Formally analyzing a cryptographic protocol standard

(or: how MLS kept this PhD student busy for three years)

Théophile Wallez, *Inria Paris*
+ work of co-authors

Introduction

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Goal of this talk: share lessons I've learned

- for protocol analysts
- for protocol designers

Analyzing cryptographic protocols

Traditional pen & paper proofs:

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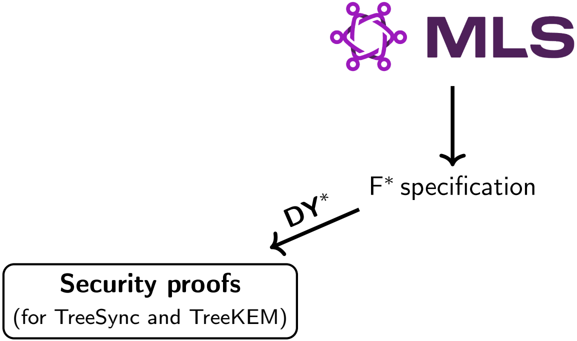
Machine-checked symbolic proofs:
👍 several tools (ProVerif, Tamarin, DY*, ...)
👍 good automation
😕 symbolic model is less precise than computational model
👍 many successes during the last decade (TLS 1.3, Signal, ...)

Our approach for protocol analysis



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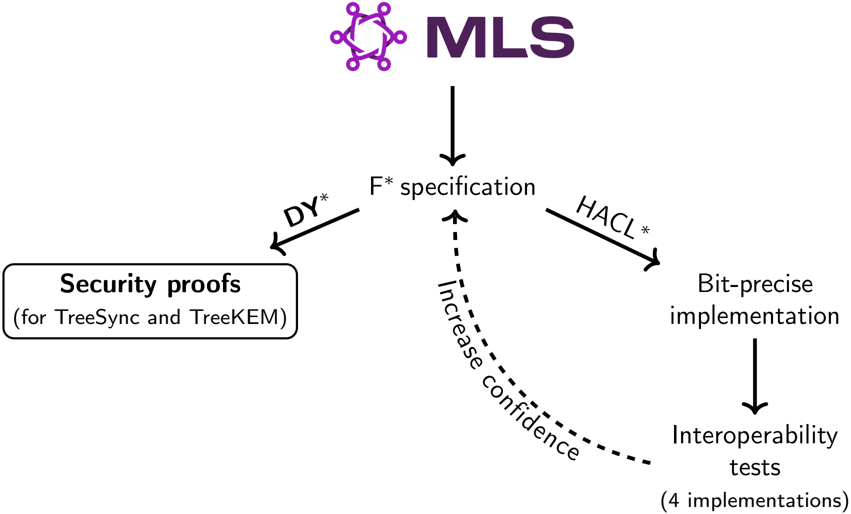

Symbolic security analysis of MLS

Towards a modular analysis of MLS

MLS specification (RFC 9420): 120 pages

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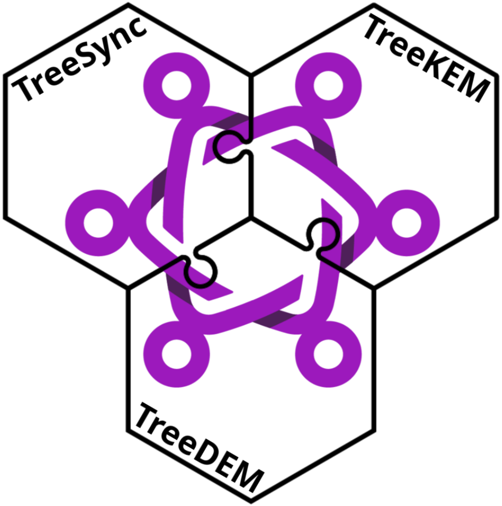

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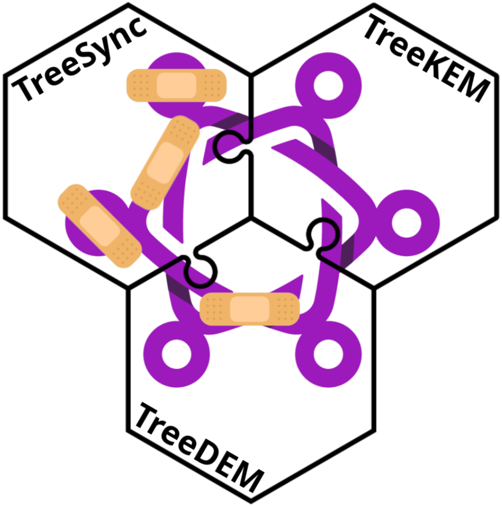

