State Machine Issues in Network Stacks and Application to SSH

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Plan

Plan

Context: Specification and Implementations

- Network protocols are defined in specs such as RFCs
- They are written in English (and not in a formal language)
  - ambiguities
  - incomplete specifications

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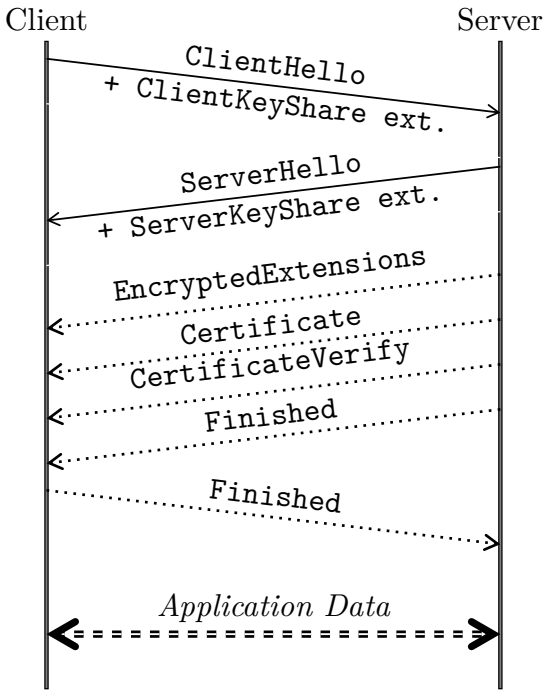
In this presentation, we focus on state machine issues

- e.g. CVE-2020-24613
- (server authentication bypass in TLS)

CVE-2020-24613: The Flaw



In a normal TLS 1.3 message flaw

- the server presents its (`Certificate`)
- it proves its identity (`CertificateVerify`)
- this message contains a signature (requiring the private key)

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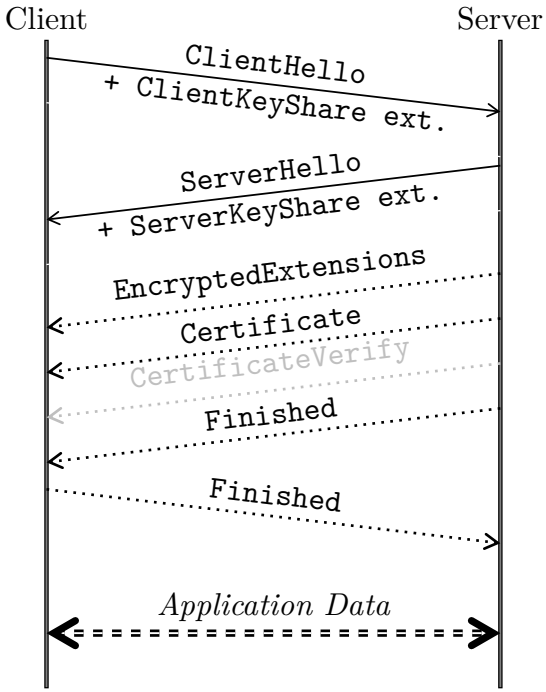

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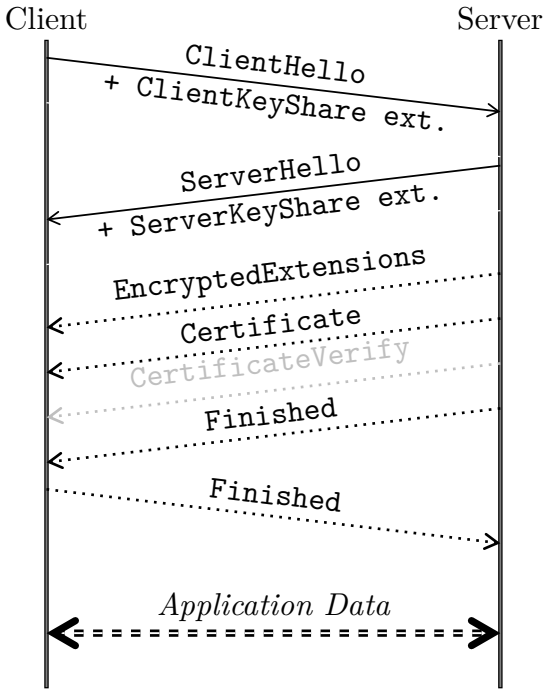

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- the server presents its (`Certificate`)
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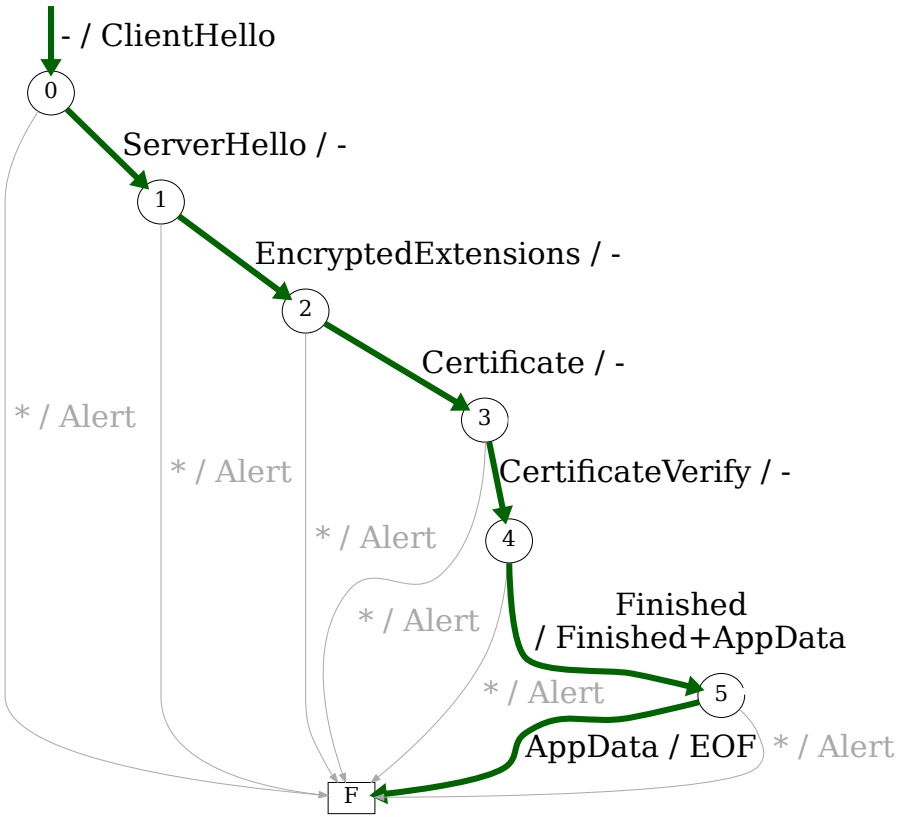
- this message contains a signature (requiring the private key)

What happens if a client accepts a connection missing the `CertificateVerify`?

- the private key is not necessary anymore for a successful handshake
- an attacker can impersonate *any server* to such a client

CVE-2020-24613: A Better Representation



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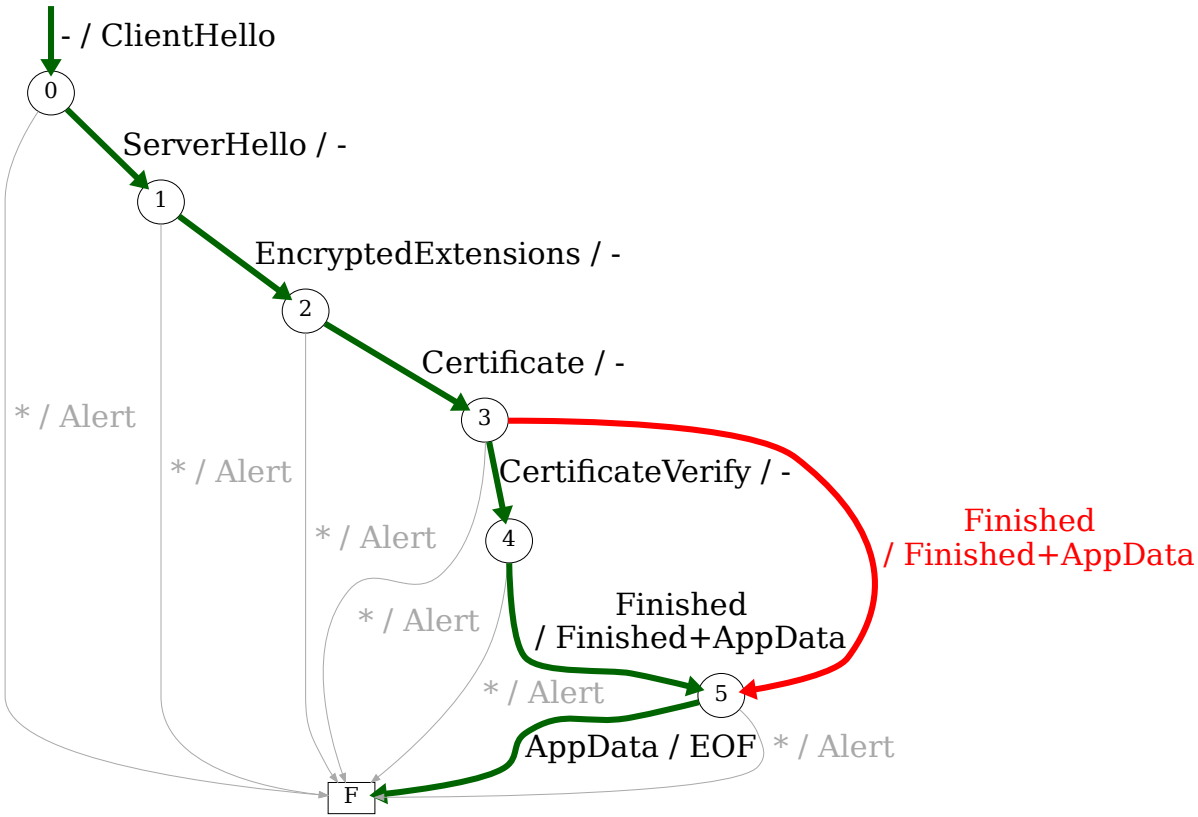
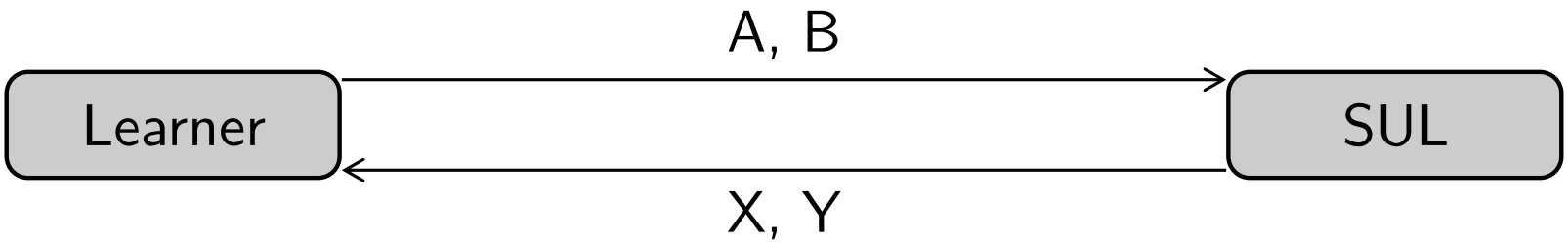


Plan

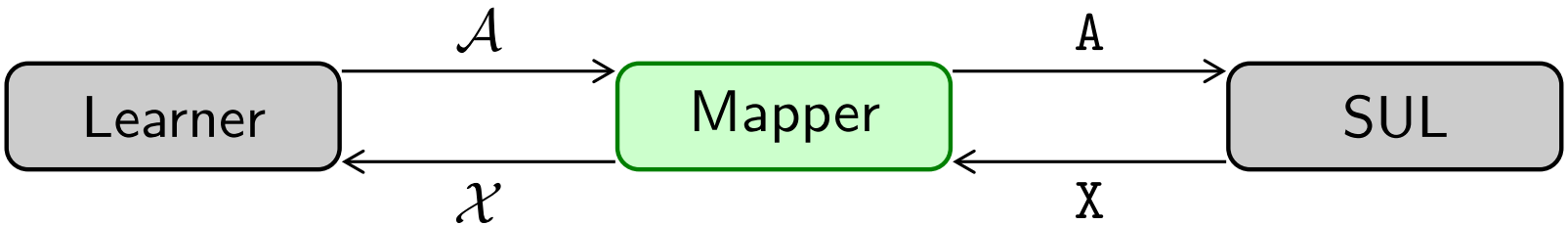
Methodology: Pipeline



SUL = System Under Learning (the stack being analyzed)

Process

Methodology: Pipeline



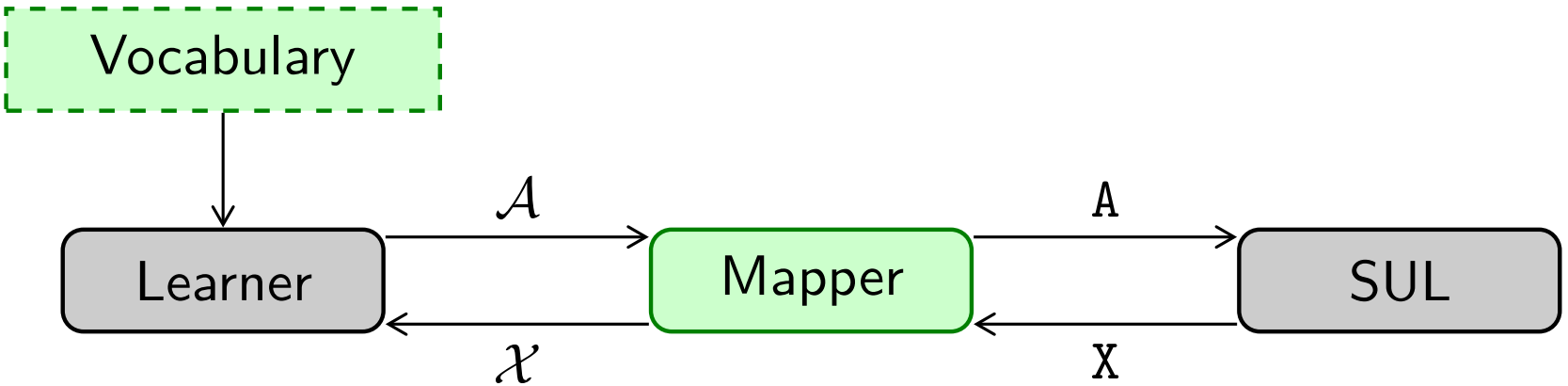
Real interactions require an intermediate component

- sending messages one at a time
- using concrete messages (bytes on the wire)

Process

Contribution

Methodology: Pipeline



Process

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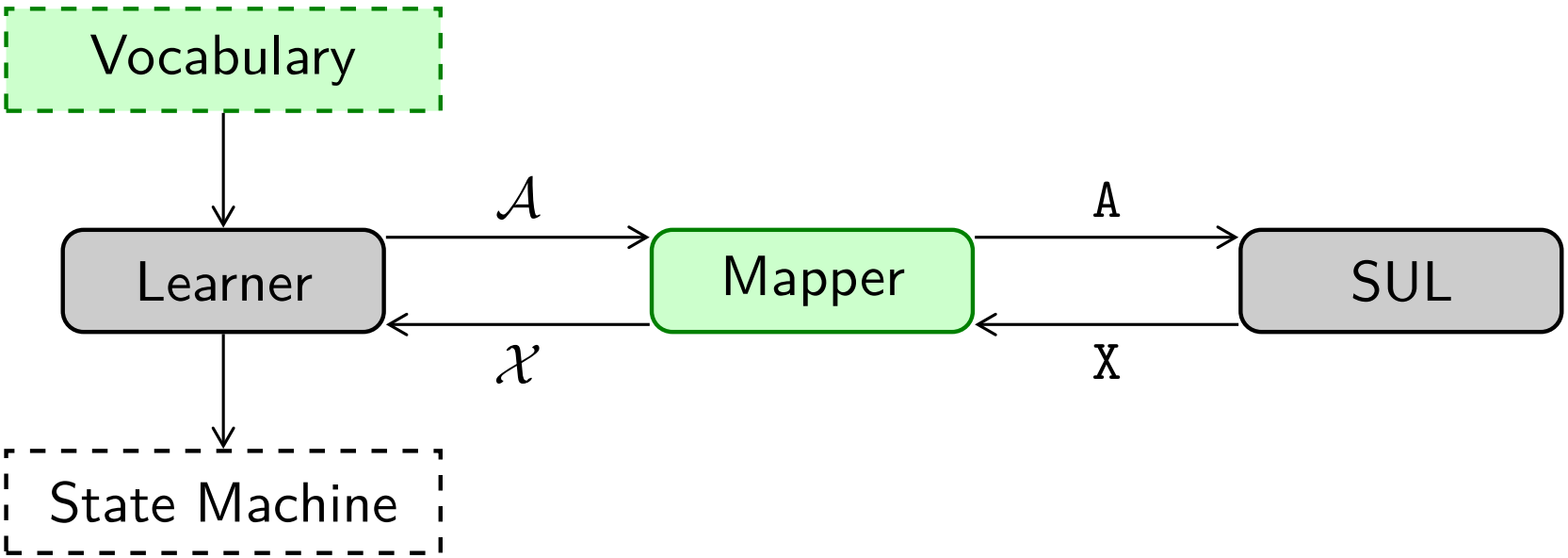
Data

