maTLS: How to Make TLS middlebox-aware?

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Overview

In this seminar, I will talk about

1

2

3

* You may refer to https://middlebox-aware-tls.github.io for the detail

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In this seminar, I will talk about

1. A brief introduction to TLS
   (based on TLS 1.2)

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3.

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Overview

In this seminar, I will talk about

1. A brief introduction to TLS
   (based on TLS 1.2)

2. Problems in TLS with Middleboxes

3. Middlebox-aware TLS (maTLS)
   with Auditable Middleboxes

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1 A brief introduction to TLS

(based on TLS 1.2)

Transport Layer Security

Client
(Alice)

Server
(www.bob.com)

Transport Layer Security

Transport Layer Security

Client
(Alice)

Server
(www.bob.com)

Hello! I'm Bob!

Transport Layer Security

Transport Layer Security

① The peer is intended!

Transport Layer Security

Transport Layer Security

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Transport Layer Security

Transport Layer Security

Transport Layer Security

TLS aims to guarantee

① Authentication

② Confidentiality

③ Integrity

Transport Layer Security

TLS consists of

Transport Layer Security

TLS consists of

- TLS handshake protocol
  - ✓ Authentication
  - ✓ Key Establishment

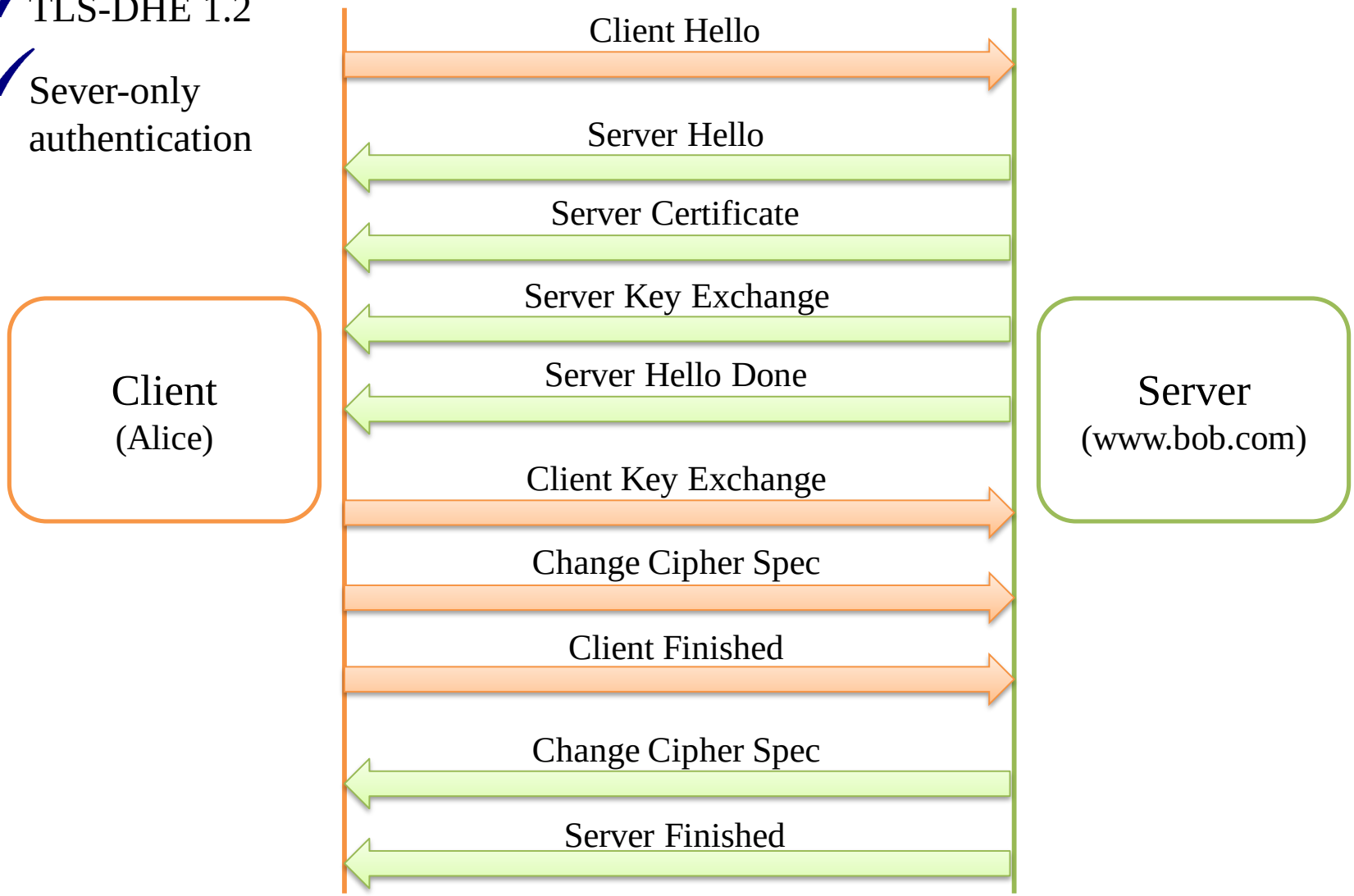
Transport Layer Security

TLS consists of

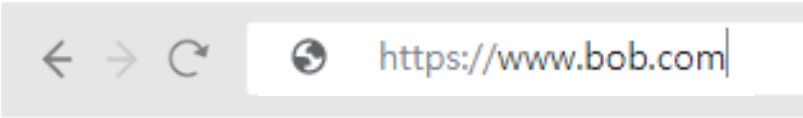
- TLS handshake protocol
  - ✓ Authentication
  - ✓ Key Establishment
- TLS record protocol
  - ✓ Stateful Encryption/Decryption