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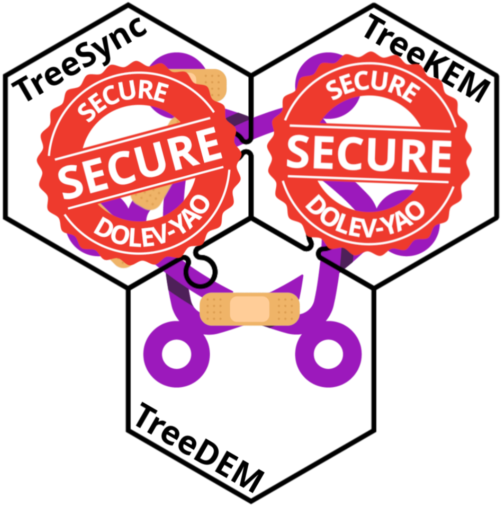

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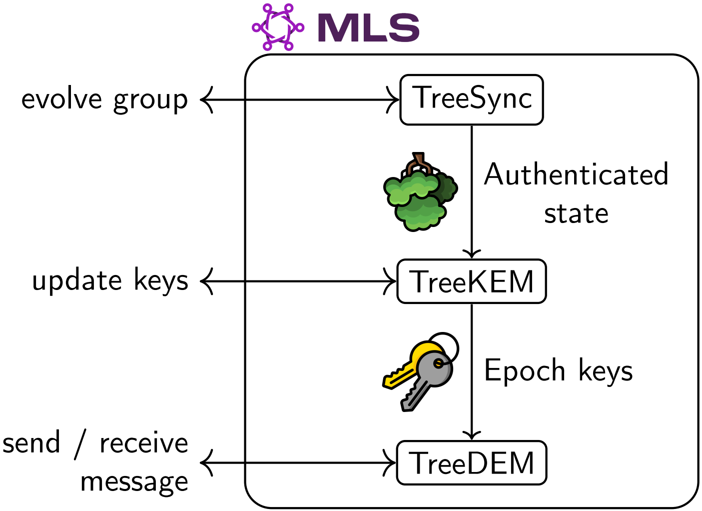
Modularizing MLS

("TreeSync: ...", USENIX Security '23, https://ia.cr/2022/1732)



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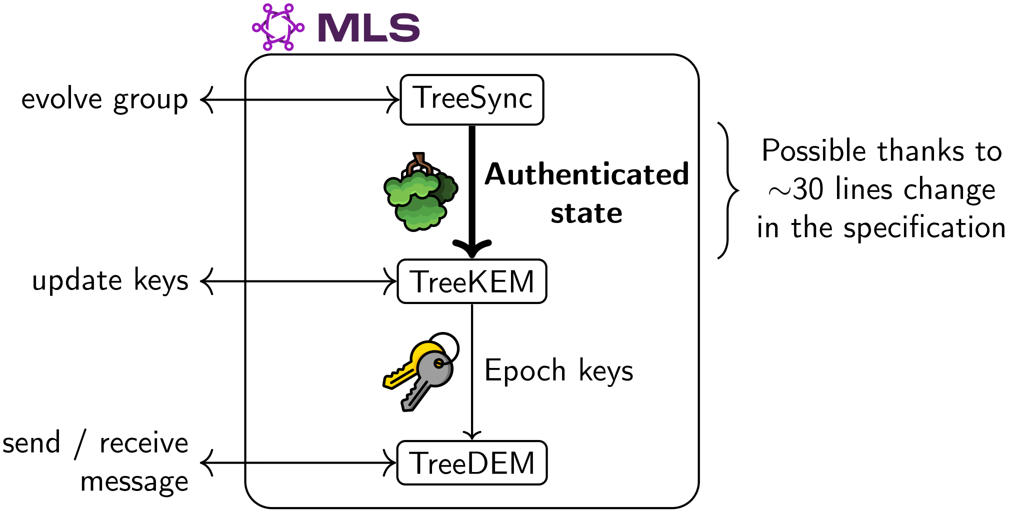
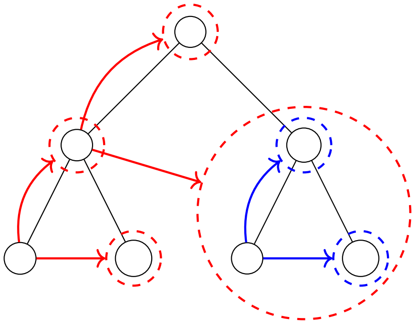


