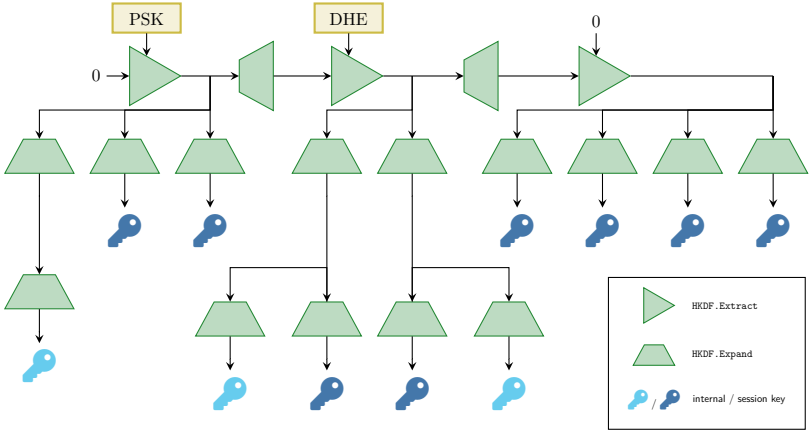


Proof becomes more direct, however assumption not justfied

Bottom Line of the Solutions of DG and DJ



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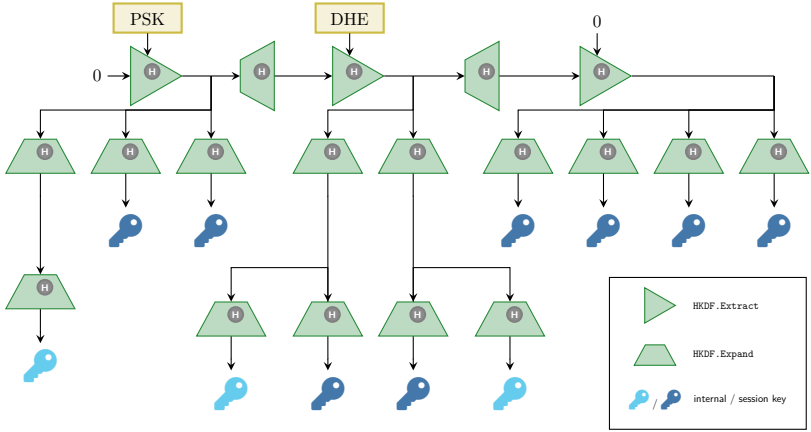
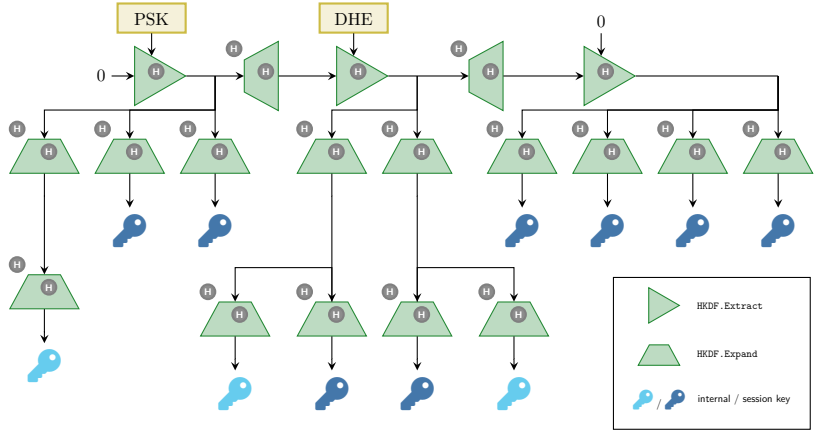


Both miss: TLS uses the same hash function for different purposes in key schedule!

Bottom Line of the Solutions of DG and DJ



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Our Modularization using Indifferentiability [MRH04]

Theorem

$$\mathsf{Adv}(\mathcal{A}, \text{TLS-PSK}) \leq \mathsf{Adv}(\mathcal{B}_1, \text{Abstracted TLS-PSK}) + \mathsf{Adv}^{\text{Indiff.}}(\mathcal{B}_2, \text{Abstraction})$$