Methodology: Pipeline



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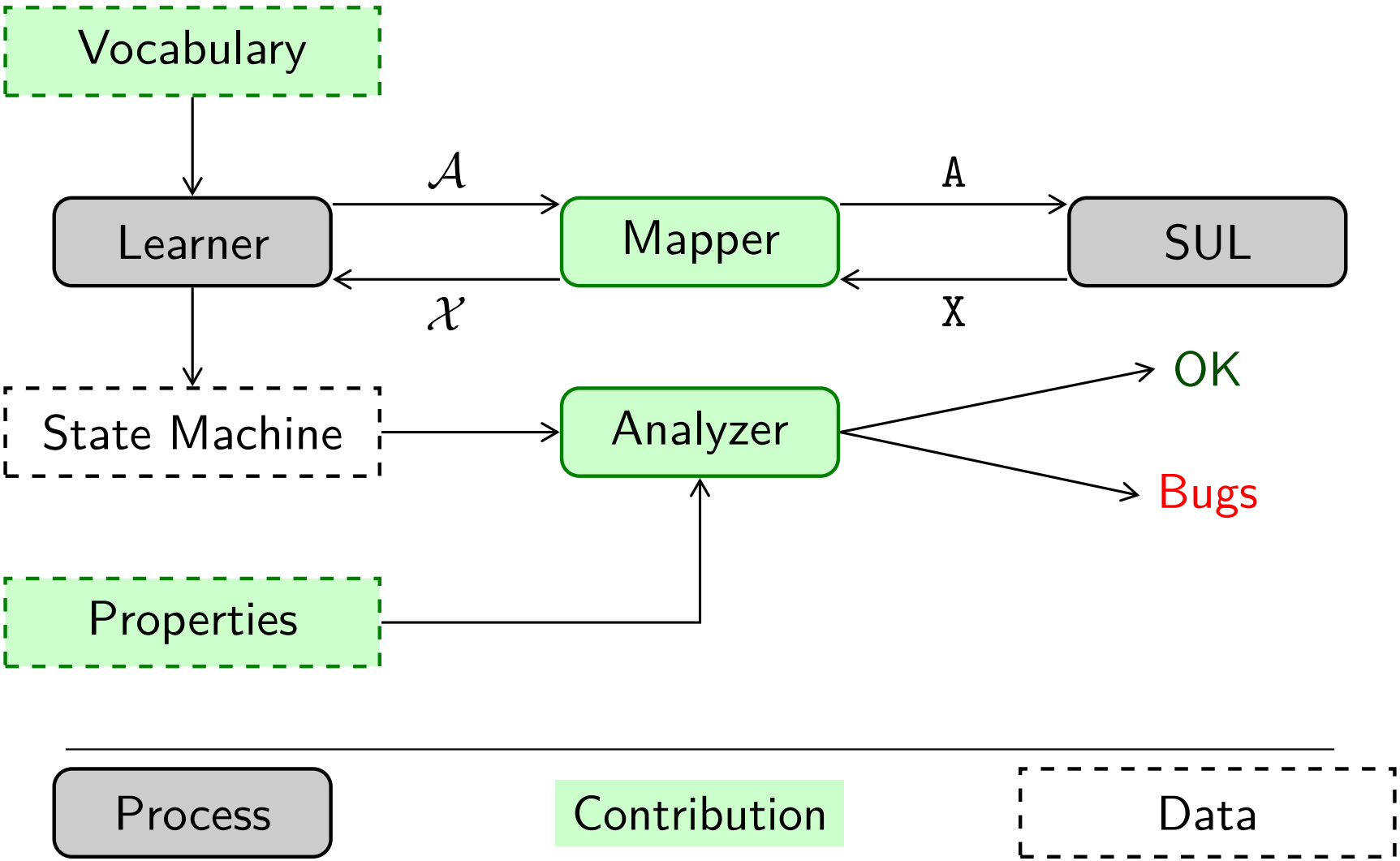
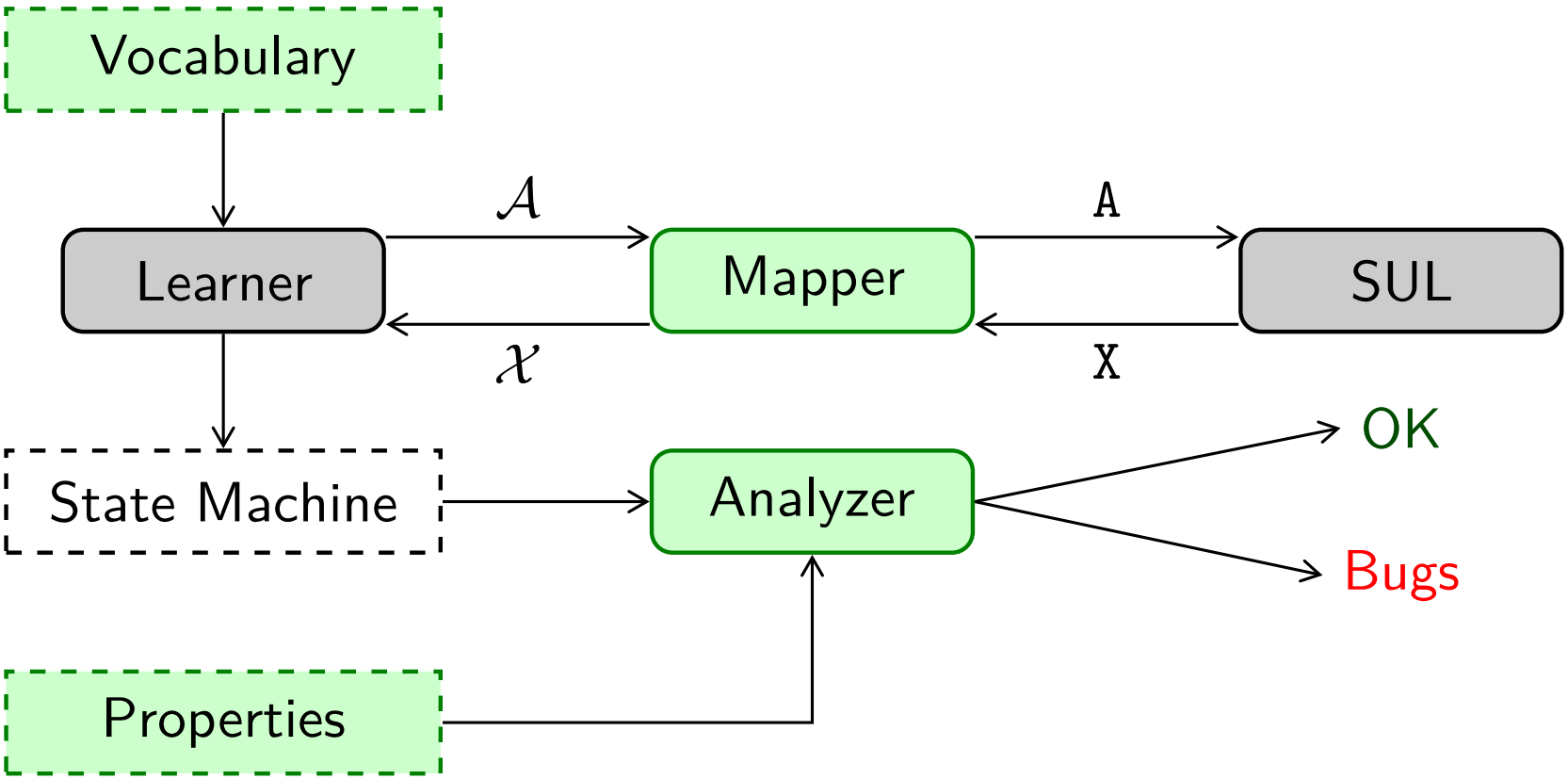


Methodology: Pain Points



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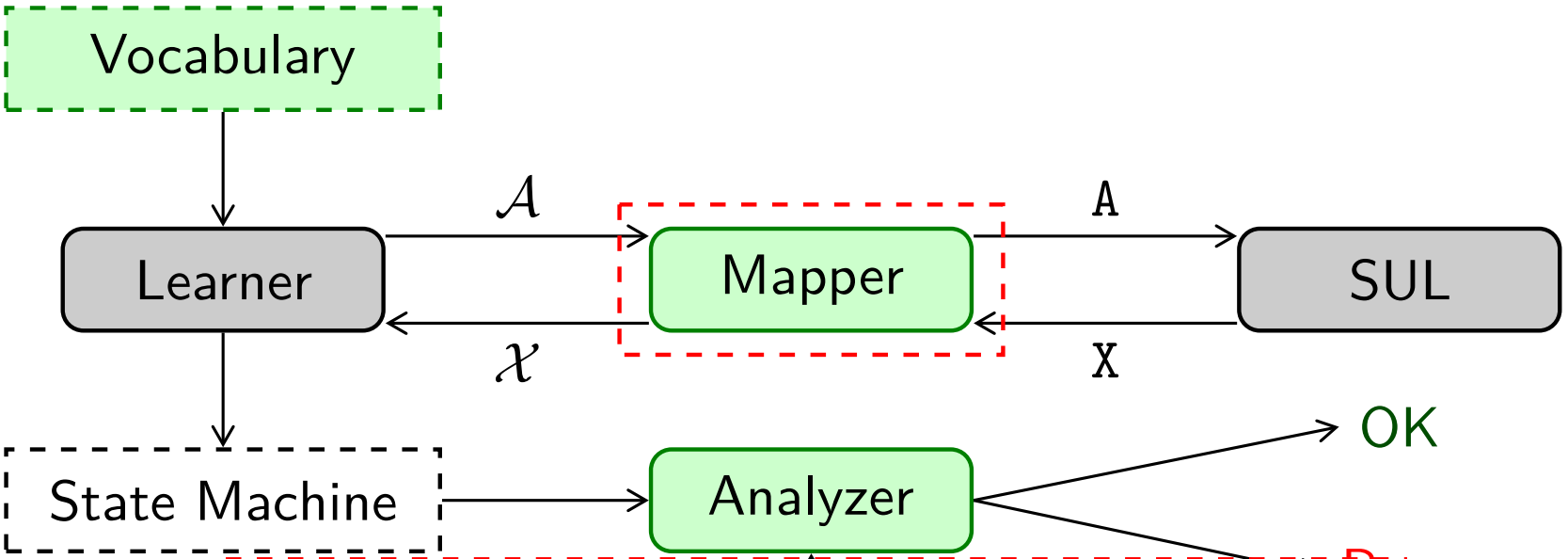
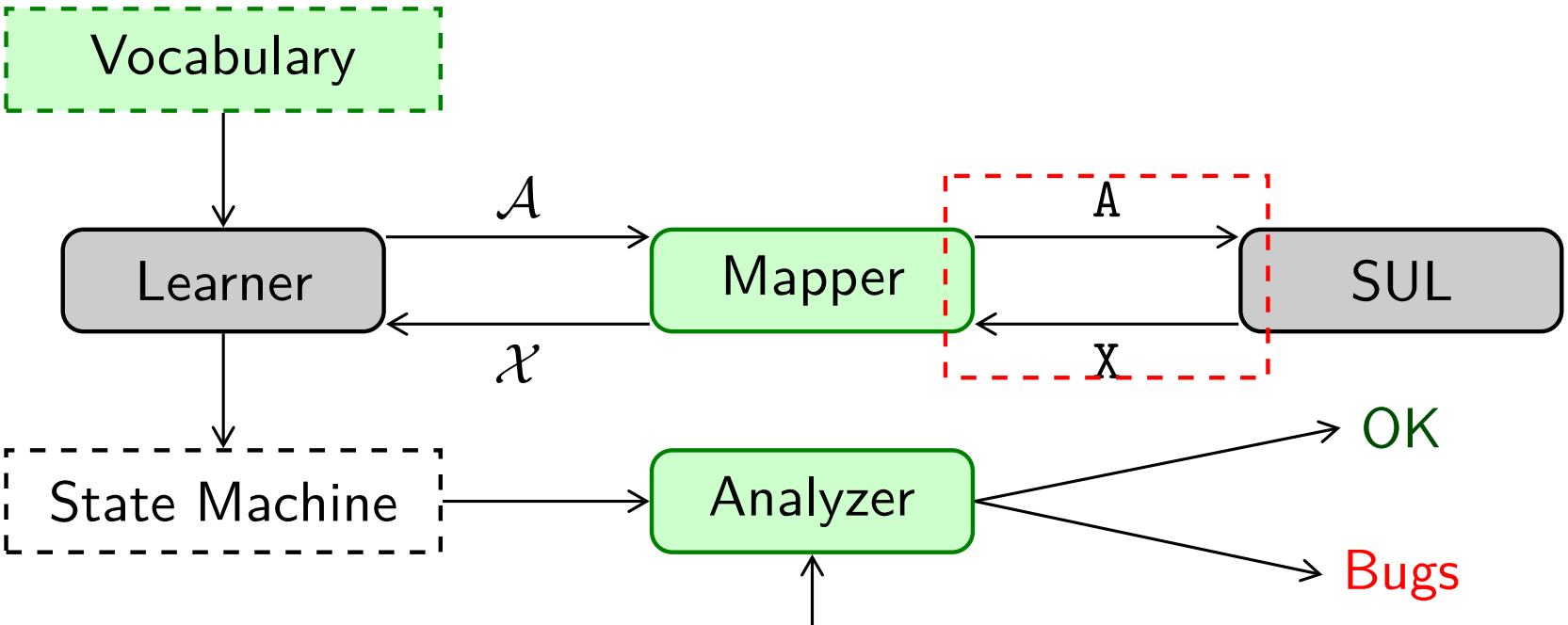


Writing a new mapper for each protocol

- we (almost) need a protocol implementation...
- which is flexible and robust
- where every choice is ideally clear and explicit