Lesson for protocol designers: modularize protocols

- Collaborate with protocol analysts
- Bonus: protocol is easier to understand
- Bonus: help implementers

Proving security of TreeSync

("TreeSync: . . .", USENIX Security '23, `https://ia.cr/2022/1732`)



- prove agreement theorem (incl. membership agreement)
- relies on minimal assumptions on TreeKEM and TreeDEM

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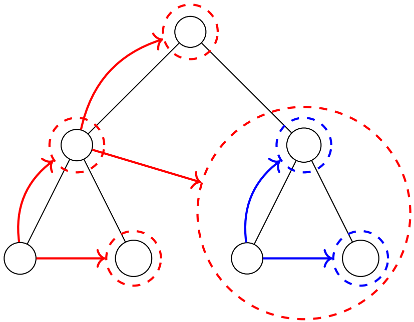

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...however these assumption were initially not true

Signature ambiguity in MLS draft 12

("TreeSync: ...", USENIX Security '23, https://ia.cr/2022/1732)

TreeSync

$$\text{sig} = \text{sign}(\text{sk}, \text{serialize}_{T1}(\text{msg}_1))$$

$$\text{verify}(\text{pk}, \text{sig}, \text{serialize}_{T1}(\text{msg}_1))$$

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TreeDEM

$\text{sig} = \text{sign}(\text{sk}, \text{serialize}_{T2}(\text{msg}_2))$

$\text{verify}(\text{pk}, \text{sig}, \text{serialize}_{T2}(\text{msg}_2))$

Signature ambiguity in MLS draft 12

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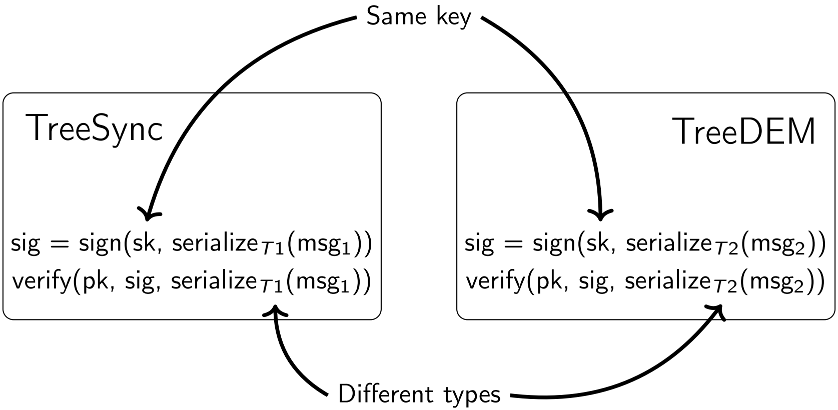

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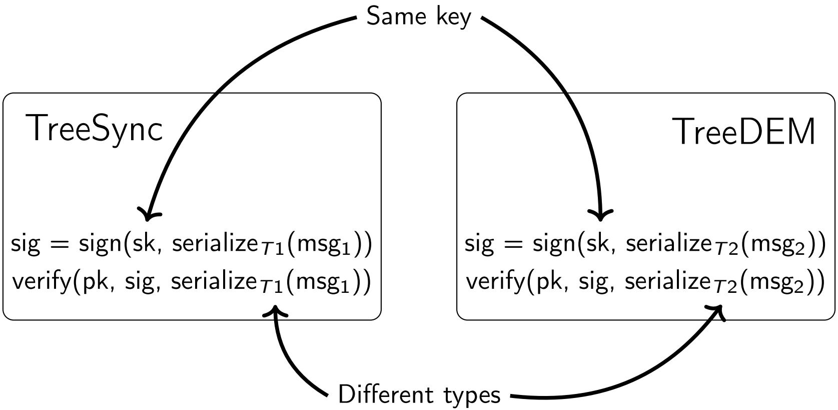

What if $\text{serialize}_{T1}(\text{msg}_1) = \text{serialize}_{T2}(\text{msg}_2)$?
First step for an attack:
TreeDEM signature on msg_2 is a signature forgery on msg_1 in TreeSync!