TLS Handshake Protocol

- ✓ TLS-DHE 1.2
- ✓ Sever-only authentication



TLS Handshake Protocol in Detail

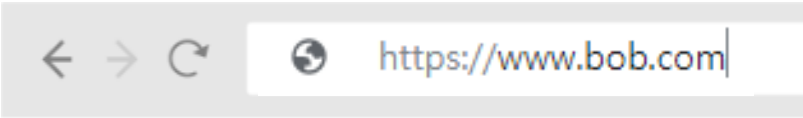


Client
(Alice)

Server
(www.bob.com)

TLS Handshake Protocol in Detail

Alice wants to talk with

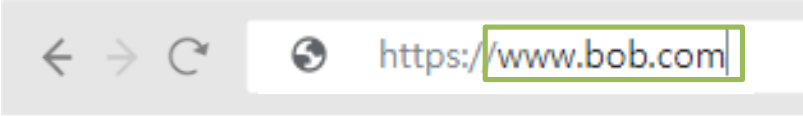


Client
(Alice)

Server
(www.bob.com)

TLS Handshake Protocol in Detail

Alice wants to talk with www.bob.com

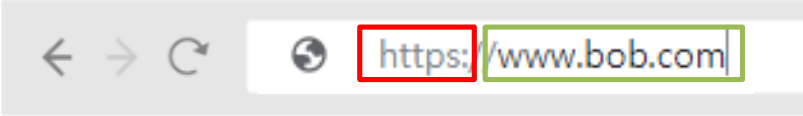


Client
(Alice)

Server
(www.bob.com)

TLS Handshake Protocol in Detail

Alice wants to talk with www.bob.com via HTTPS (HTTP over TLS)



Client
(Alice)

Server
(www.bob.com)

TLS Handshake Protocol in Detail

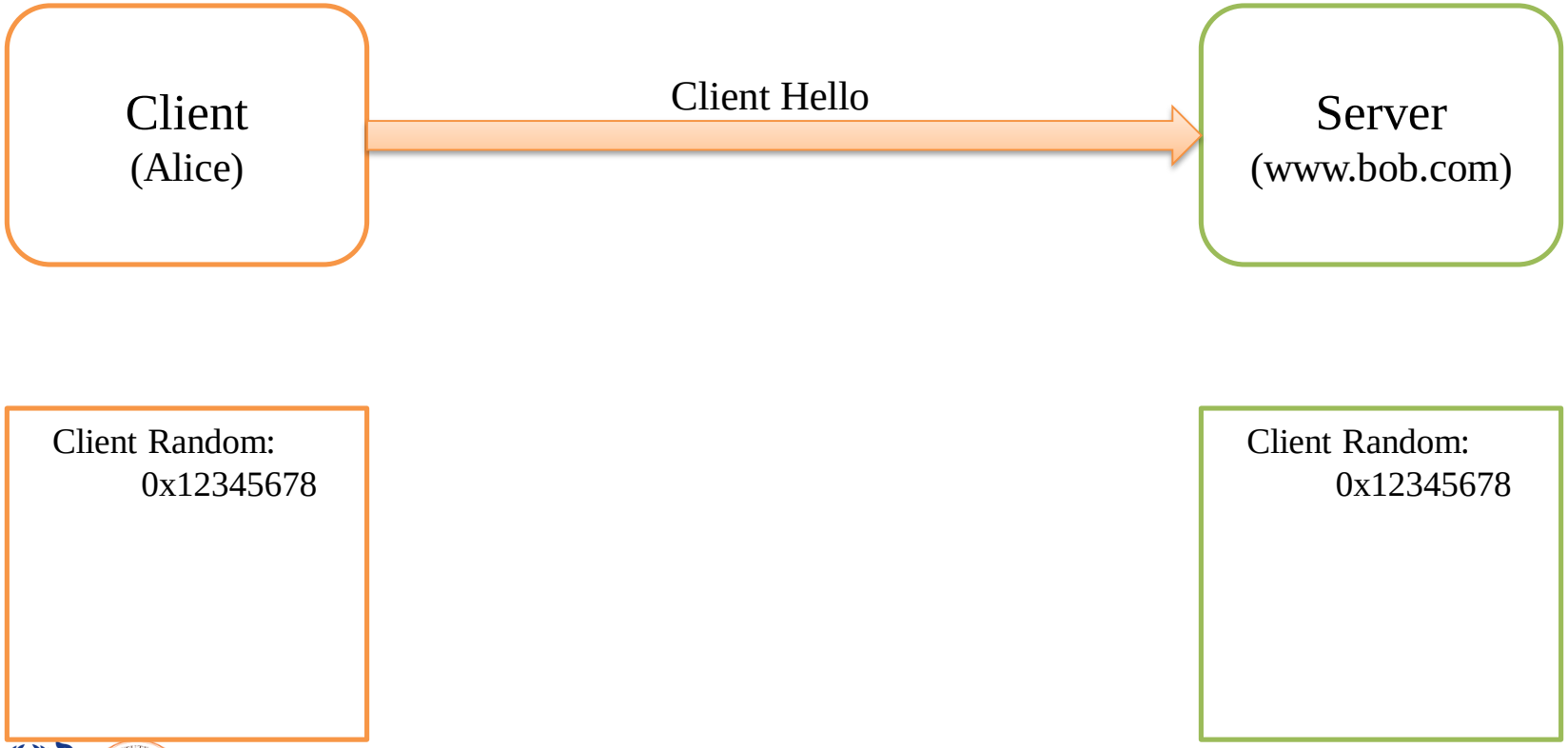
Hello! My **random number** is 0x12345678
The highest TLS **version** I can support is 1.3
I can talk with you by using the **ciphersuites**
AEAD-AES-128-GCM-SHA256, ECDSA-ECDHE-AES-128-GCM-SHA256, …
I support **extensions** ...