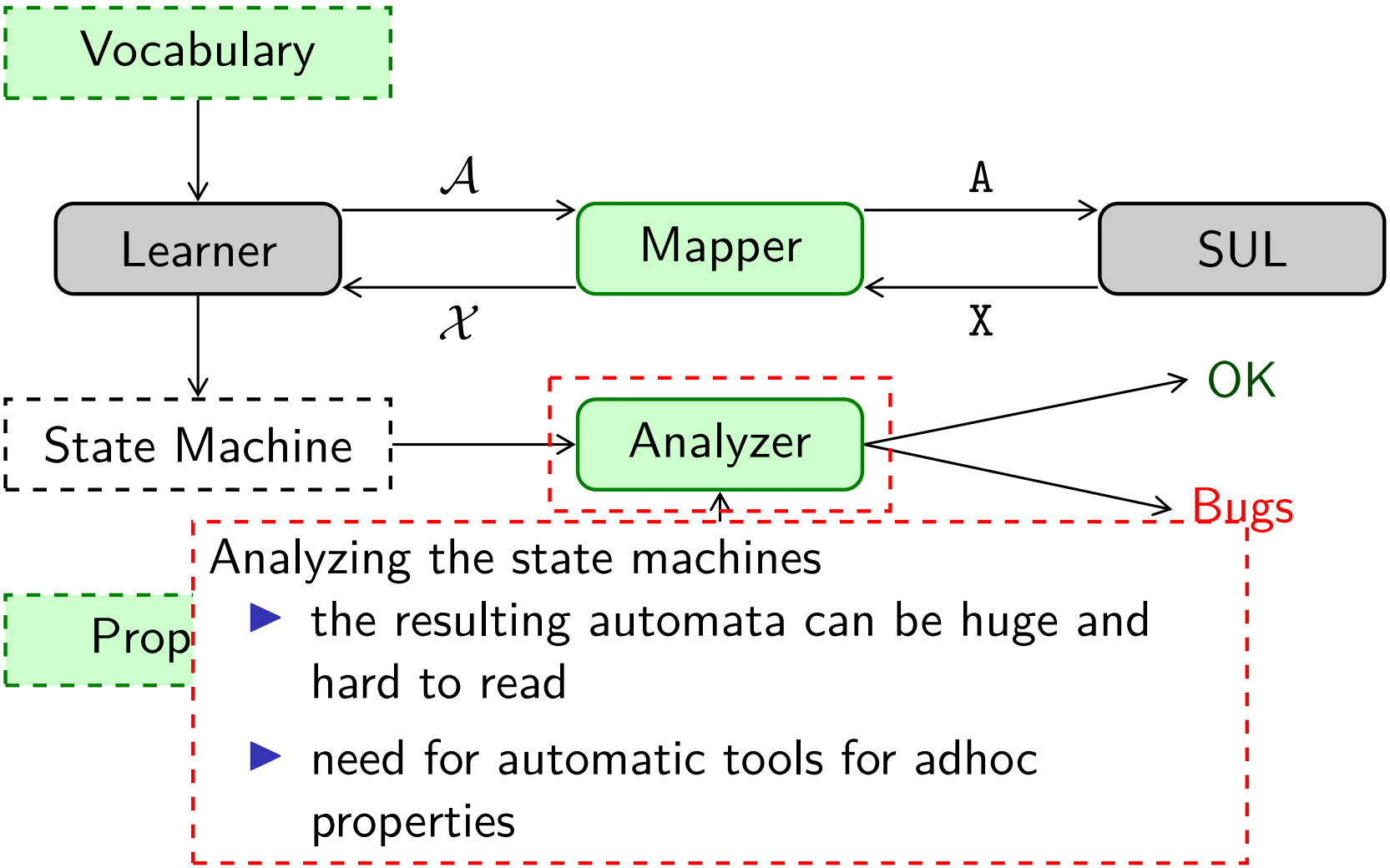
Methodology: Pain Points



Handling timeouts

- we do not know when SUL is done talking
- low values lead to missed messages
- high values lead to inefficiency

Methodology: Pain Points



Plan

Projects and Team

Various projects have been funding this line of work at Télécom SudParis

- GASP, an ANR project
- CERES, funded by the CIEDS
- GINS, a one-year IMT Carnot Télécom project

Team

- Aina Rasoamanana on TLS and SSH, PhD (GASP, defense in 2023)
- Arthur Tran Van, PhD on OPC-UA, adaptive learning and automatic verification (CERES, defense in November 2025)
- Yohan Pipereau, PostDoc on Greybox Inference (GINS)
- Interns: Eva Gagliardi (2019), Sébastien Naud (2020), Martin Horth (2022), Quentin Rabouin (2023), Mohamed Mziou (2025)

Studied Protocols

TLS

- the **S** of HTTP**S**
- one of the fundamental block of internet security

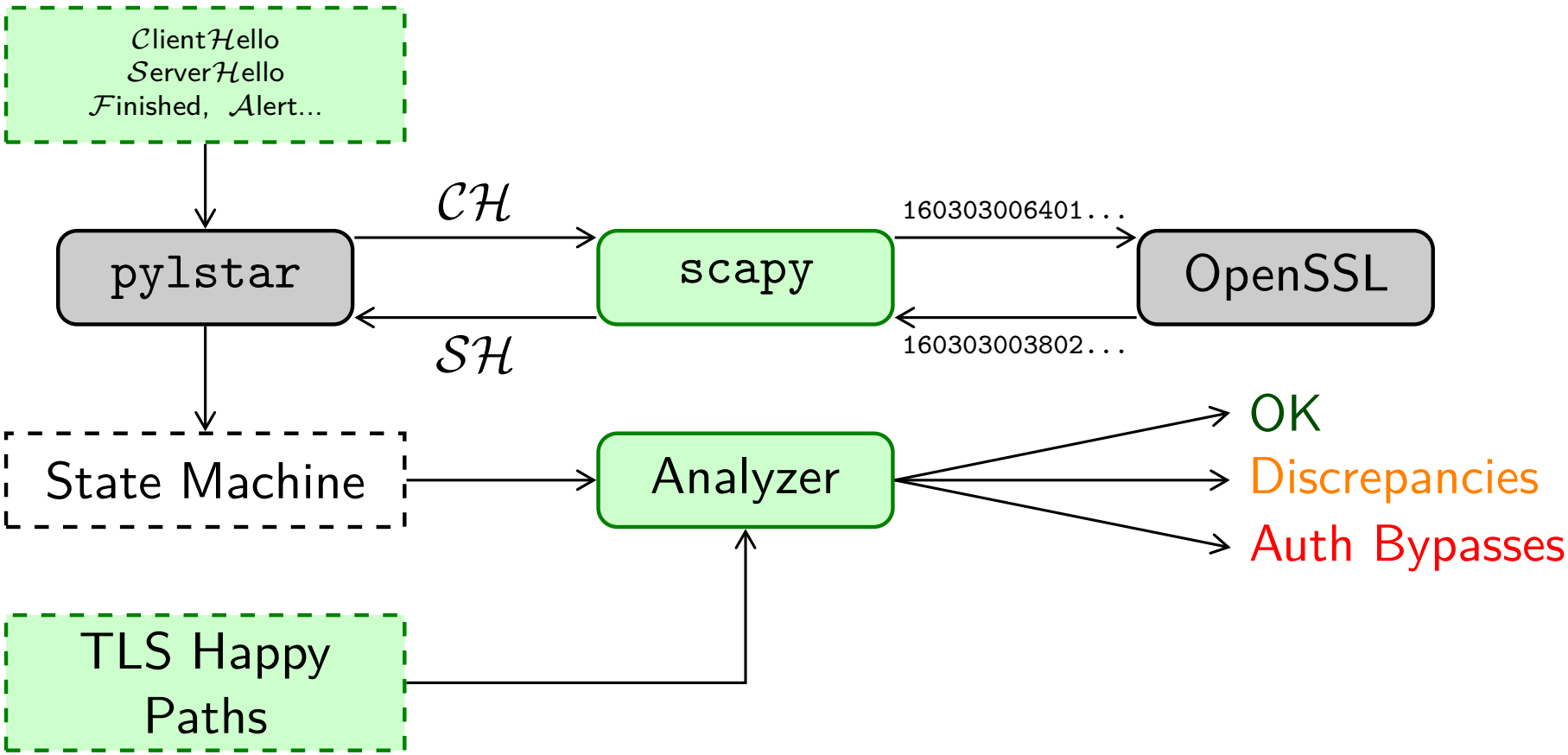
OPC-UA

- a protocol used in industrial systems
- it includes security features (encryption, authentication)

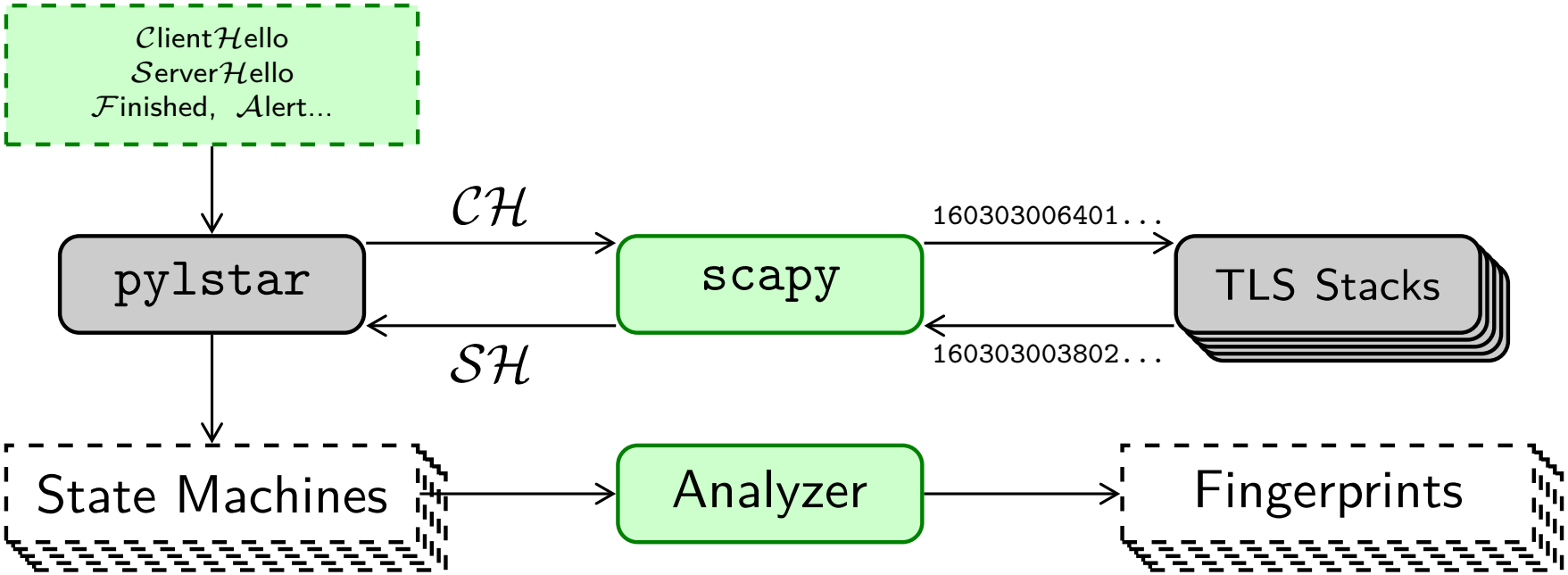
SSH

- remote secure shell and file copy
- designed to replace older cleartext protocols

Application to TLS: Authentication Bypasses [ESORICS22]



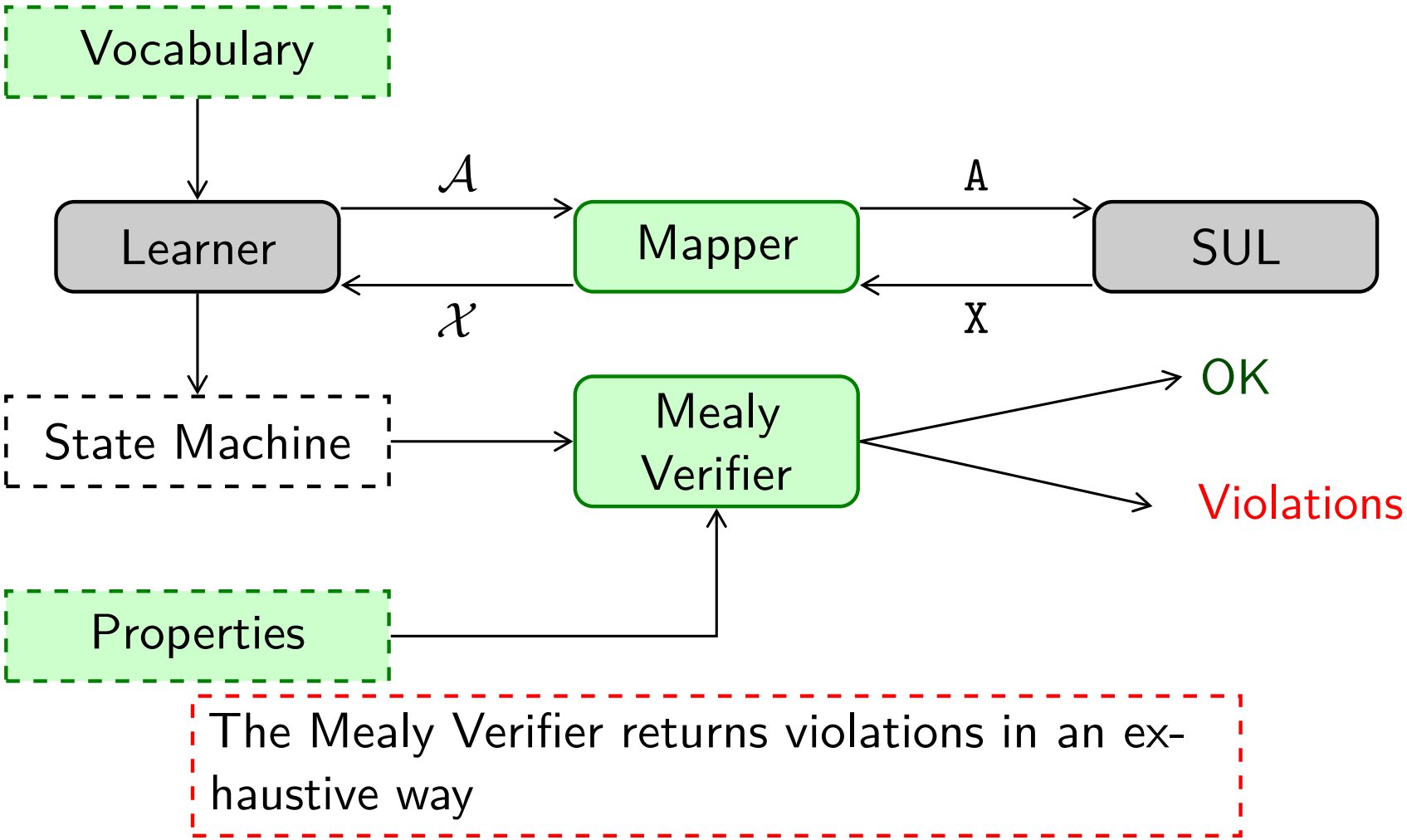
Application to TLS: Fingerprinting [ESORICS22]



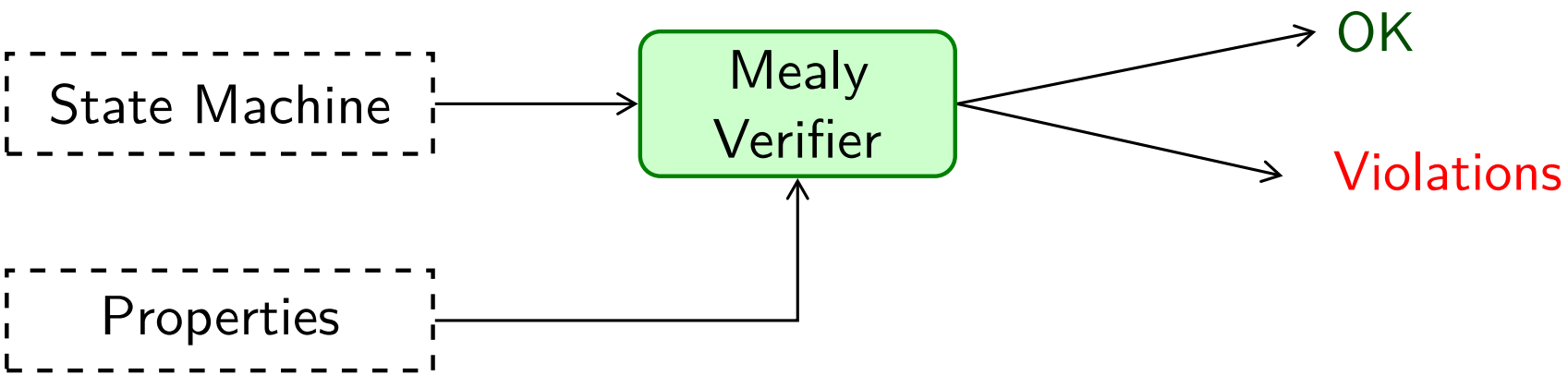
TLS stacks actually vary in their behavior

- the distinguishing sequences lead to fingerprints
- possibly more robust than other techniques

Application to OPC-UA: The Mealy Verifer [ARES24]



Application to SSH: The Mealy Verifer [ARES24]



Reproduction of existing results

- reuse of the inferred state machines
- transposition of the properties
- more precise results (thanks to the exhaustiveness)

Plan

SSH in a Nutshell (1/2)