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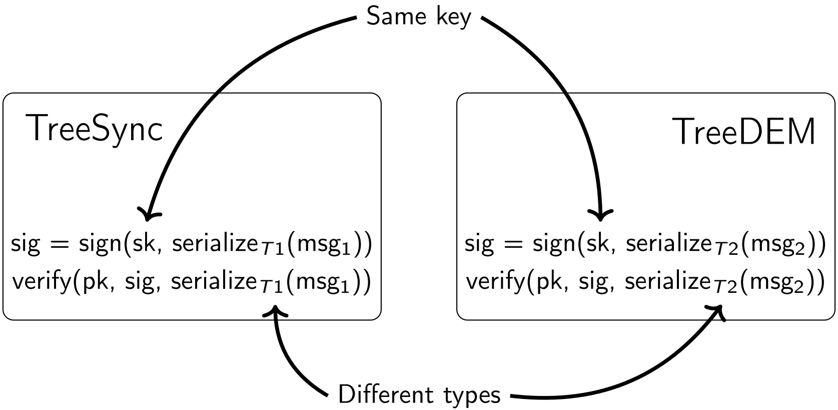

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Two questions

From a protocol designer perspective:

- How did this attack survive 4 years and 12 drafts of the MLS standard, although this is a classic issue known as “lack of domain-separation”?

Our answer:

- there is no rigorous definition for “domain-separation”
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From a protocol analyst perspective:

- Why was this attack not caught by previous pen & paper security proofs?

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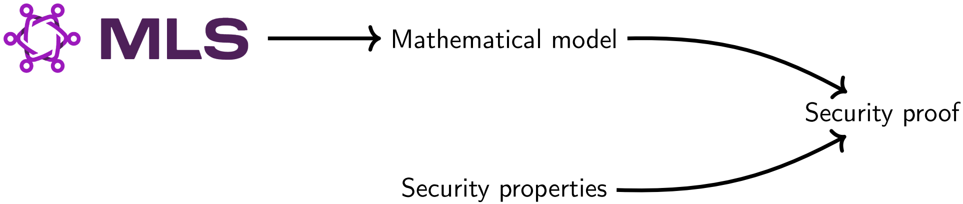

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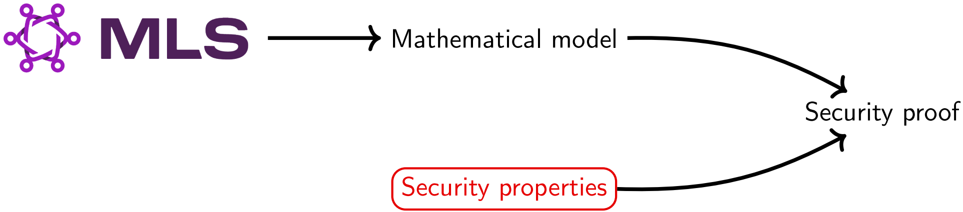

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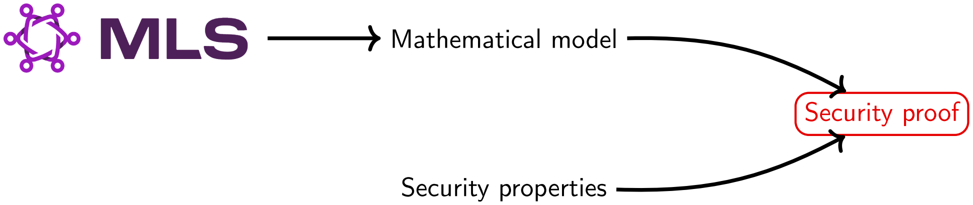