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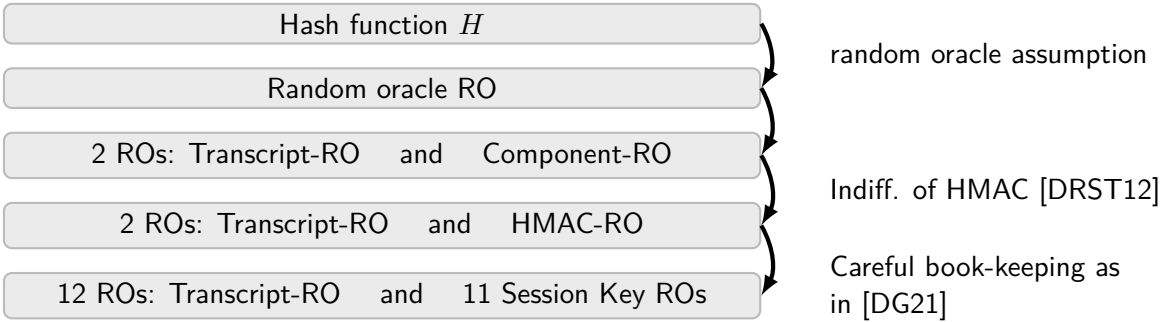
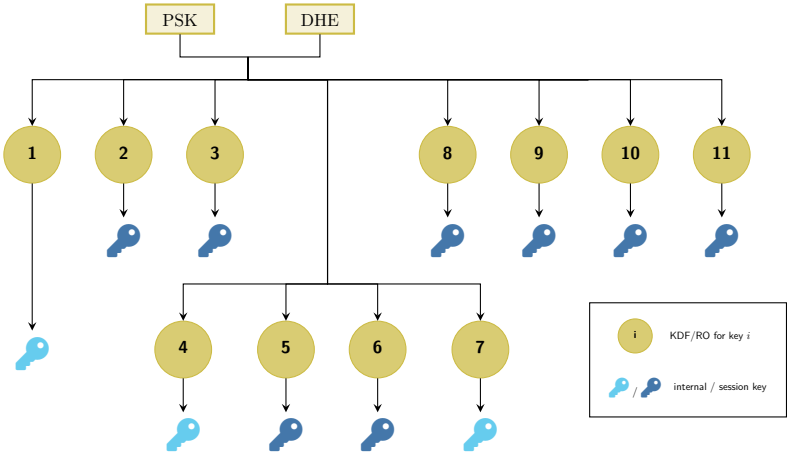
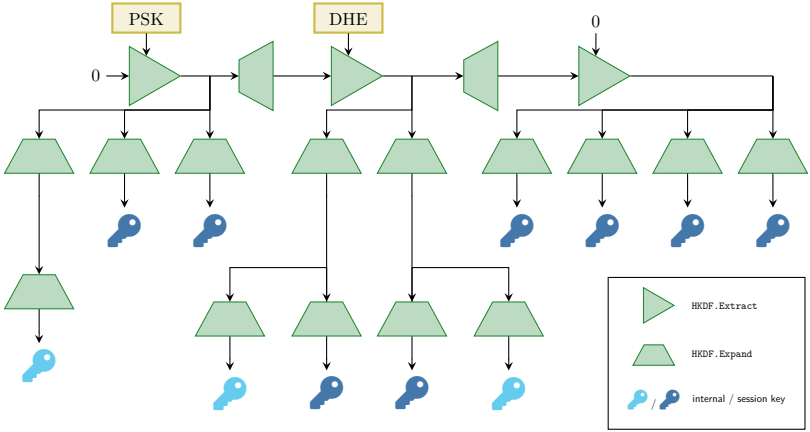
Justifying the Abstraction:



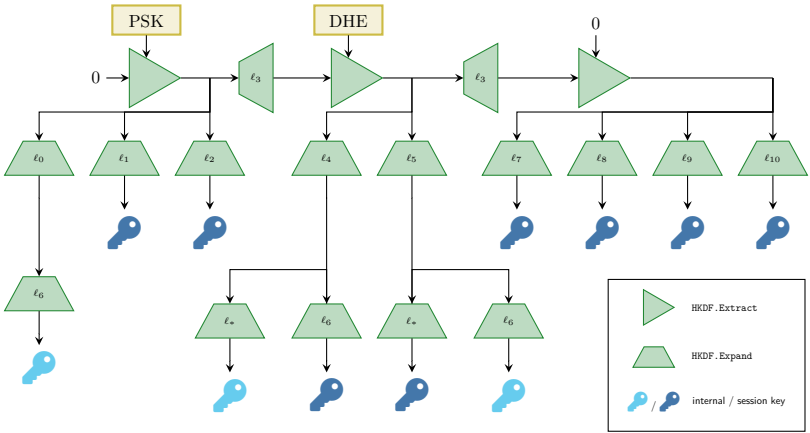
Our Key Schedule Abstraction (simplified)



HMAC-RO $\Longrightarrow$ 11 Session Key ROs

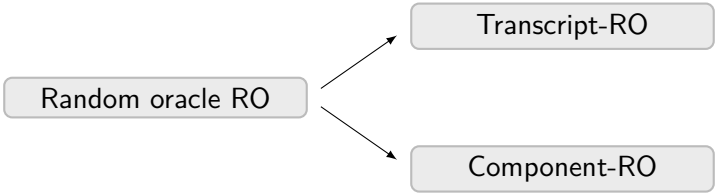


HMAC-RO $\Longrightarrow$ 11 Session Key ROs



➔ `HKDF.Expand` is explicitly domain separated using labels
$\texttt{HKDF.Expand}(K, \ell \,\|\, \cdots) = \mathsf{HMAC}(K, \ell \,\|\, \cdots \|\, \texttt{0x01})$

Lack of Domain Separation



- No explicit domain separation (e.g., labels) for uses of hash function
- Separating the uses of the hash function = distinguishing inputs

$$\text{input} \stackrel{?}{=} \text{transcript / HMAC call / HDKF call}$$

Domain separation works except for PSK-only with SHA384 mode

Summary

- Tight bounds for the TLS 1.3 PSK modes and a concrete evaluation
- New abstraction of the TLS 1.3 key schedule used in the PSK mode
- Identify a lack of domain separation in TLS 1.3 PSK-only with SHA384

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Thank you!

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