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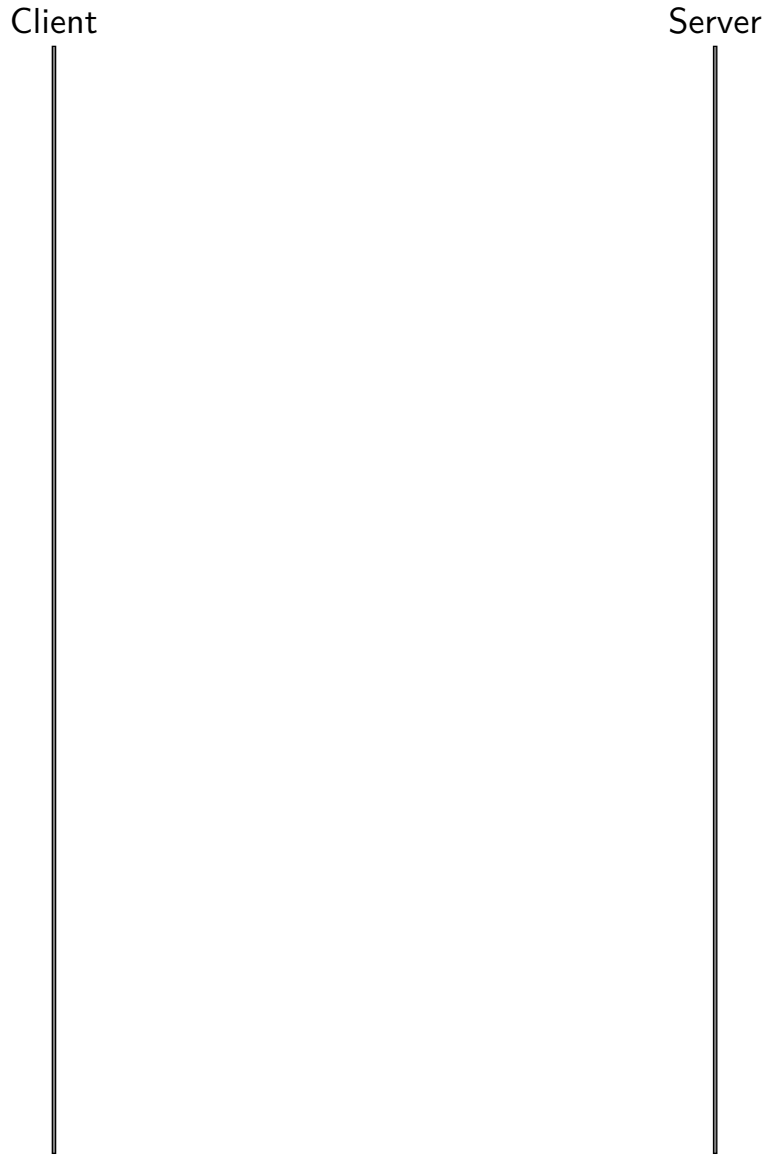
- SSH means SSH-2 in this presentation

SSH in a Nutshell (1/2)

- SSH means SSH-2 in this presentation
- SSH is a 3-layer protocol
  - Transport: key exchange, server authentication and channel protection
  - User Authentication
  - Connection: multiplexing application data channels

SSH in a Nutshell (2/2)



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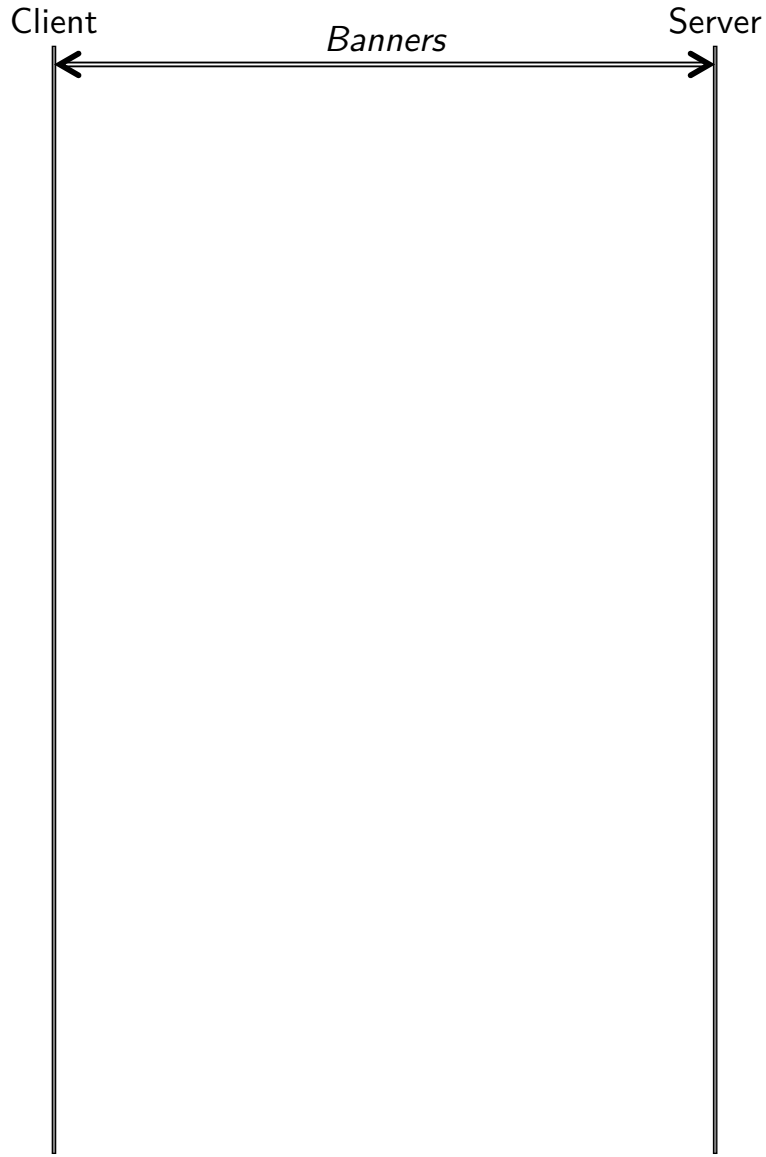

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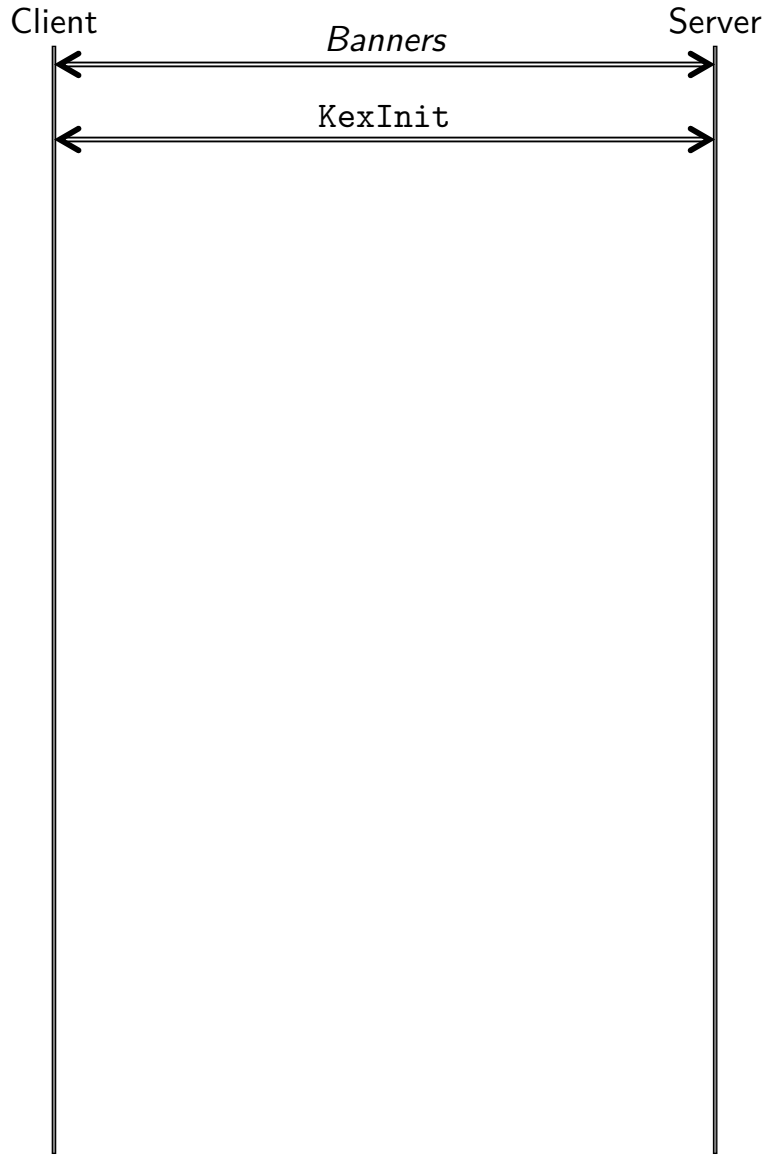

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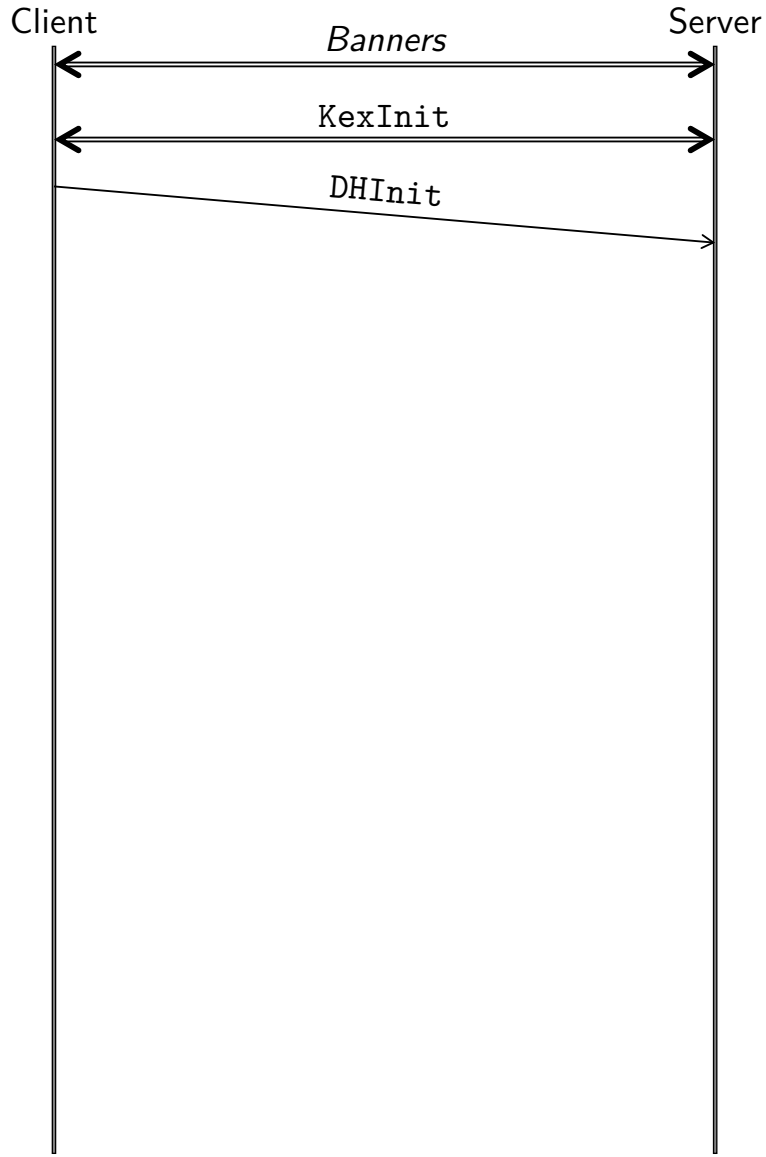

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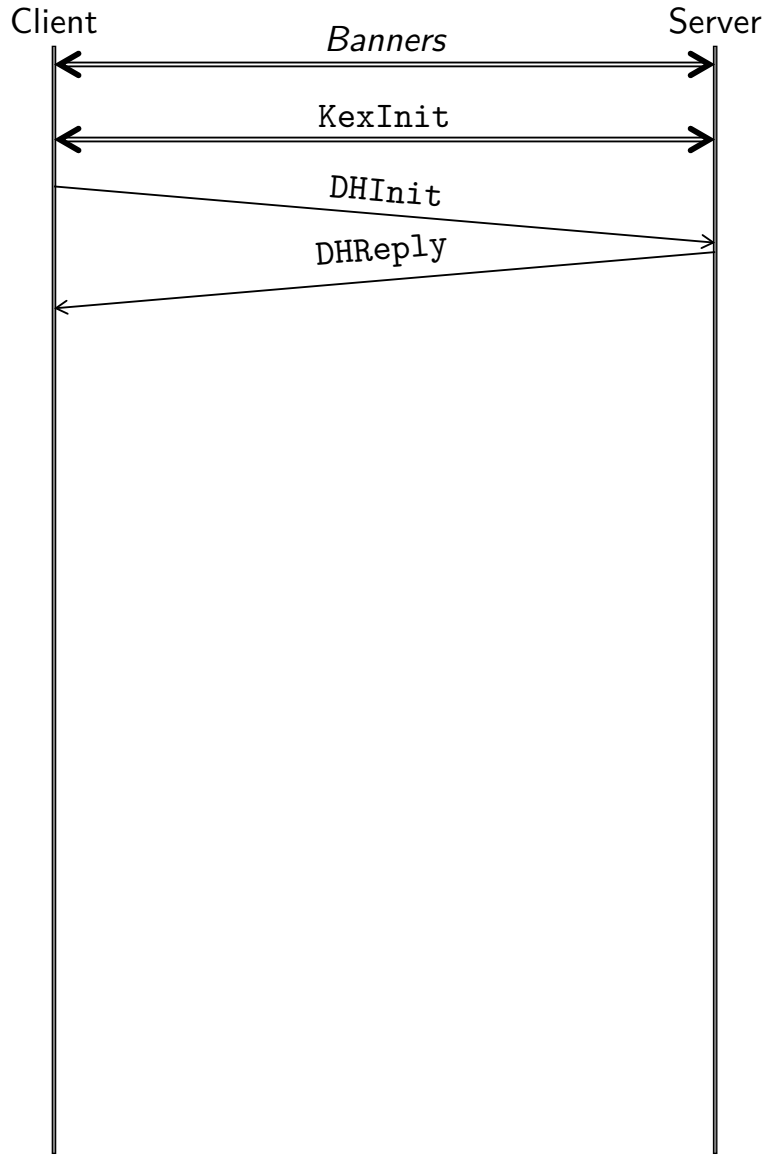

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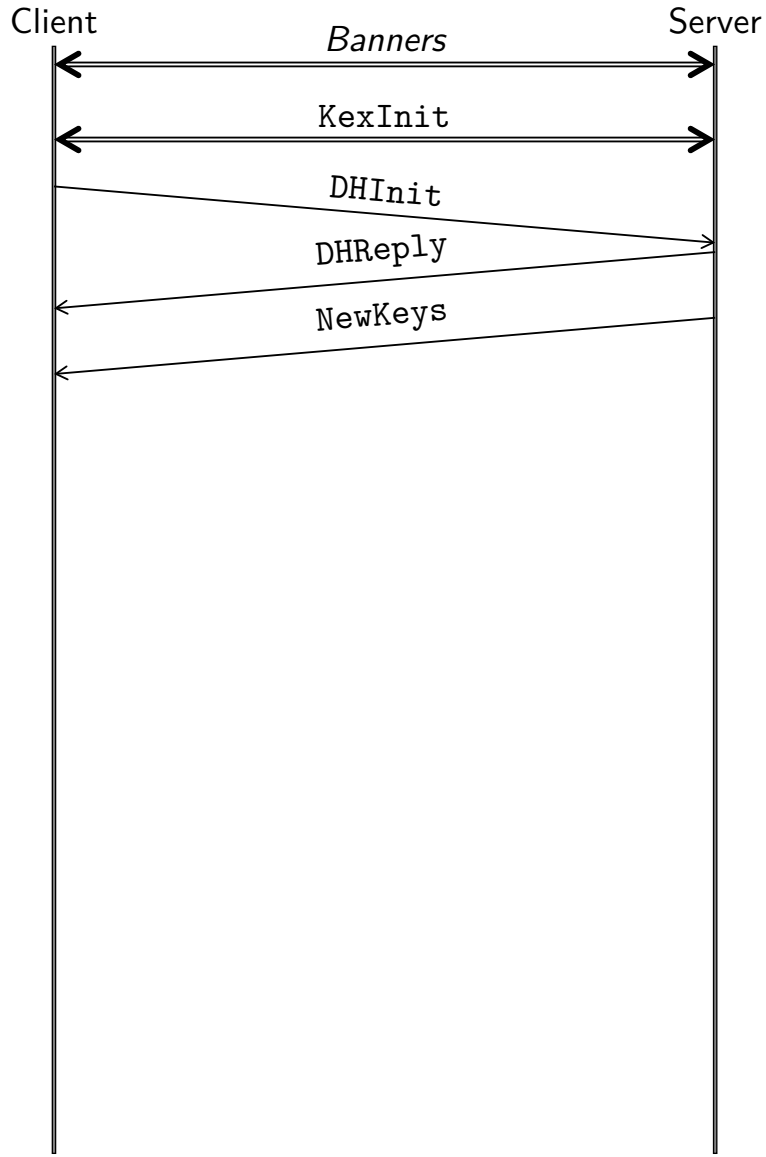