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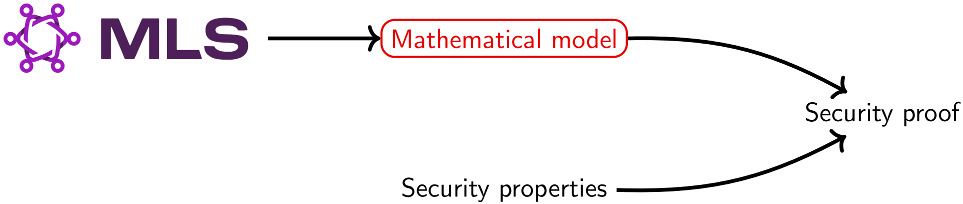

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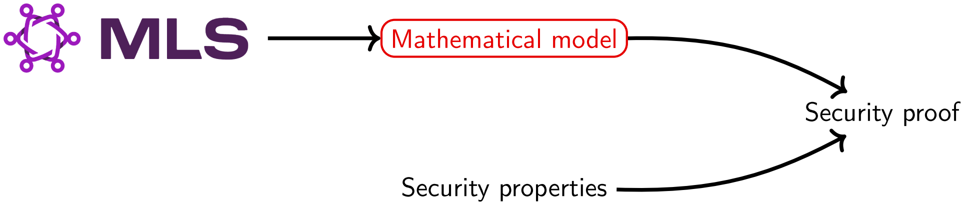

In mathematical models of MLS: no precise message format

$\mathsf{leafNodeTBS} \leftarrow (\mathtt{id}, \mathsf{pk}, \mathsf{spk}, \mathsf{parentHash}, \mathsf{ln\_source}, \mathsf{source})$
$\mathsf{sig} \leftarrow \mathsf{Sig.Sign}(\mathsf{ssk}, \mathsf{leafNodeTBS})$
...
$\mathtt{groupInfoTBS} \leftarrow (\mathsf{groupCtxt}, \gamma'.\tau.\mathsf{public}(), \mathtt{confTag}, \gamma'.\mathsf{leafIdx}())$
$\mathsf{sig} \leftarrow \mathsf{Sig.Sign}(\gamma'.\mathsf{ssk}, \mathtt{groupInfoTBS})$

"ETK: External-Operations TreeKEM and the Security of MLS in RFC 9420", C. Cremers, E. Günsay, V. Wesselkamp, M. Zhao

Lesson for protocol analysts: reason on precise mathematical models

- catch subtle attacks
- bonus: also provide a reference implementation

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Problem: reasoning on message formats makes proof more complex

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Problem: reasoning on message formats makes proof more complex

Our solution:

- define a rigorous notion of “secure formats”
- secure formats can soundly be abstracted away
- make a tool to check if a format is secure (Comparse)

Security critical message formats

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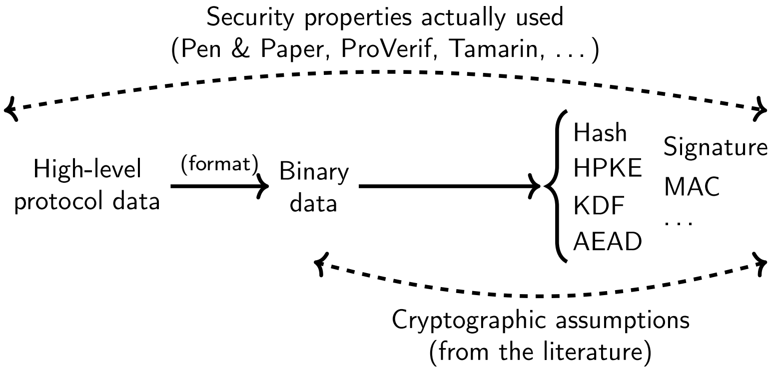
("Comparse: . . .", ACM CCS 2023, `https://ia.cr/2023/1390`)



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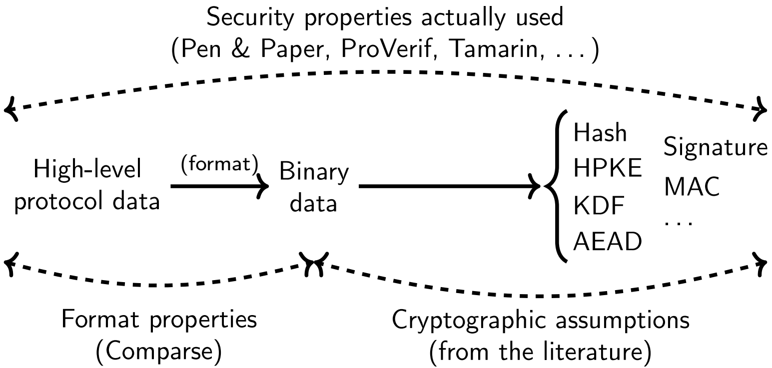

A rigorous approach toward domain separation

("Comparse: . . . ", ACM CCS 2023, `https://ia.cr/2023/1390`)

We build a systematic approach toward secure formats and "good domain-separation".