Client
(Alice)

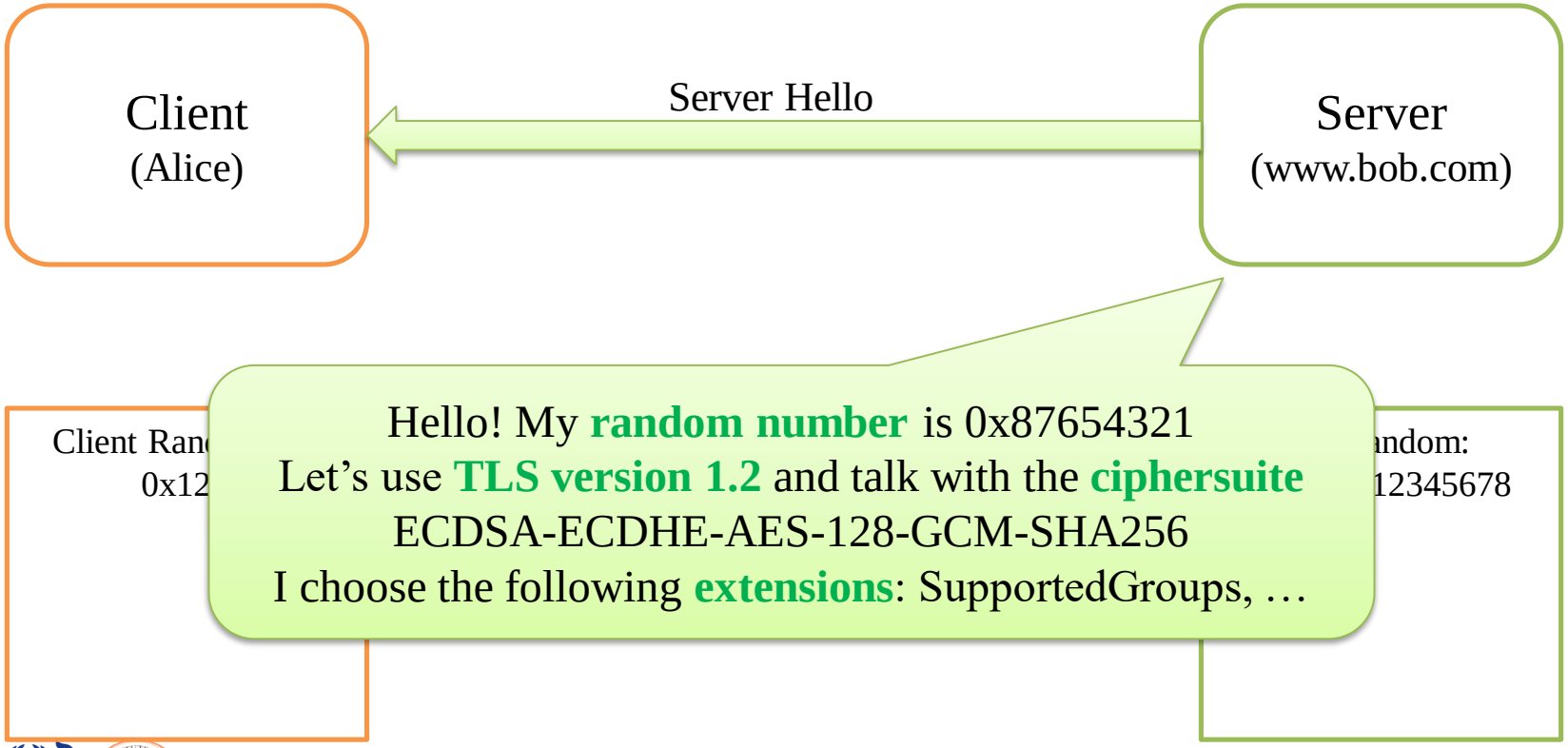
Client Hello →

Server
(www.bob.com)