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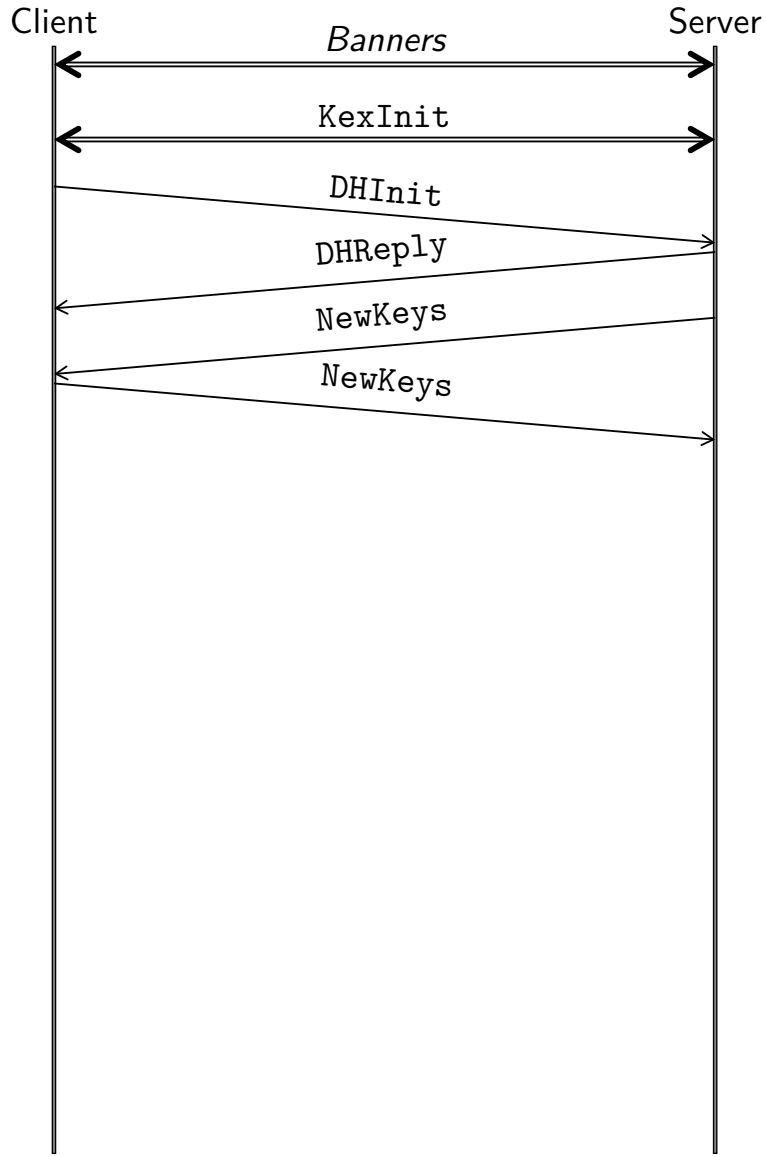

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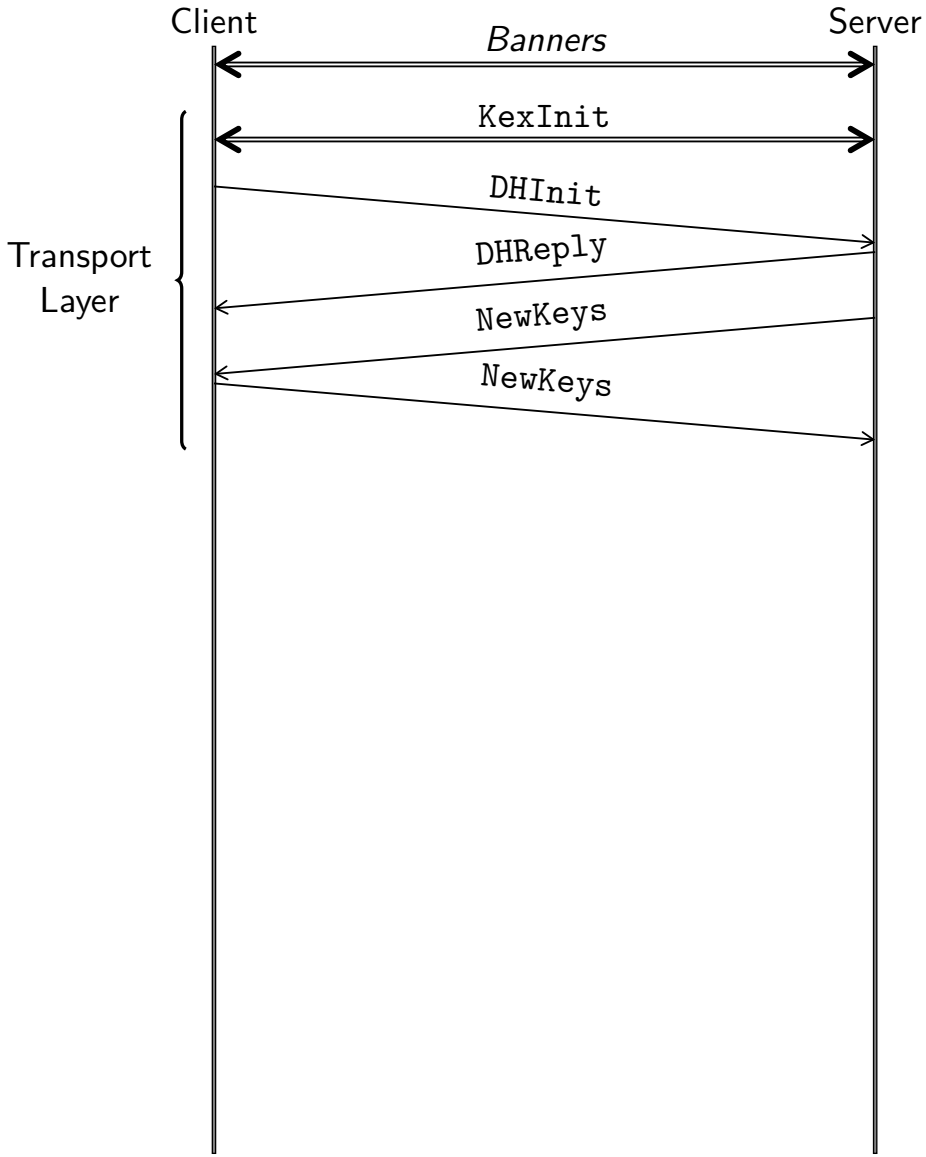

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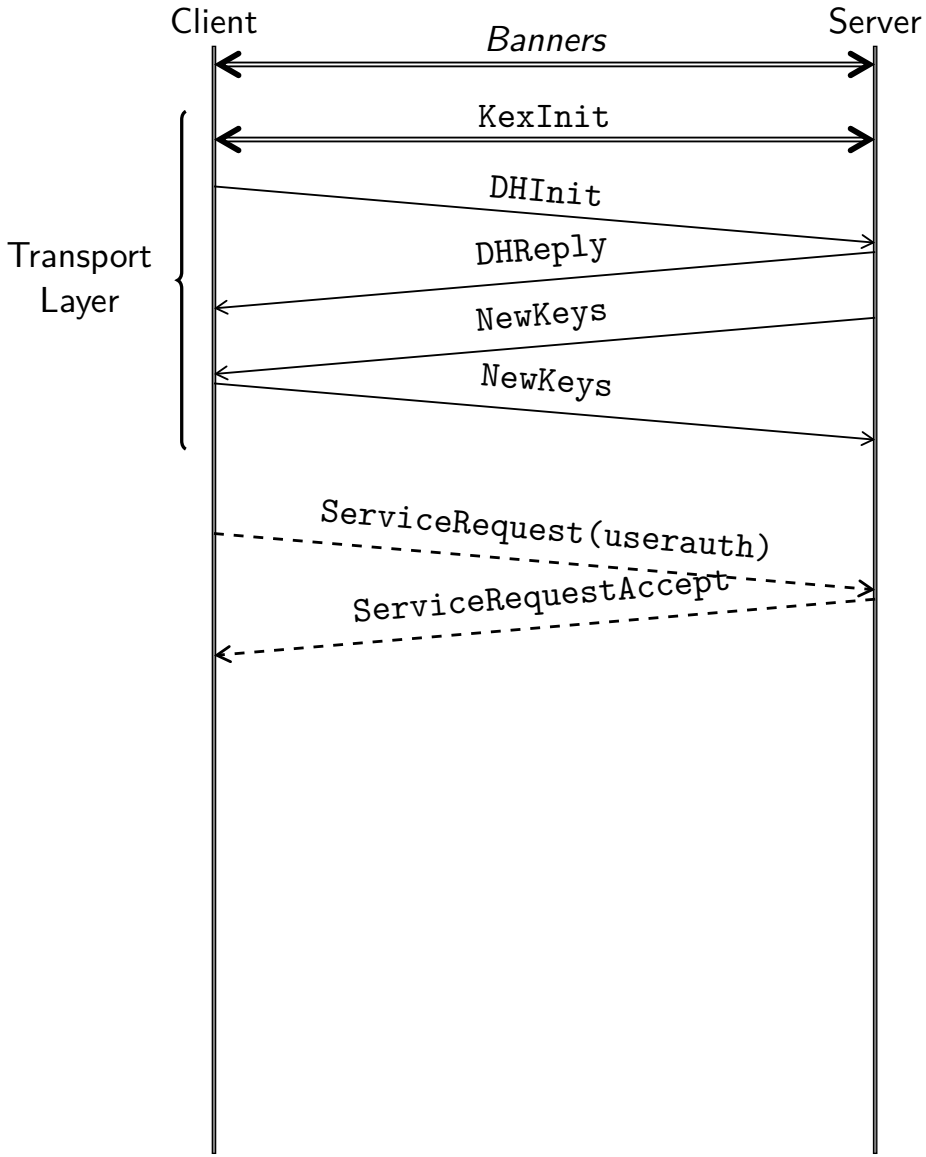

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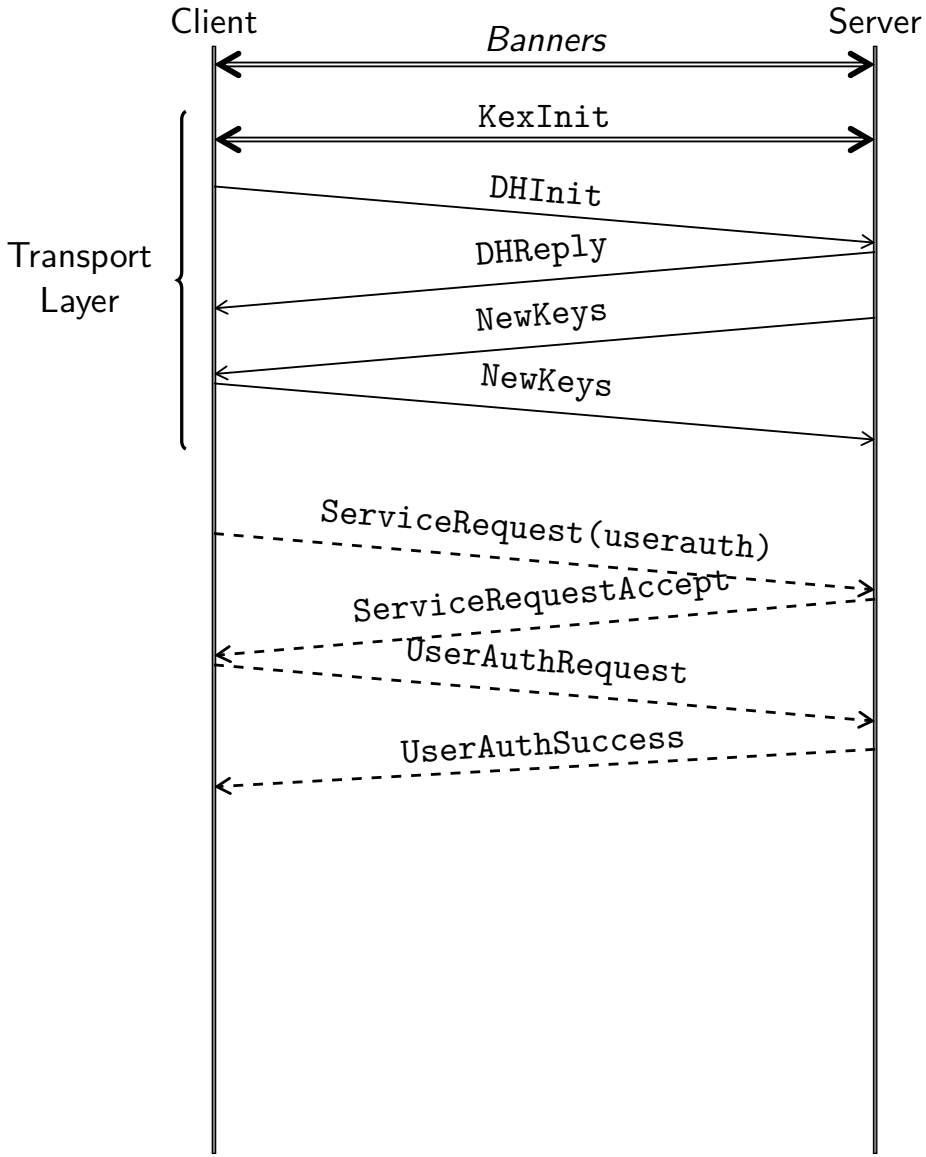

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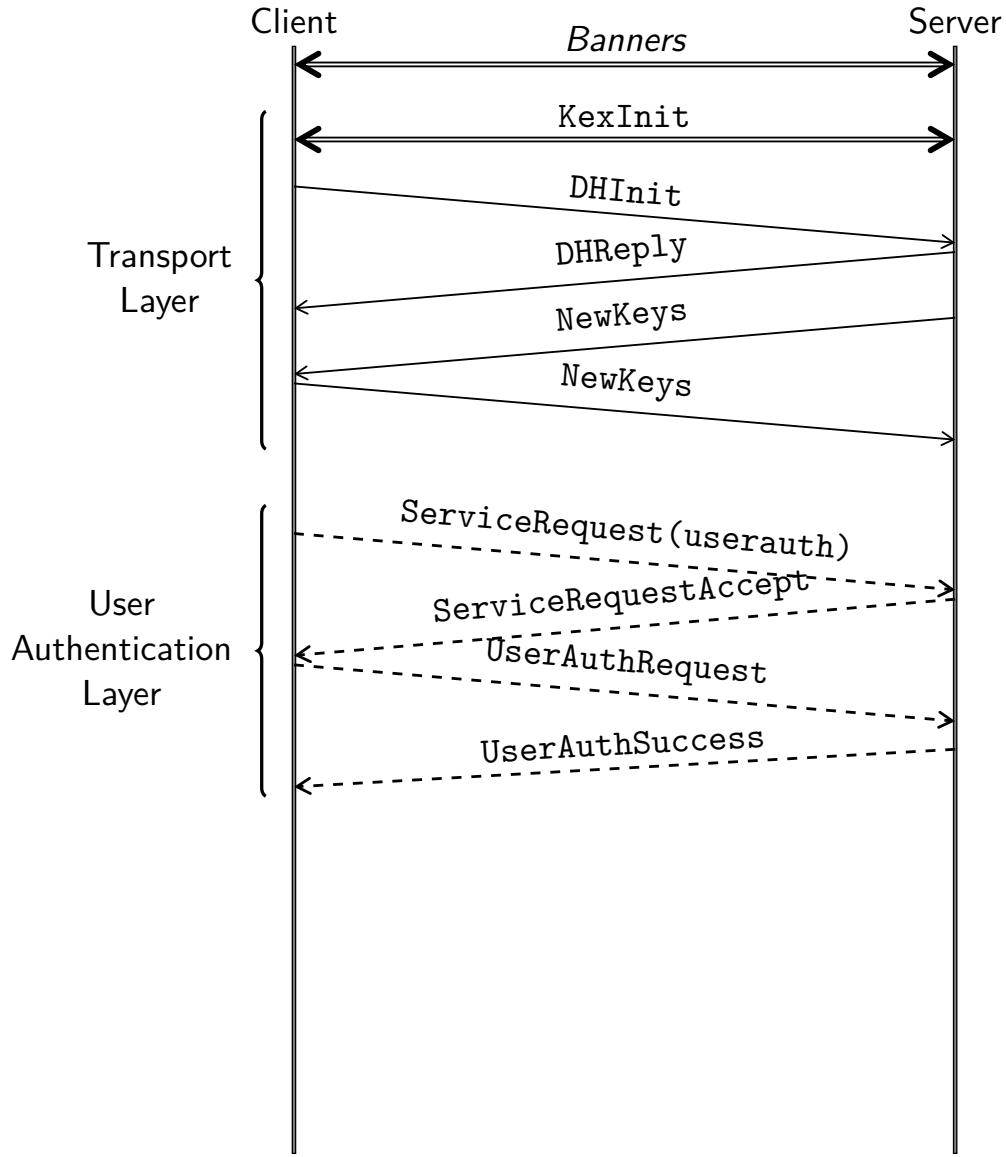