For example, we define "good domain-separation" for signatures as:

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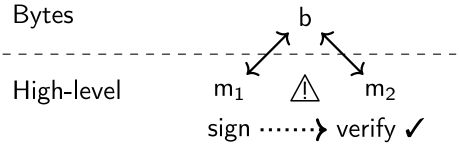

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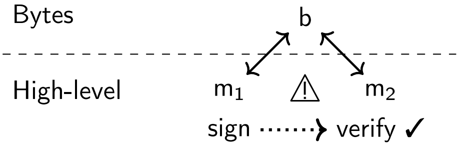

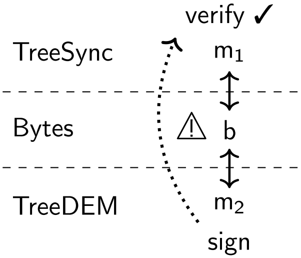

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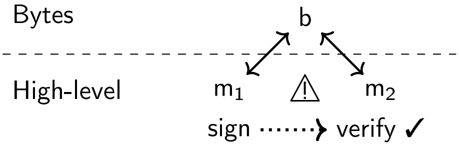
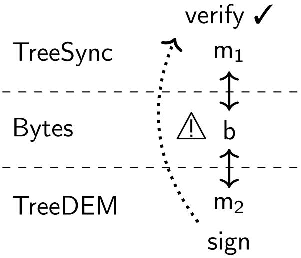
This is a sufficient and necessary condition to abstract formats away in signatures!





Good domain-separation in real-world protocols

Claim: in real-world protocols, data sent on the network have “good domain-separation”.

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```
enum {
    client_hello(1),
    server_hello(2),
    ...
    (255)
} HandshakeType;

struct {
    HandshakeType msg_type;    /* handshake type */
    uint24 length;             /* remaining bytes in message */
    select (Handshake.msg_type) {
        case client_hello:          ClientHello;
        case server_hello:          ServerHello;
        ...
    };
} Handshake;
```

TLS 1.3 Handshake message, properly domain-separated across versions since 1996 (SSLv3)

Ugly message formats in real-world protocols

In the same specification, TLS 1.3 Transcript hash