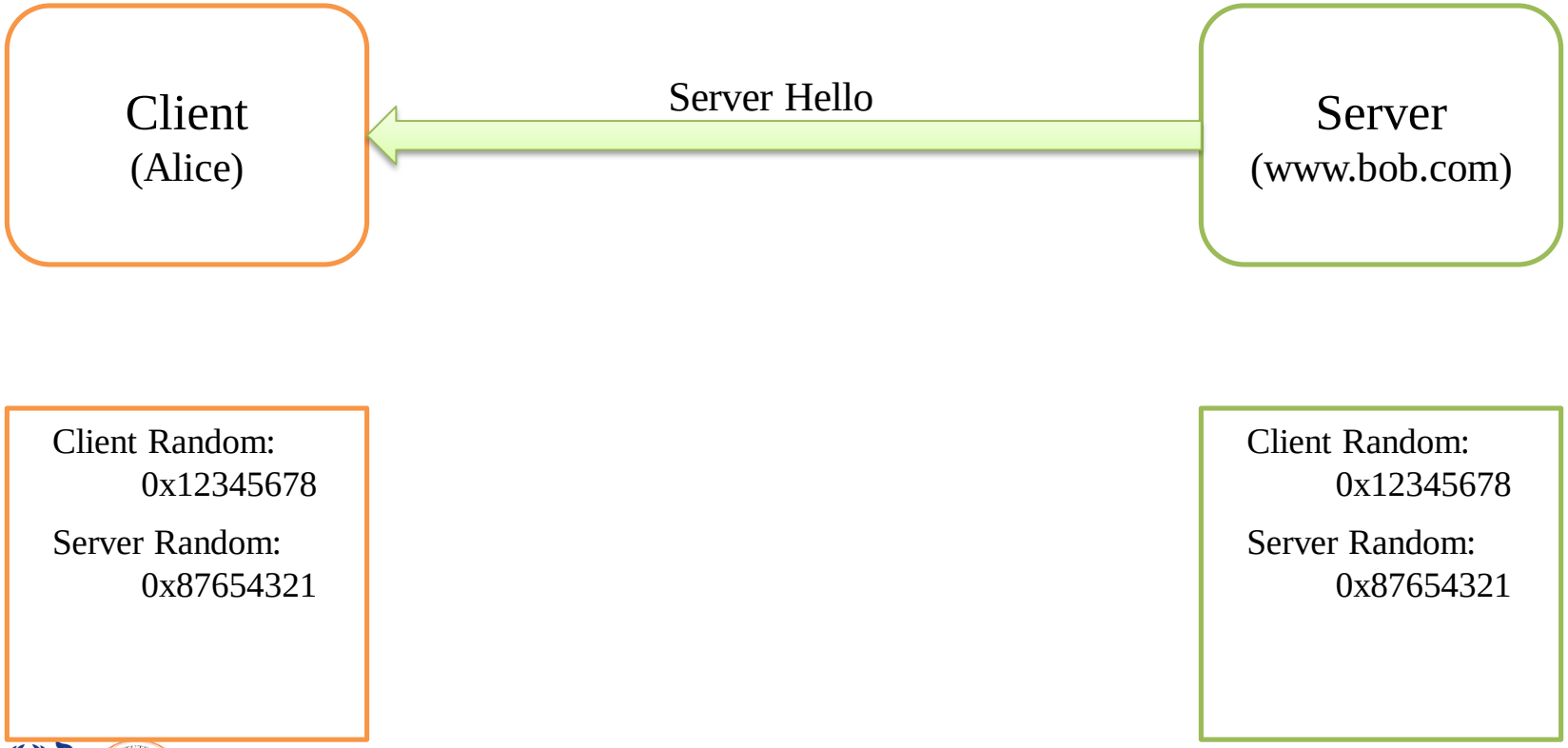
TLS Handshake Protocol in Detail



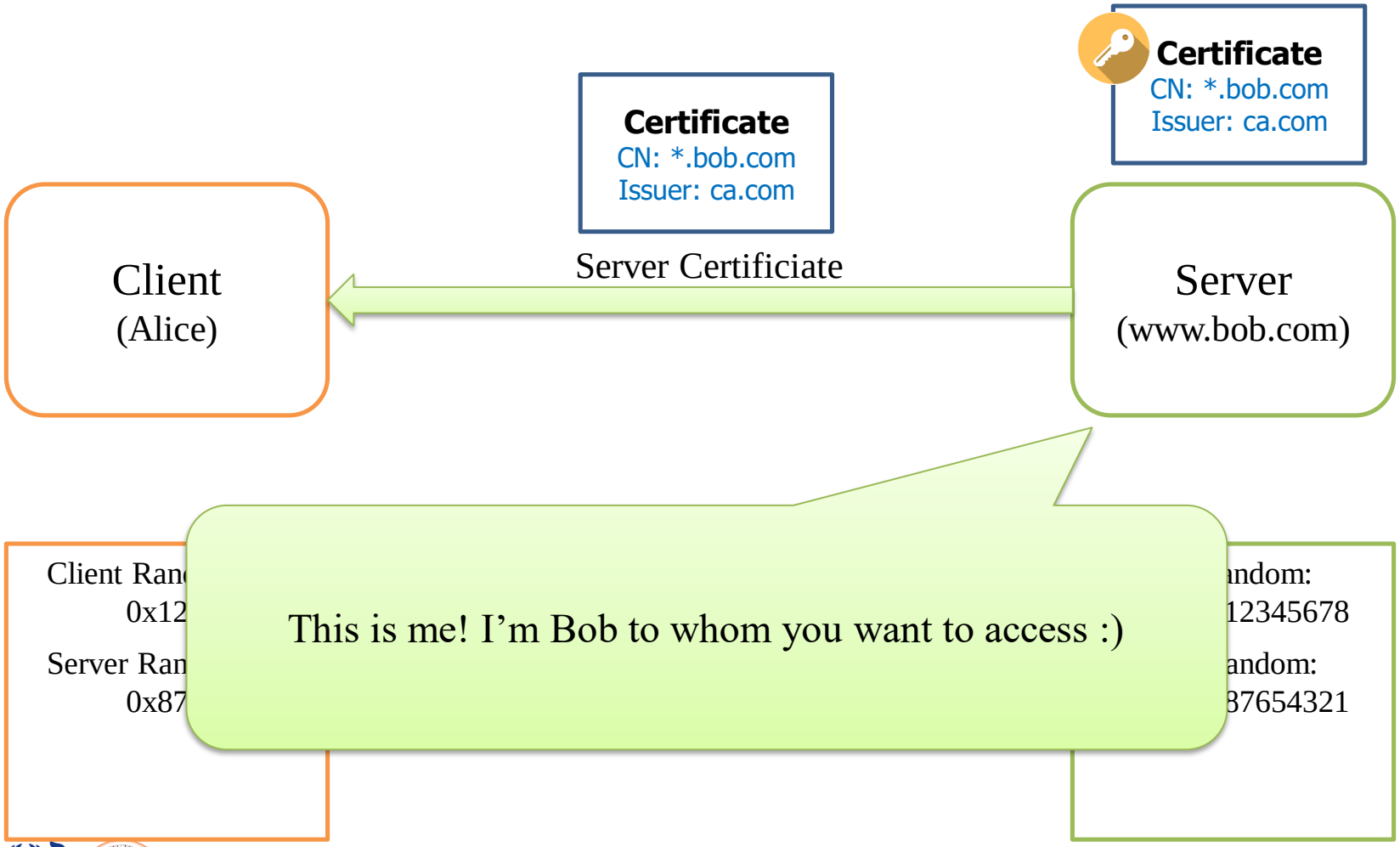
TLS Handshake Protocol in Detail



TLS Handshake Protocol in Detail



TLS Handshake Protocol in Detail



TLS Handshake Protocol in Detail

Certificate
CN: *.bob.com
Issuer: ca.com

Certificate
CN: *.bob.com
Issuer: ca.com

Client
(Alice)

Server
(www.bob.com)

Client Random:
0x12345678

Server Random:
0x87654321

Client Random:
0x12345678

Server Random:
0x87654321

TLS Handshake Protocol in Detail

DH Key Pair: (b, g^b)

Certificate
CN: *.bob.com
Issuer: ca.com

Certificate
CN: *.bob.com
Issuer: ca.com

Client
(Alice)

Server
(www.bob.com)

Client Random:
0x12345678

Server Random:
0x87654321

Client Random:
0x12345678

Server Random:
0x87654321

TLS Handshake Protocol in Detail

DH Key Pair: (b, g^b)

Certificate
CN: *.bob.com
Issuer: ca.com

Certificate
CN: *.bob.com
Issuer: ca.com

$g^b || Sign(\text{🔑}, cr||sr||g^b)$

Server Key Exchange

Client
(Alice)

Server
(www.bob.com)

Client Ran
0x12

Server Ran
0x87

andom:
12345678

andom:
87654321

For our session key, this is my Diffie-Hellman Key Share and the signature over the **client random**, the **server random**, and the **key share**, signed with 🔑

TLS Handshake Protocol in Detail

DH Key Pair: (b, g^b)

Certificate

Certificate

Alice authenticates Bob with Bob's Certificate, verifying the signature

0x12345678

Server Random:
0x87654321

0x12345678

Server Random:
0x87654321

TLS Handshake Protocol in Detail

DH Key Pair: (b, g^b)