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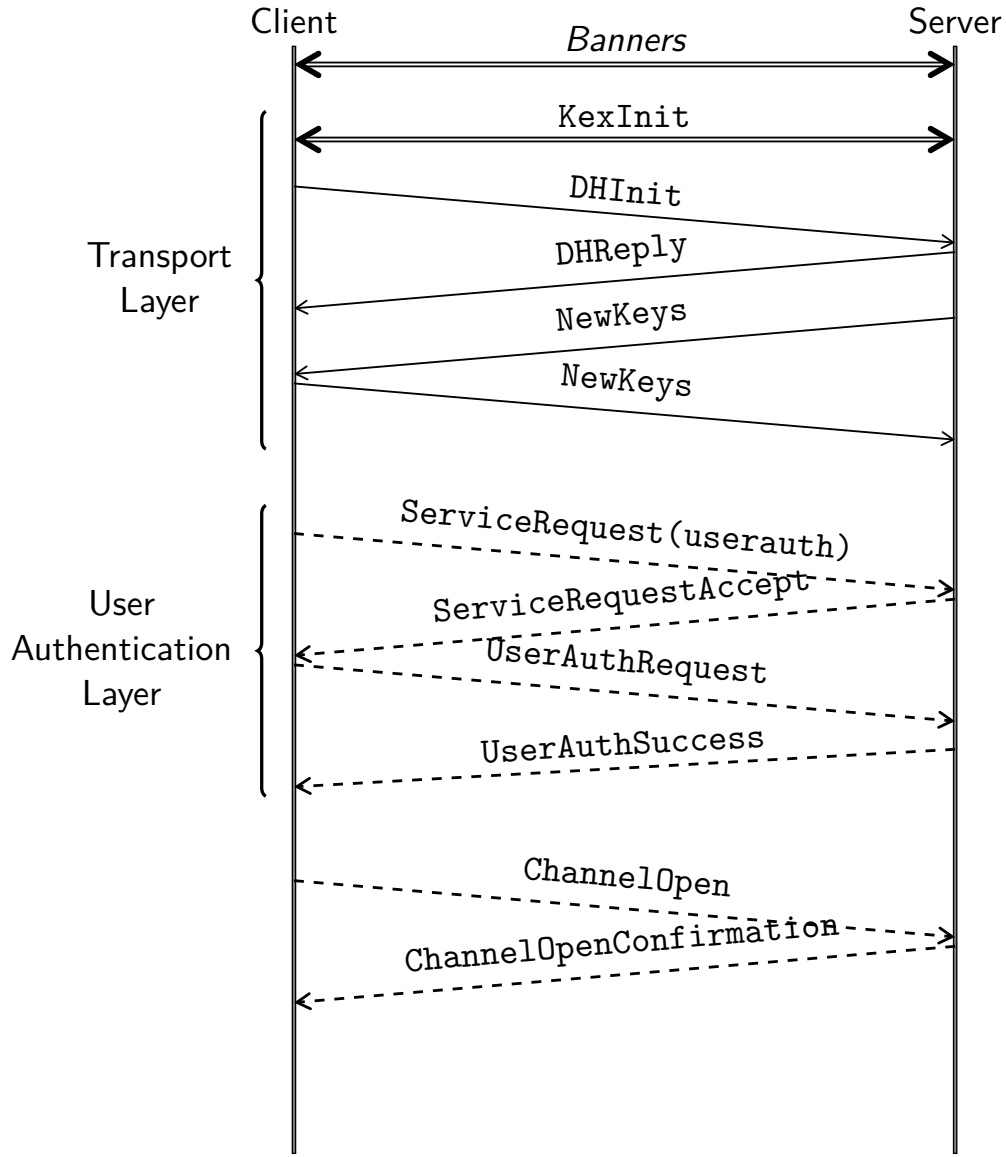

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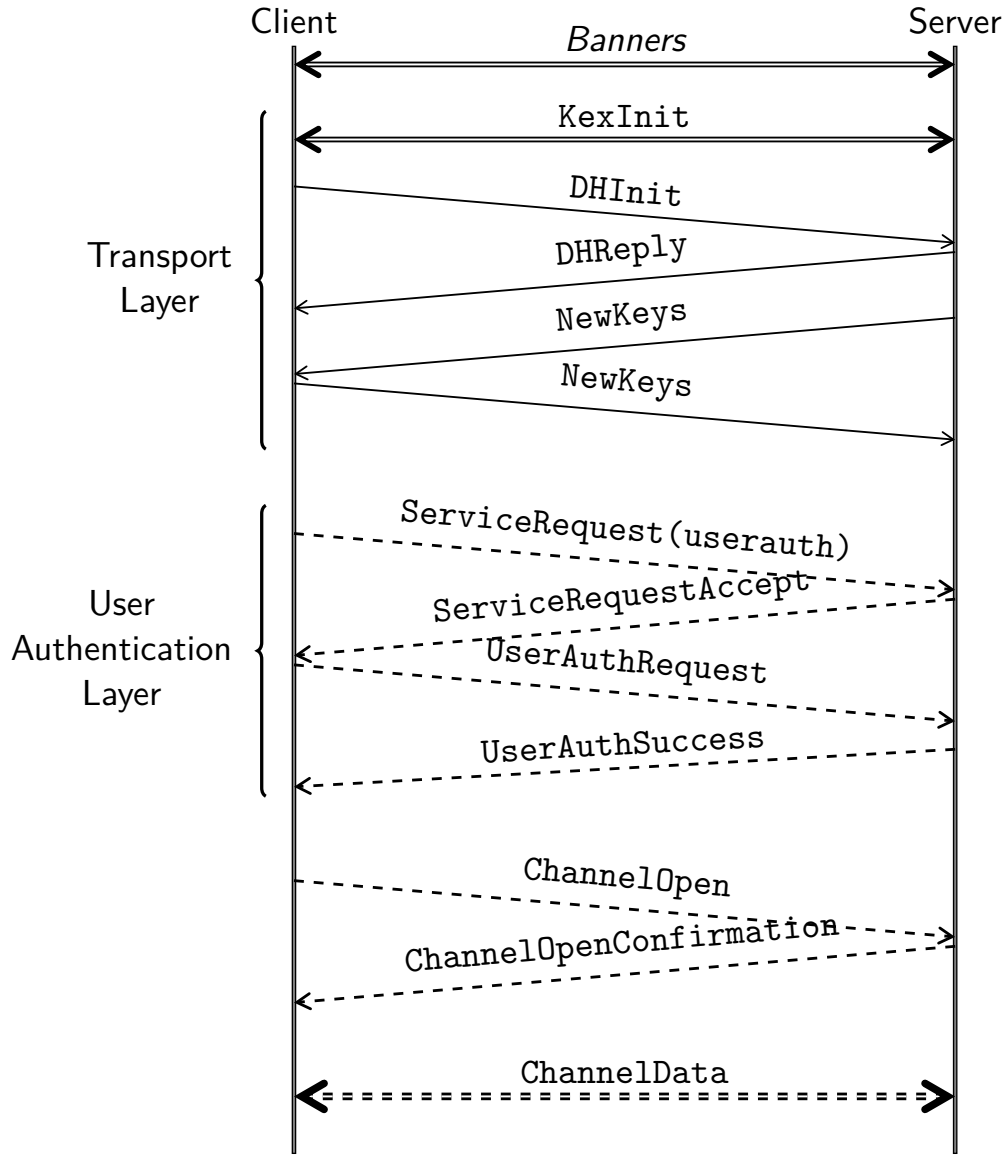

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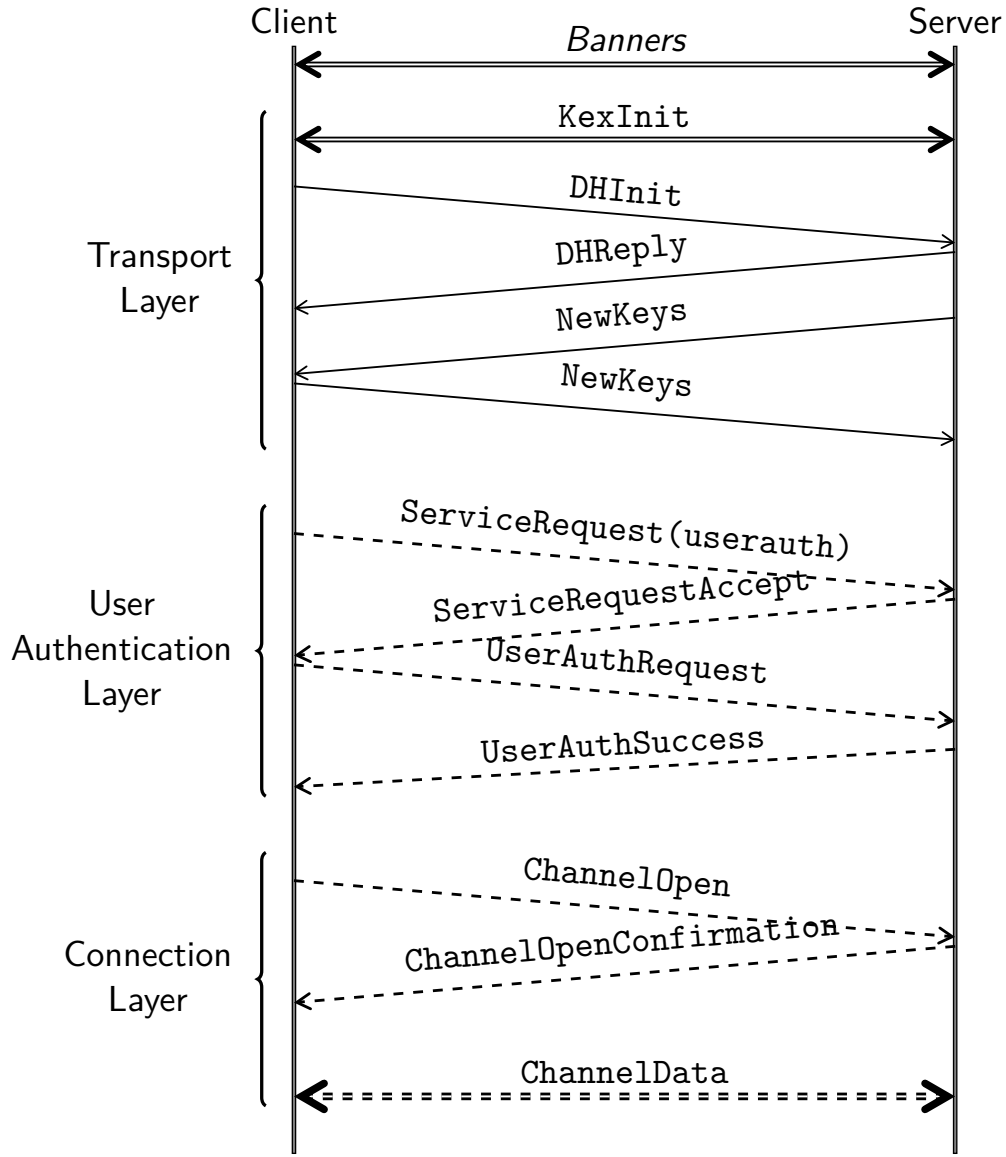


Challenges with SSH State Machine Inference

SSH is an *interesting* protocol

Challenges with SSH State Machine Inference

SSH is an *interesting* protocol

- more messages than TLS (20-30)
  - Generic (`Disconnect`, `ServiceRequest`, `Unimplemented`...)
  - Transport (`KexInit`, `(EC)DHInit`, `NewKeys`...)
  - UserAuthentication (`AuthRequest`, `AuthSuccess`, `AuthFailure`...)
  - Connection (`ChannelOpen`, `ChannelData`, `ChannelEOF`...)

Challenges with SSH State Machine Inference

SSH is an *interesting* protocol

- more messages than TLS (20-30)
- more states
  - the Transport layer is similar to TLS
  - the UserAuthentication layer should be rather simple
  - the Connection layer complexity depends on the modeling
  - after the initial handshake, keys can be refreshed

Challenges with SSH State Machine Inference

SSH is an *interesting* protocol

- more messages than TLS (20-30)
- more states
- non-deterministic behavior
  - some stacks implement defensive timeouts during the first layers
  - the order of some messages can vary from one run to the other

Challenges with SSH State Machine Inference

SSH is an *interesting* protocol

- more messages than TLS (20-30)
- more states
- non-deterministic behavior
- non-representable behavior
  - opening channels in the midst of a key refresh operation
  - how to represent server-side timeouts in a useful way

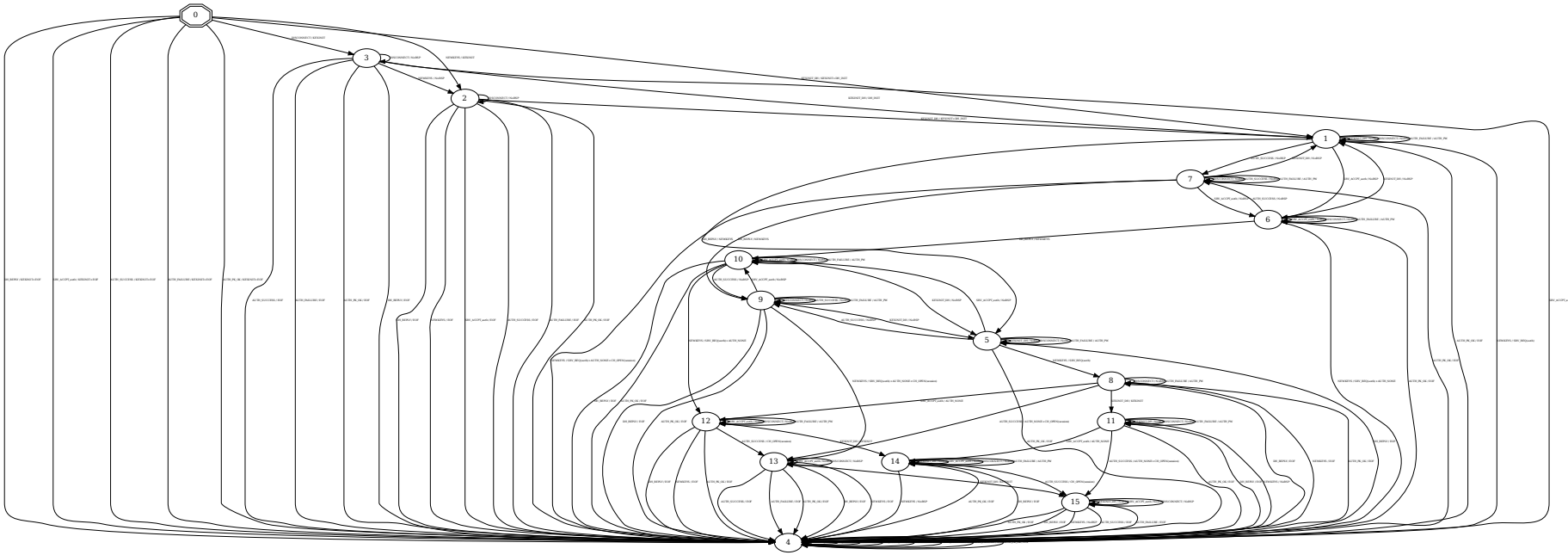
Challenges with SSH State Machine Inference

SSH is an *interesting* protocol

- more messages than TLS (20-30)
- more states
- non-deterministic behavior
- non-representable behavior

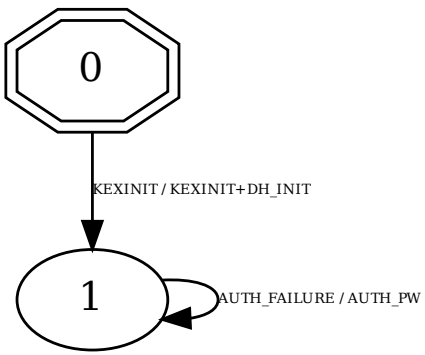
A typical TLS inference was in the minutes...
With SSH it can take hours or days

Case Study: wolfSSH 1.4.20



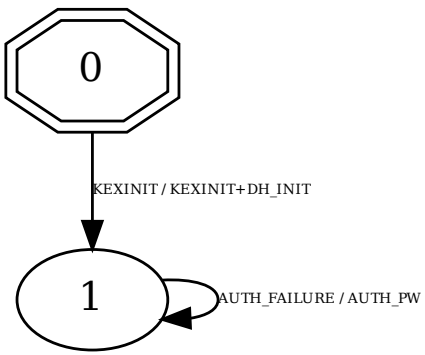
- Client state machine
- Transport + UserAuthentication layers
- 8 input messages, 16 states

Early `UserAuthFailure` (`password` Flavor)



- If a rogue server starts the handshake...
- and sends an early `UserAuthFailure` with the `password` method...