```
Transcript-Hash(M1, M2, ... Mn) = Hash(M1 || M2 || ... || Mn)
```

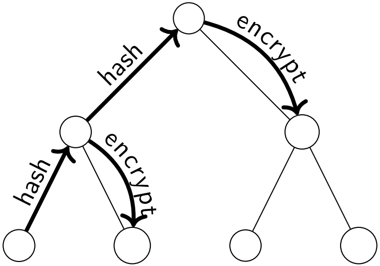
Lesson for protocol designers:
love all message formats equally

- rule out a whole class of attacks
- help protocol analysts willing to model them precisely

Symbolic security of MLS: TreeKEM

Proving security of TreeKEM

(“TreeKEM: ...”, to appear at IEEE S&P 2025, `https://ia.cr/2025/410`)



We prove a confidentiality theorem on TreeKEM.
Challenges:

- requires recursive data types
- inductive proofs
- an unbounded sequence of key derivations
- an unbounded sequence of public-key encryptions (and internally, KEMs)

DY* is a tool of choice for these challenges, still we had to heavily improve it.

Lesson for protocol analysts:
novel protocols may require new tools

// TODO: insert "modern problems require modern solutions" meme

- can't have "one tool to rule them all"
- similar to various pen & paper proof frameworks (game-hop, UC, SSP, ...)

Conclusion

- we produced machine-checked security proofs for parts of MLS (TreeSync & TreeKEM)
- developed a methodology to reason on a precise model of cryptographic standards
- shed light on the importance of message formatting in cryptographic protocols
- and propose a rigorous approach to domain-separation
- we improved the tools to perform machine-checked symbolic security proofs

</> https://github.com/Inria-Prosecco/mls-star

https://ia.cr/2022/1732 (TreeSync)
https://ia.cr/2023/1390 (Comparse)
https://ia.cr/2025/410 (TreeKEM)

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References

Théophile Wallez, Jonathan Protzenko, Benjamin Beurdouche, and Karthikeyan Bhargavan.
TreeSync: Authenticated group management for messaging layer security.
In *32nd USENIX Security Symposium (USENIX Security 23)*, August 2023.

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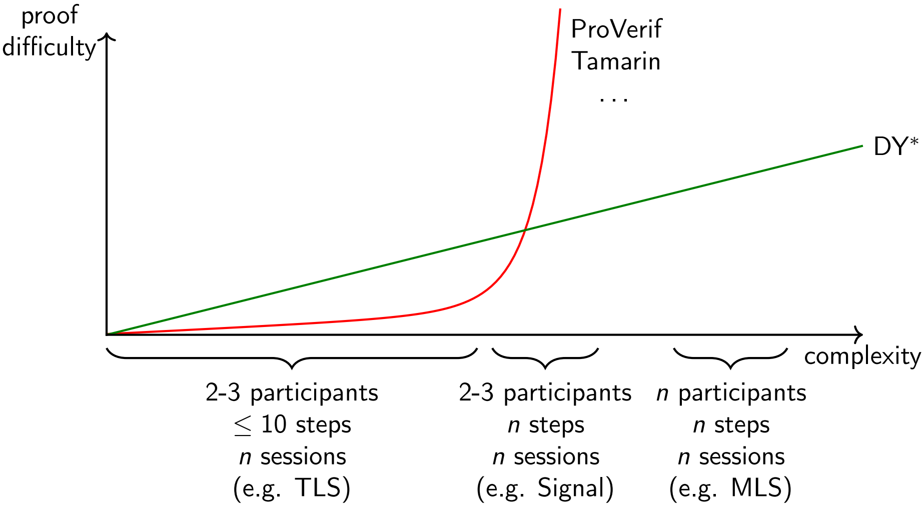
Comparse: Provably secure formats for cryptographic protocols.
In *Proceedings of the 2023 ACM SIGSAC Conference on Computer and Communications Security*, CCS '23, November 2023.

Théophile Wallez, Jonathan Protzenko, and Karthikeyan Bhargavan.
TreeKEM: A modular machine-checked symbolic security analysis of group key agreement in messaging layer security, 2025.
To appear at IEEE S&P 2025. https://eprint.iacr.org/2025/410.

Backup slides

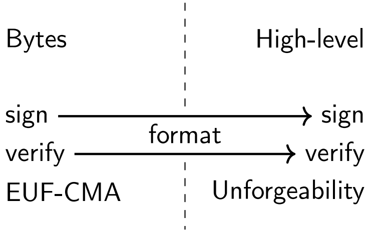
Symbolic protocol provers



A rigorous approach to domain separation

Bytes	High-level
sign	
verify	
EUF-CMA	

A rigorous approach to domain separation



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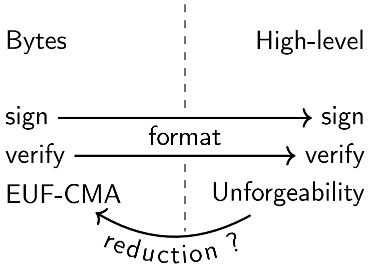

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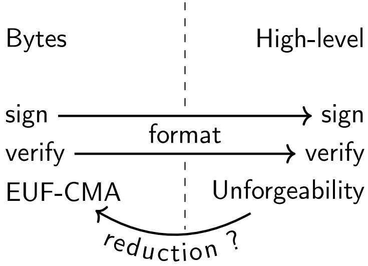

Reduction if: this format is self-contained and non-ambiguous.

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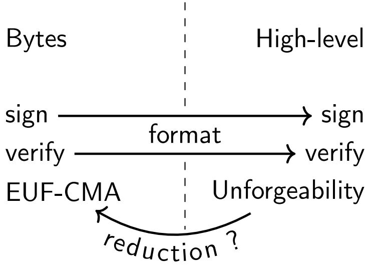

Design discipline: Each signature key is used with a single format, and

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