Certificate
CN: *.bob.com
Issuer: ca.com

Certificate
CN: *.bob.com
Issuer: ca.com

Client
(Alice)

Server
(www.bob.com)

Client Random:
0x12345678

Server Random:
0x87654321

Bob's DH Share: g^b

Client Random:
0x12345678

Server Random:
0x87654321

TLS Handshake Protocol in Detail

DH Key Pair: (b, g^b)

Certificate
CN: *.bob.com
Issuer: ca.com

Certificate
CN: *.bob.com
Issuer: ca.com

Client
(Alice)

Server Hello Done

Server
(www.bob.com)

Client Ran
0x12

Server Ran
0x87

Bob's DH Share: g^b

Done!

andom:
12345678

andom:
87654321

TLS Handshake Protocol in Detail

DH Key Pair: (a, g^a)

Certificate
CN: *.bob.com
Issuer: ca.com

Client
(Alice)

Client Random:
0x12345678

Server Random:
0x87654321

Bob's DH Share: g^b

DH Key Pair: (b, g^b)

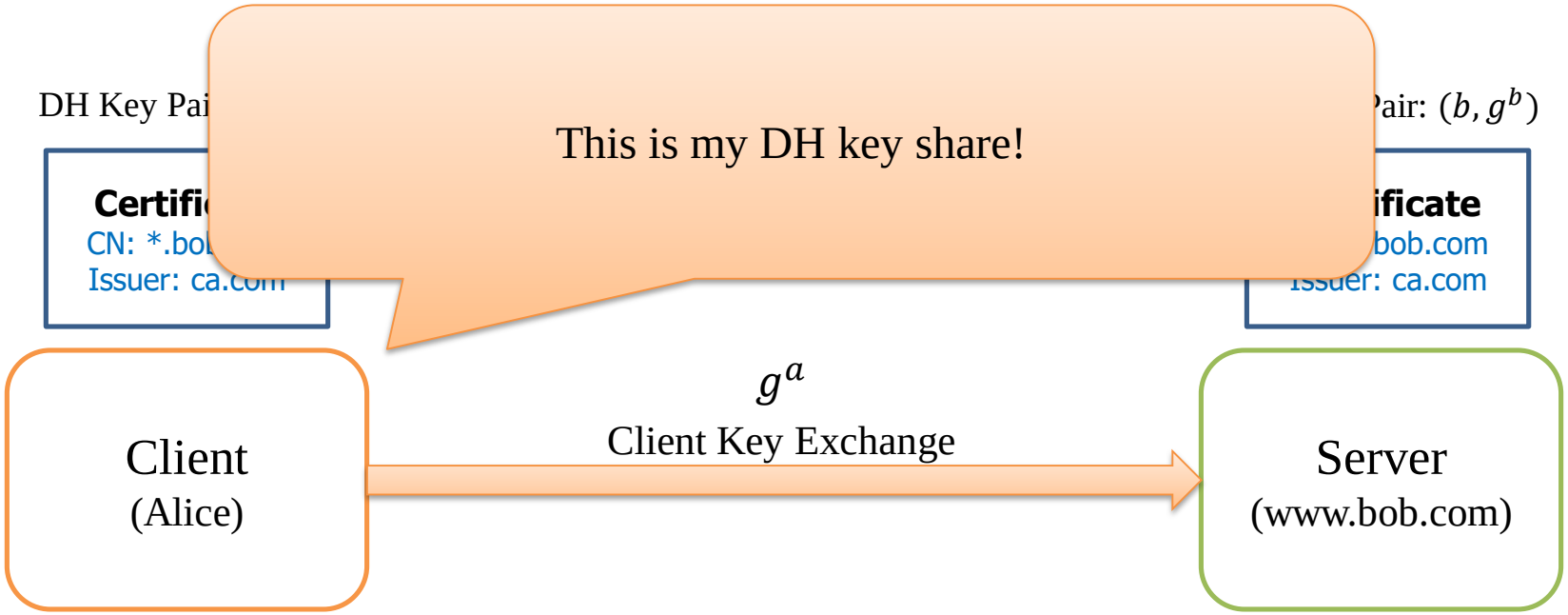
Certificate
CN: *.bob.com
Issuer: ca.com

Server
(www.bob.com)

Client Random:
0x12345678

Server Random:
0x87654321

TLS Handshake Protocol in Detail



Client Random:
0x12345678

Server Random:
0x87654321

Bob's DH Share: g^b

Client Random:
0x12345678

Server Random:
0x87654321

TLS Handshake Protocol in Detail

DH Key Pair: (a, g^a)

Certificate
CN: *.bob.com
Issuer: ca.com

Client
(Alice)

Client Random:
0x12345678

Server Random:
0x87654321

Bob's DH Share: g^b

DH Key Pair: (b, g^b)

Certificate
CN: *.bob.com
Issuer: ca.com

Server
(www.bob.com)