Early `UserAuthFailure` (`password` Flavor)



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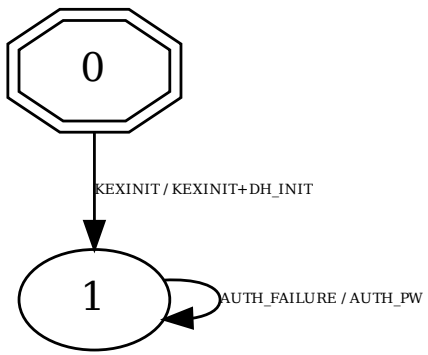

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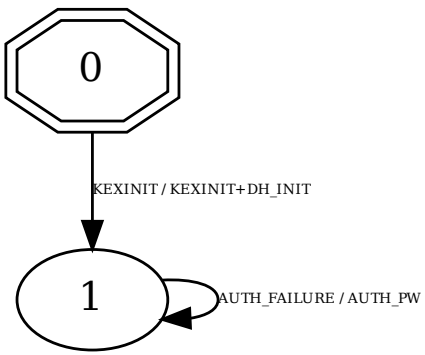

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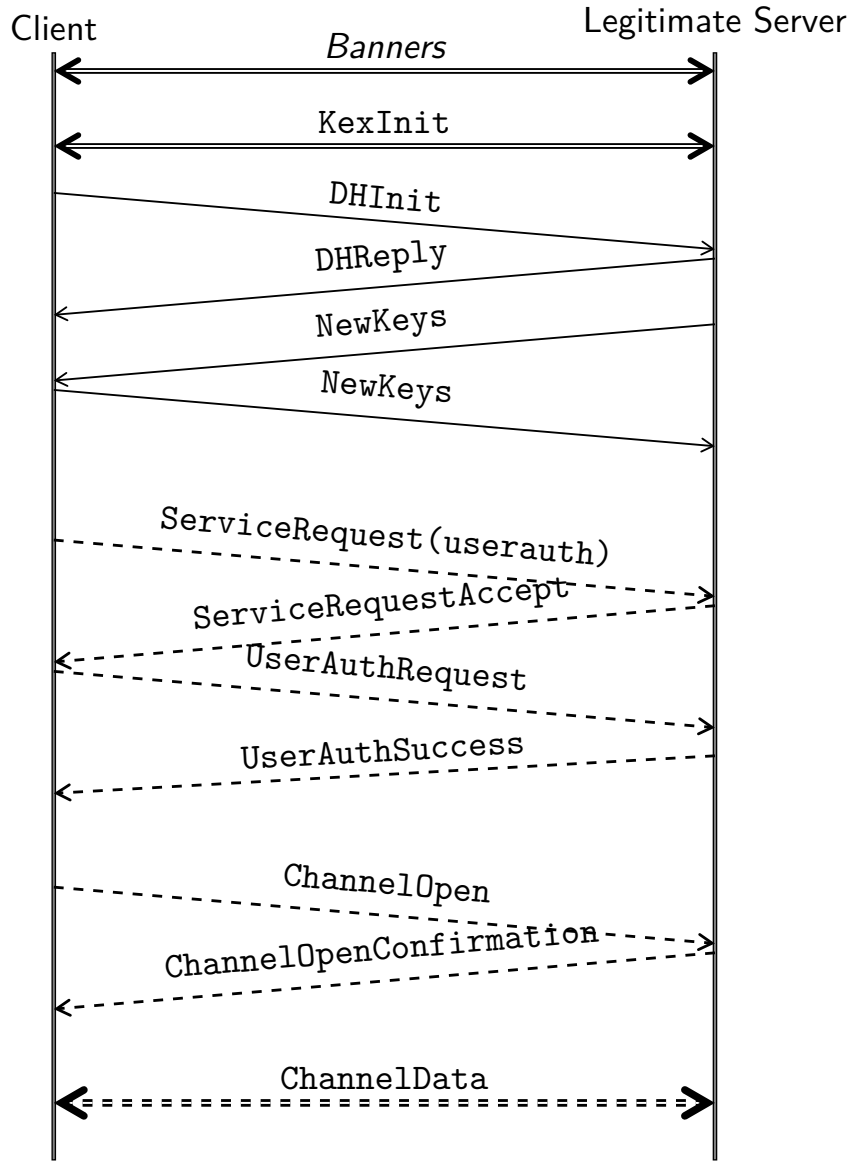
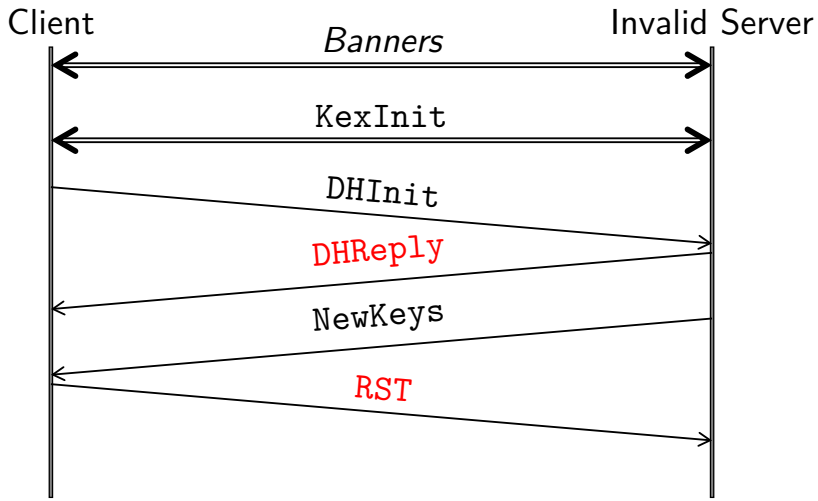
Demo

Early UserAuthFailure (legitimate)

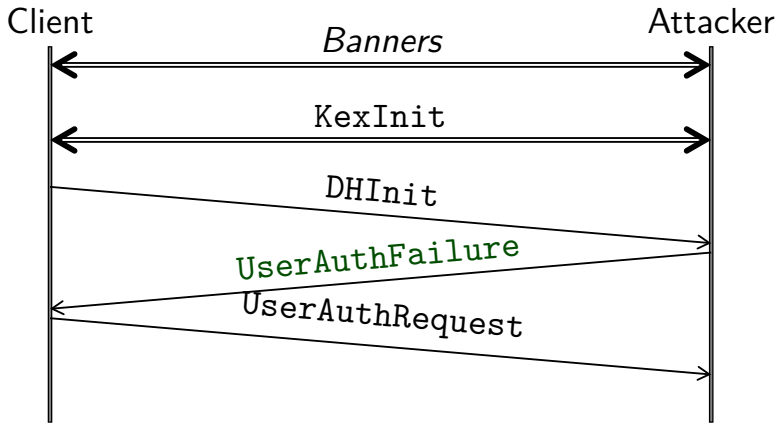


Early `UserAuthFailure` (`invalid`)



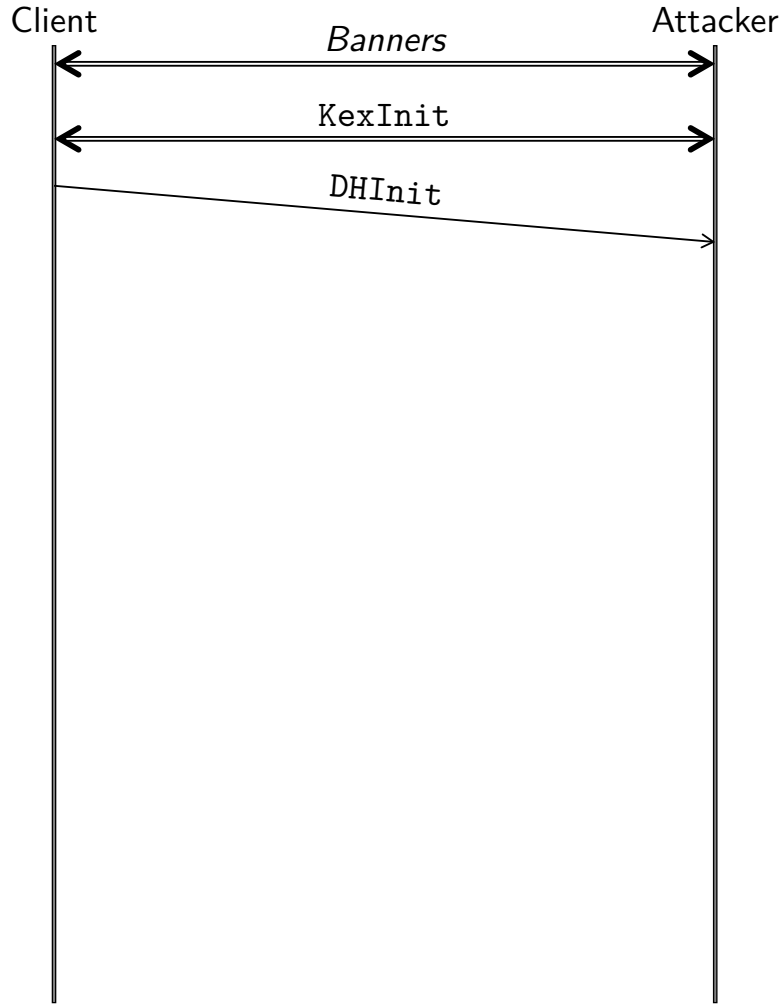
- Since the server presents an unknown public key,
- the client rejects the connecion

Early `UserAuthFailure` (attacker)



- We skip the server authentication...
- and send a bogus `UserAuthFailure` message...
- which triggers the client to send its password,
- in cleartext, and to an unauthenticated server

Early `UserAuthSuccess`



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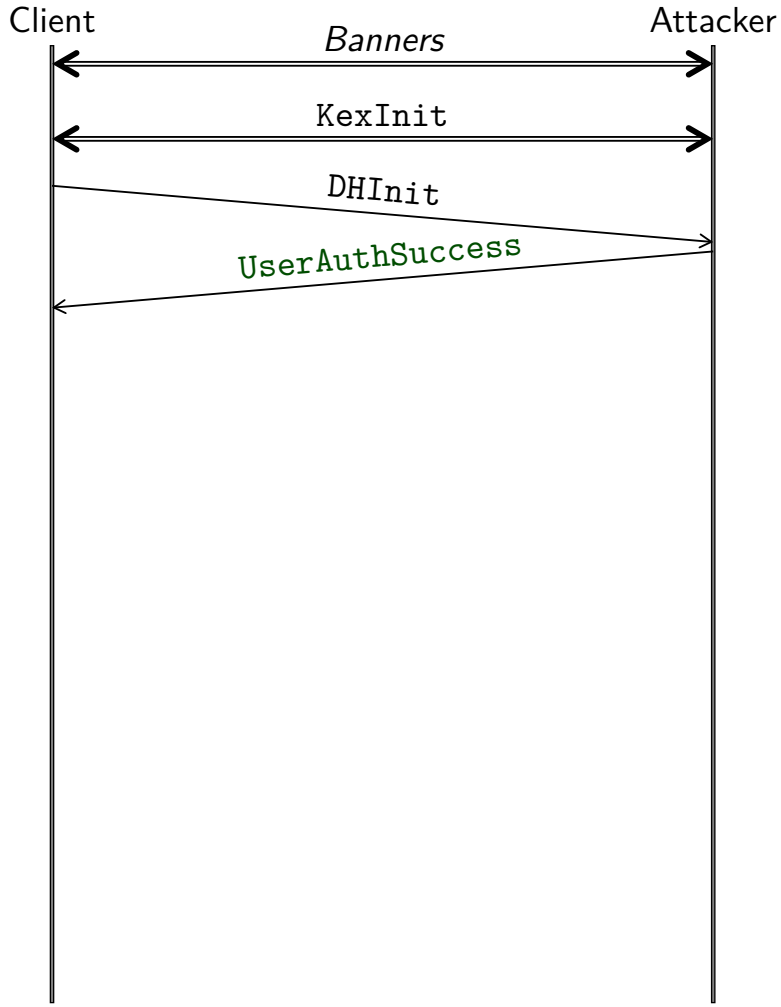

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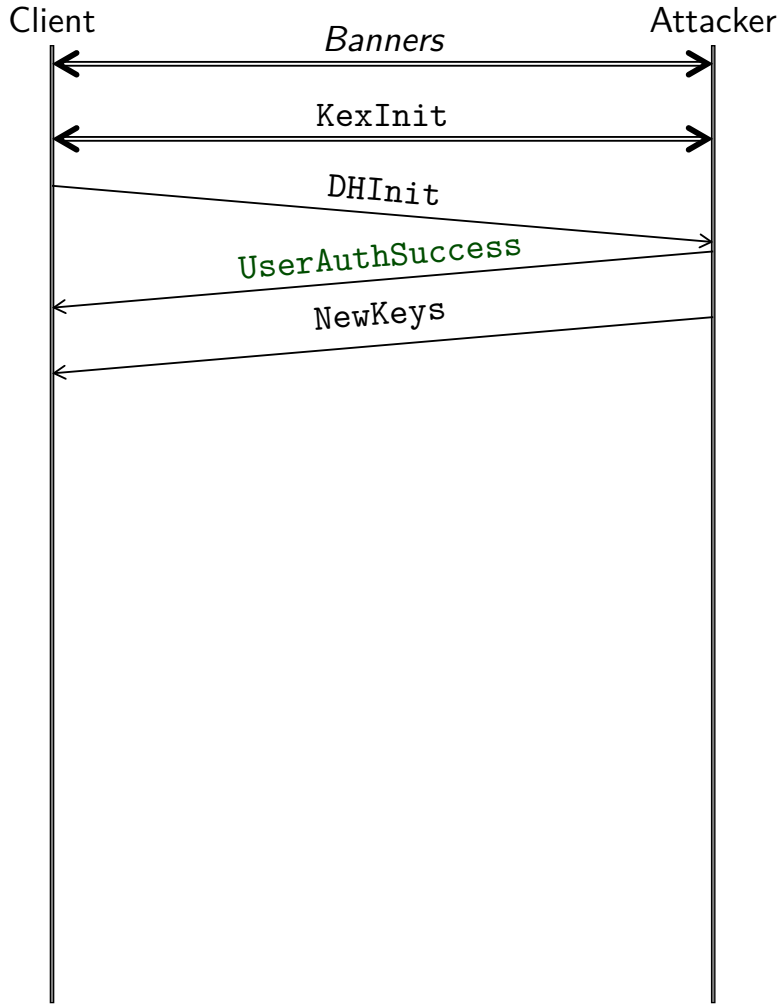