Client Random:
0x12345678

Server Random:
0x87654321

Alice's DH Share: g^a

TLS Handshake Protocol in Detail

DH Key Pair: (a, g^a)

Certificate
CN: *.bob.com
Issuer: ca.com

Client
(Alice)

Client Random:
0x12345678

Server Random:
0x87654321

Bob's DH Share: g^b

$(g^b)^a = g^{ab}$

DH Key Pair: (b, g^b)

Certificate
CN: *.bob.com
Issuer: ca.com

Server
(www.bob.com)

Client Random:
0x12345678

Server Random:
0x87654321

Alice's DH Share: g^a

$(g^a)^b = g^{ab}$

TLS Handshake Protocol in Detail

DH Key Pair: (a, g^a)

Certificate
CN: *.bob.com
Issuer: ca.com

Client
(Alice)

DH Key Pair: (b, g^b)

Certificate
CN: *.bob.com
Issuer: ca.com

Server
(www.bob.com)

Client Random:
0x12345678

Server Random:
0x87654321

Bob's DH Share: g^b

$(g^b)^a = g^{ab}$

Master Secret =
KDF(Client Random, Server Random, g^{ab})

Client Random:
0x12345678

Server Random:
0x87654321

Alice's DH Share: g^a

$(g^a)^b = g^{ab}$

* KDF: Key Derivation Function

TLS Handshake Protocol in Detail

DH Key Pair: (a, g^a)

Certificate
CN: *.bob.com
Issuer: ca.com

Client
(Alice)

DH Key Pair: (b, g^b)

Certificate
CN: *.bob.com
Issuer: ca.com

Server
(www.bob.com)

Master Secret:
0x#2gc2145

Master Secret =
KDF(Client Random, Server Random, g^{ab})

Master Secret:
0x#2gc2145

* KDF: Key Derivation Function

TLS Handshake Protocol in Detail

DH Key Pair: (a, g^a)

DH Key Pair: (b, g^b)

Certificate

Certificate

Attacker cannot generate Master Secret without knowledge of a or b!