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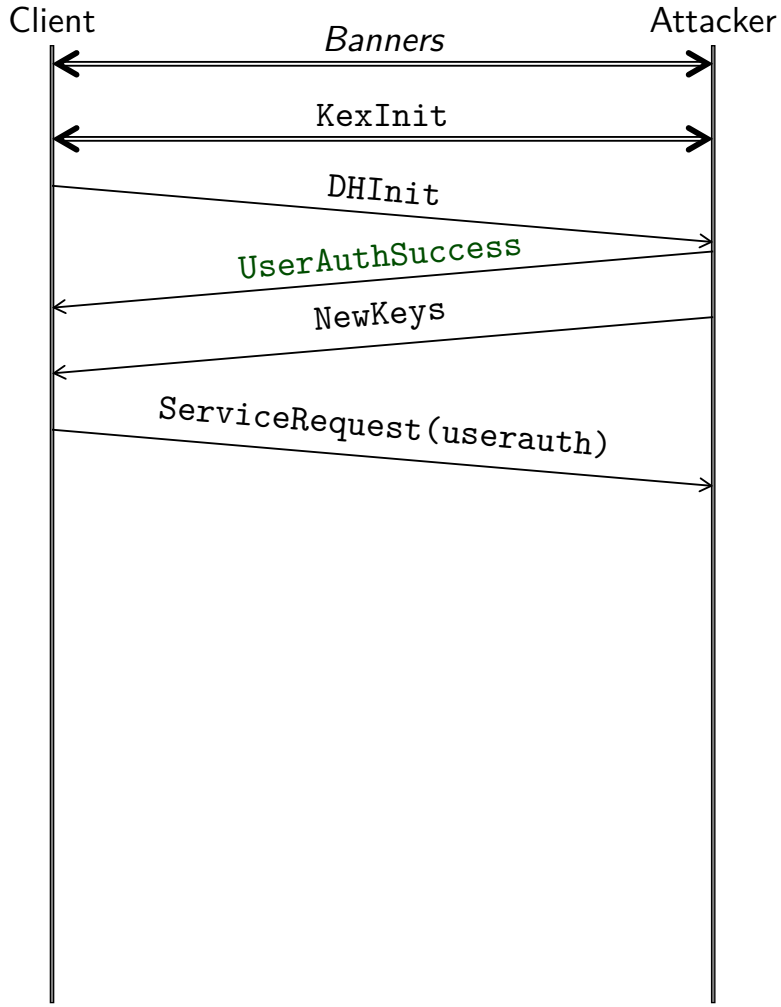

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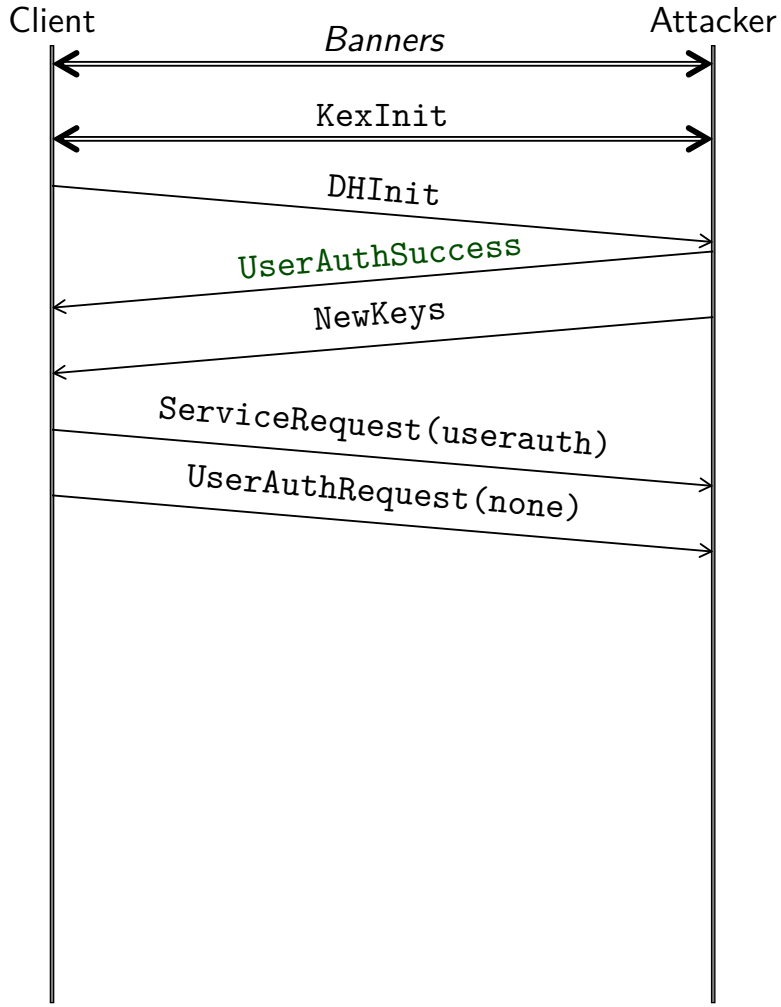
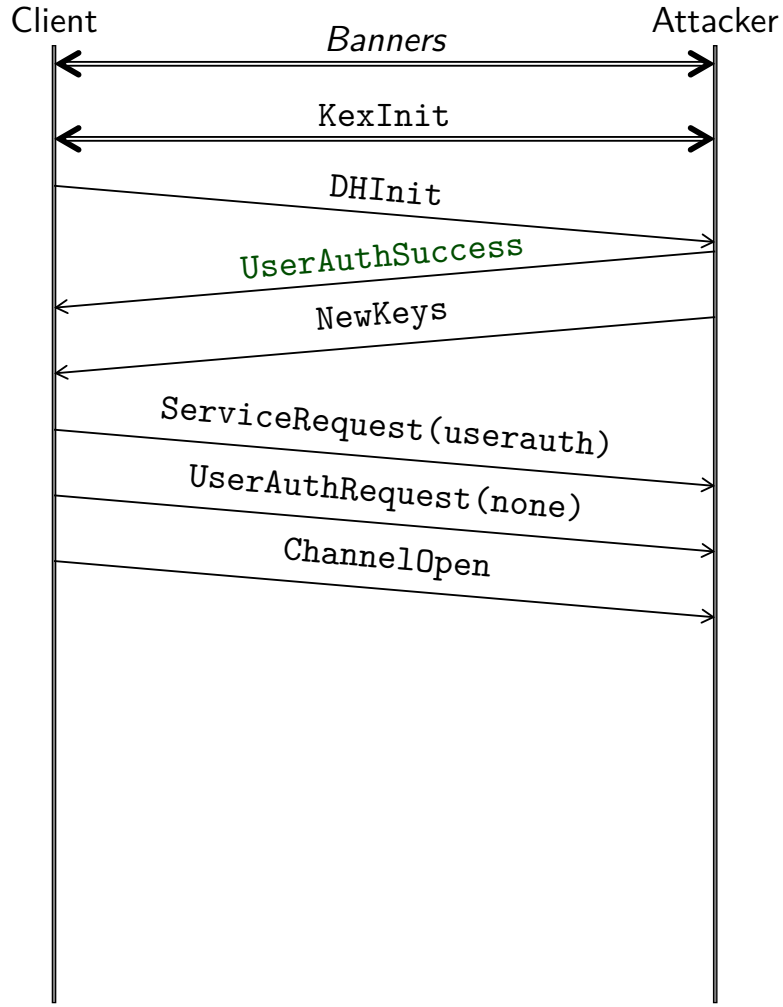
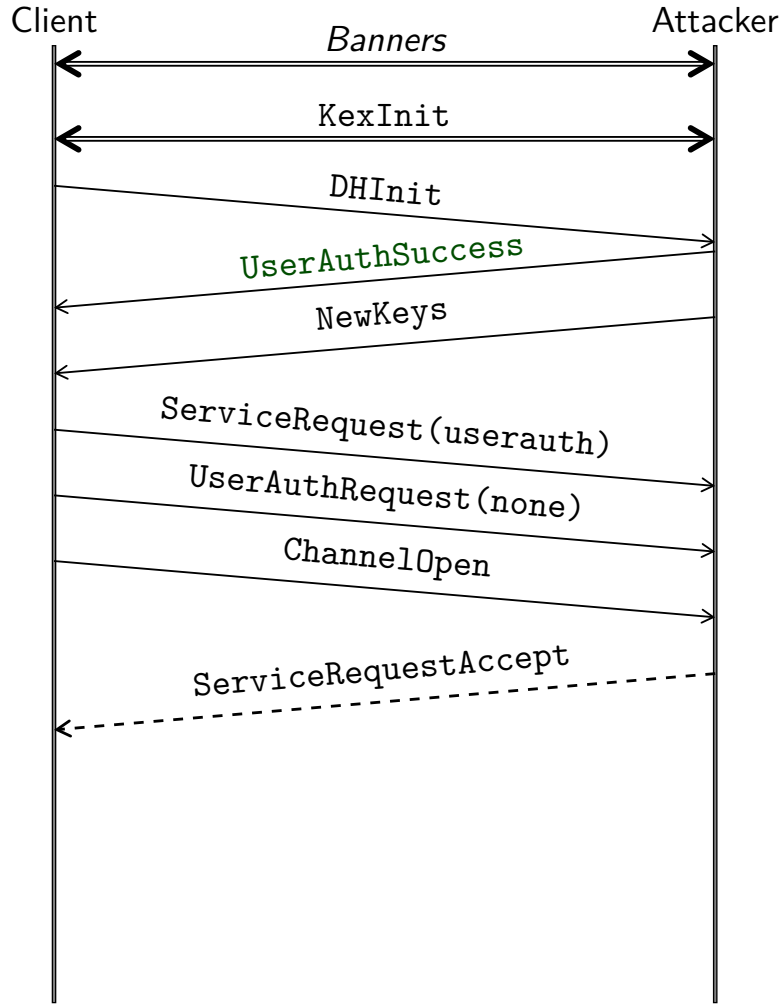


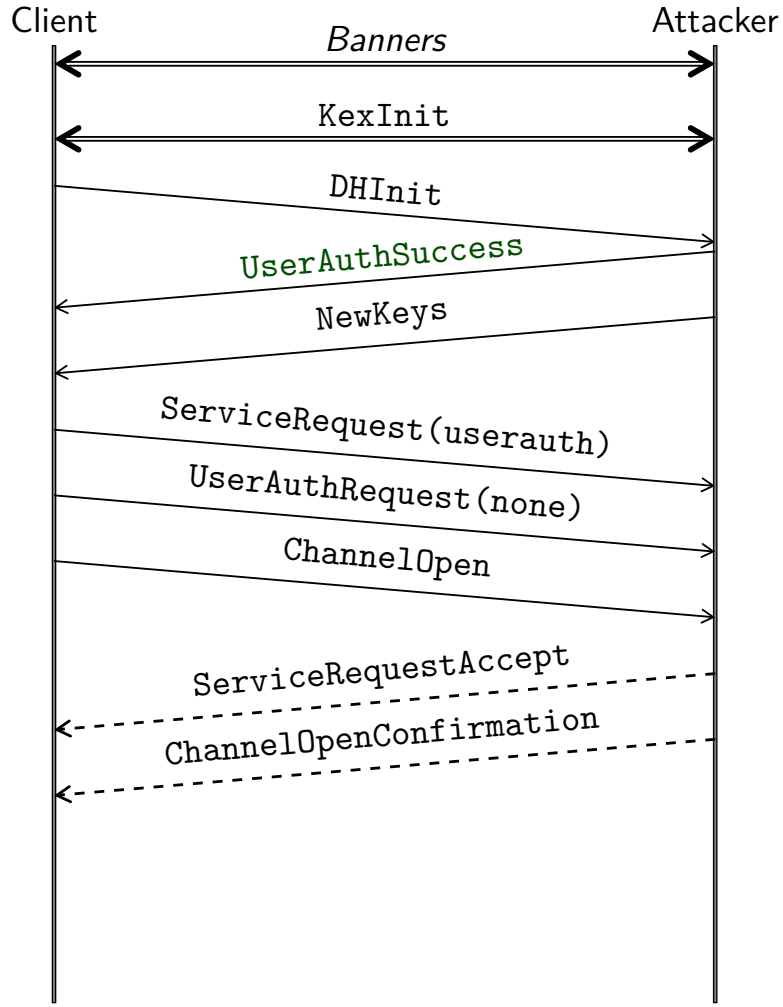
Early UserAuthSuccess



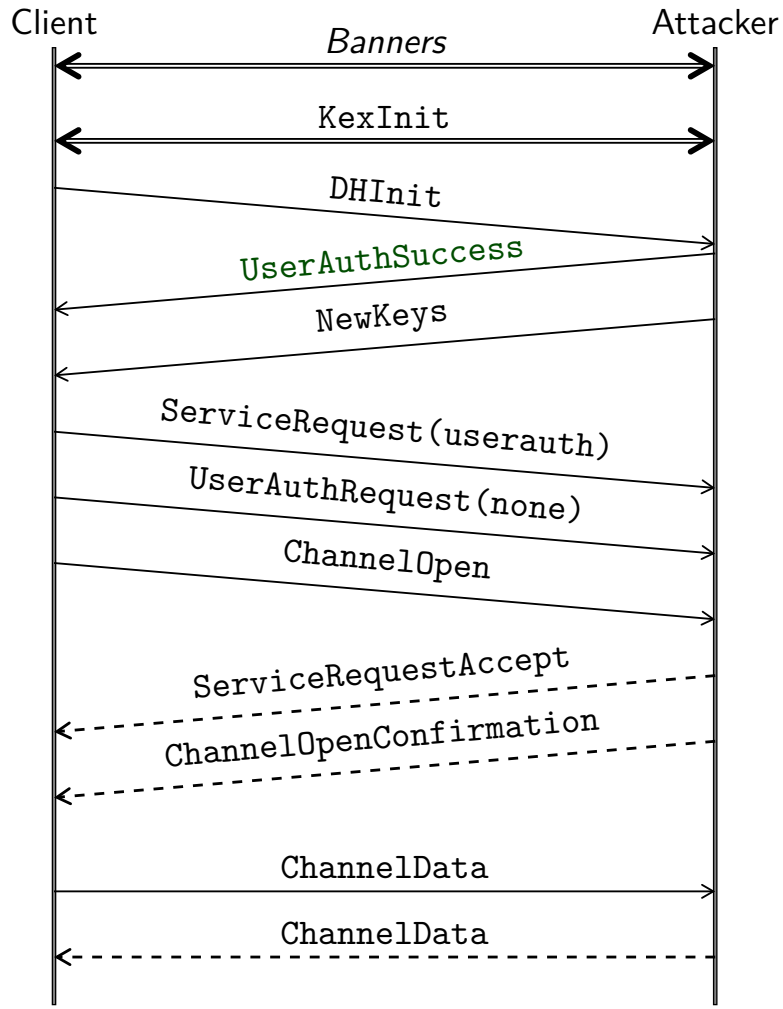
Early UserAuthSuccess



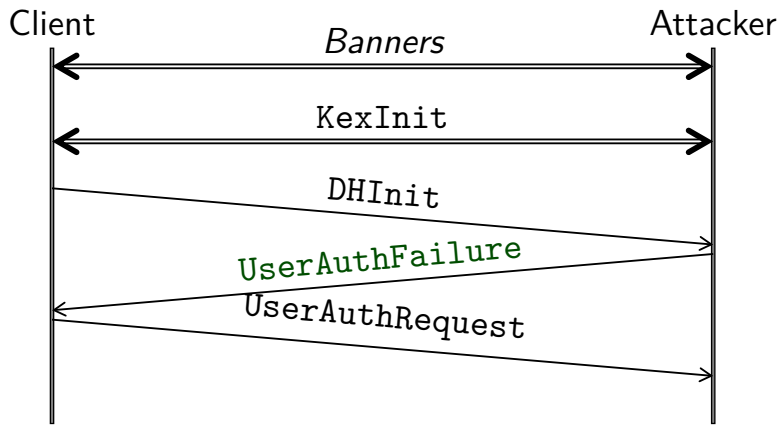
Early UserAuthSuccess



Early UserAuthSuccess



Early `UserAuthFailure` (`publickey` flavor)



- We skip the server authentication...
- and send a bogus `UserAuthFailure` message (with the `publickey` method)...
- which triggers the client to sign an empty context with its private key
- Such a signature could be used against other buggy servers...

Plan

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- a paper on the challenges and our answers
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Longer-term

- towards automatic mappers
- extension to other domains (syscalls, APIs)

Questions

Thank you for your attention

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