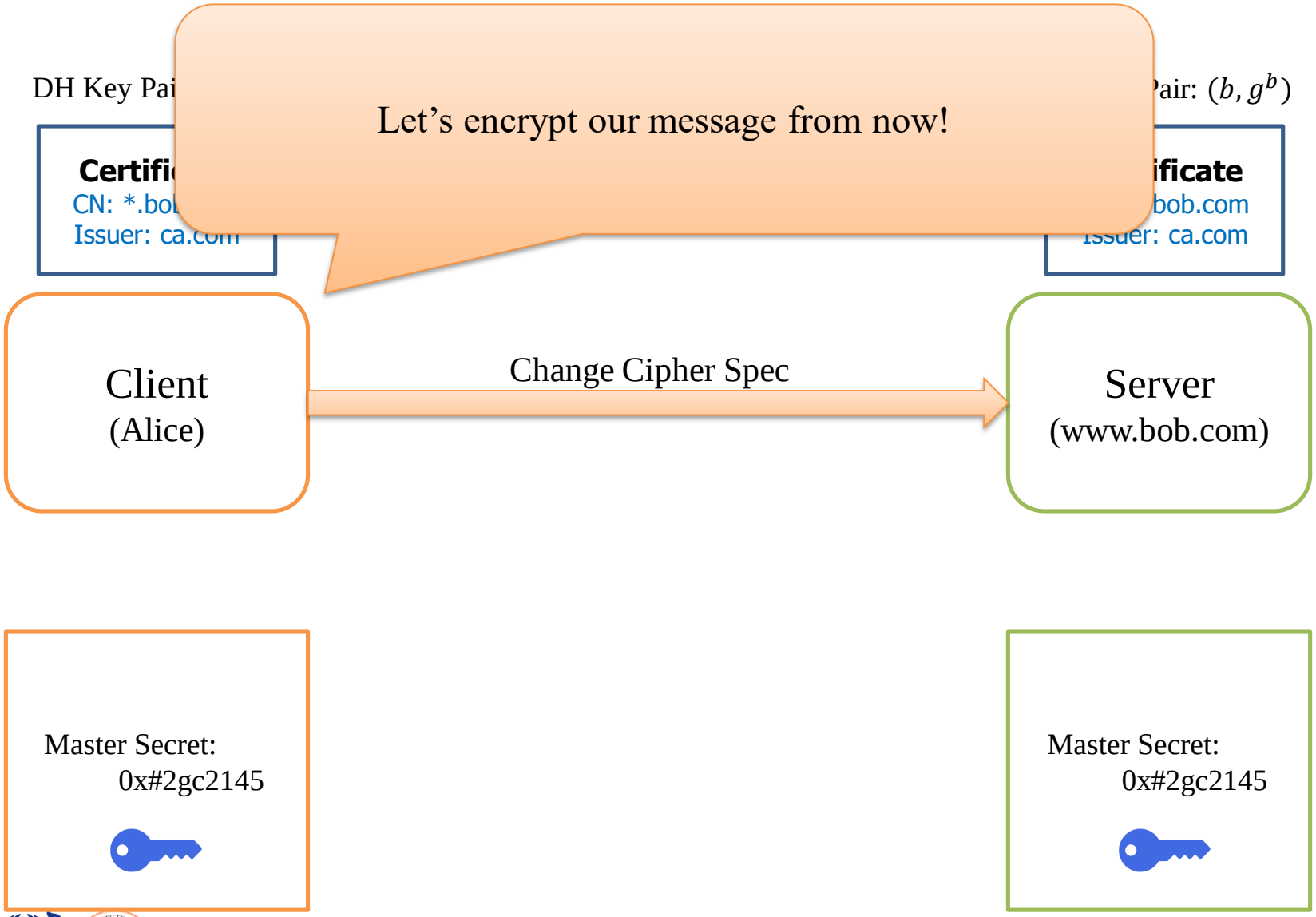
Master Secret:
0x#2gc2145

Master Secret =
KDF(Client Random, Server Random, g^{ab})

Master Secret:
0x#2gc2145

* KDF: Key Derivation Function

TLS Handshake Protocol in Detail



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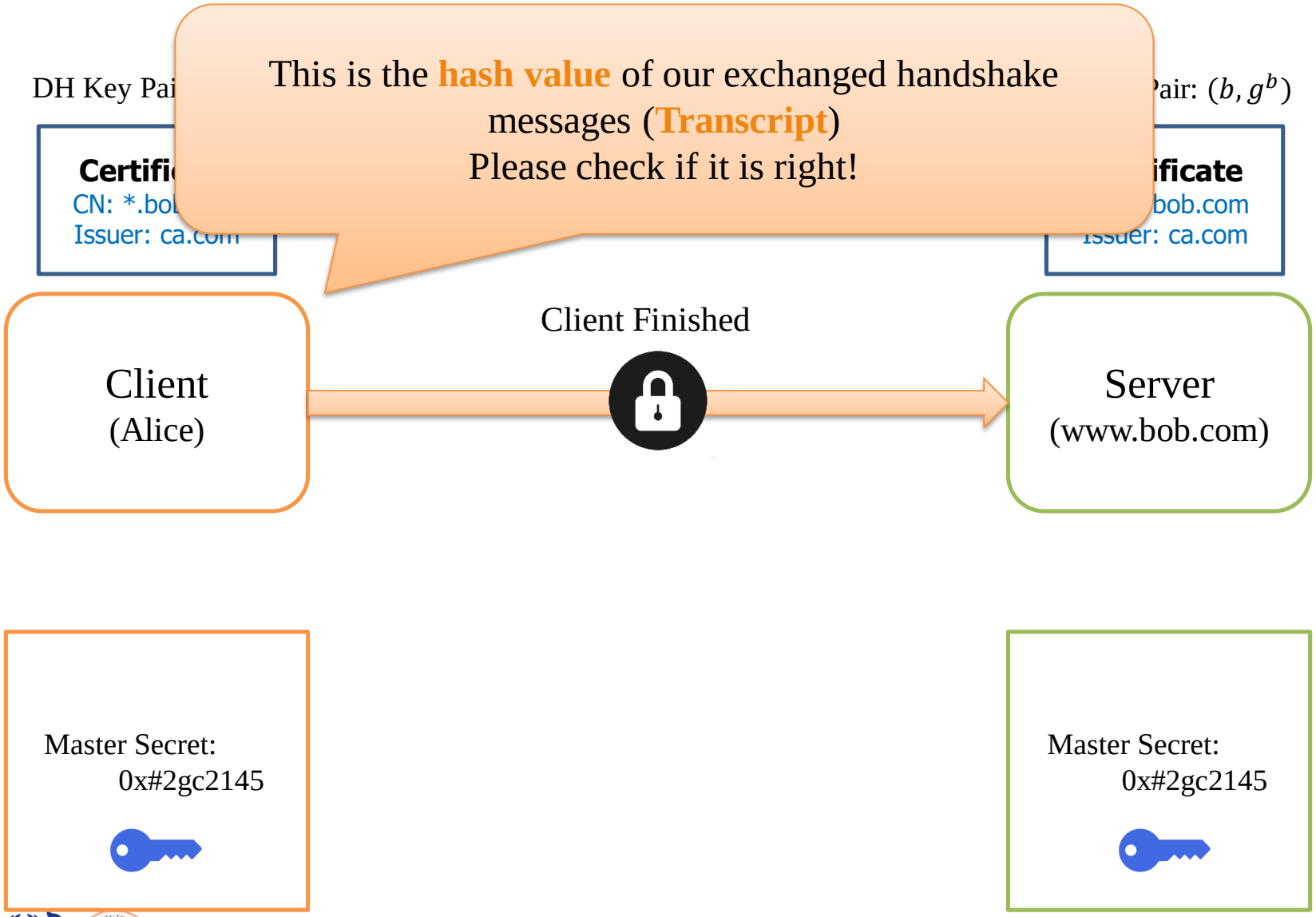

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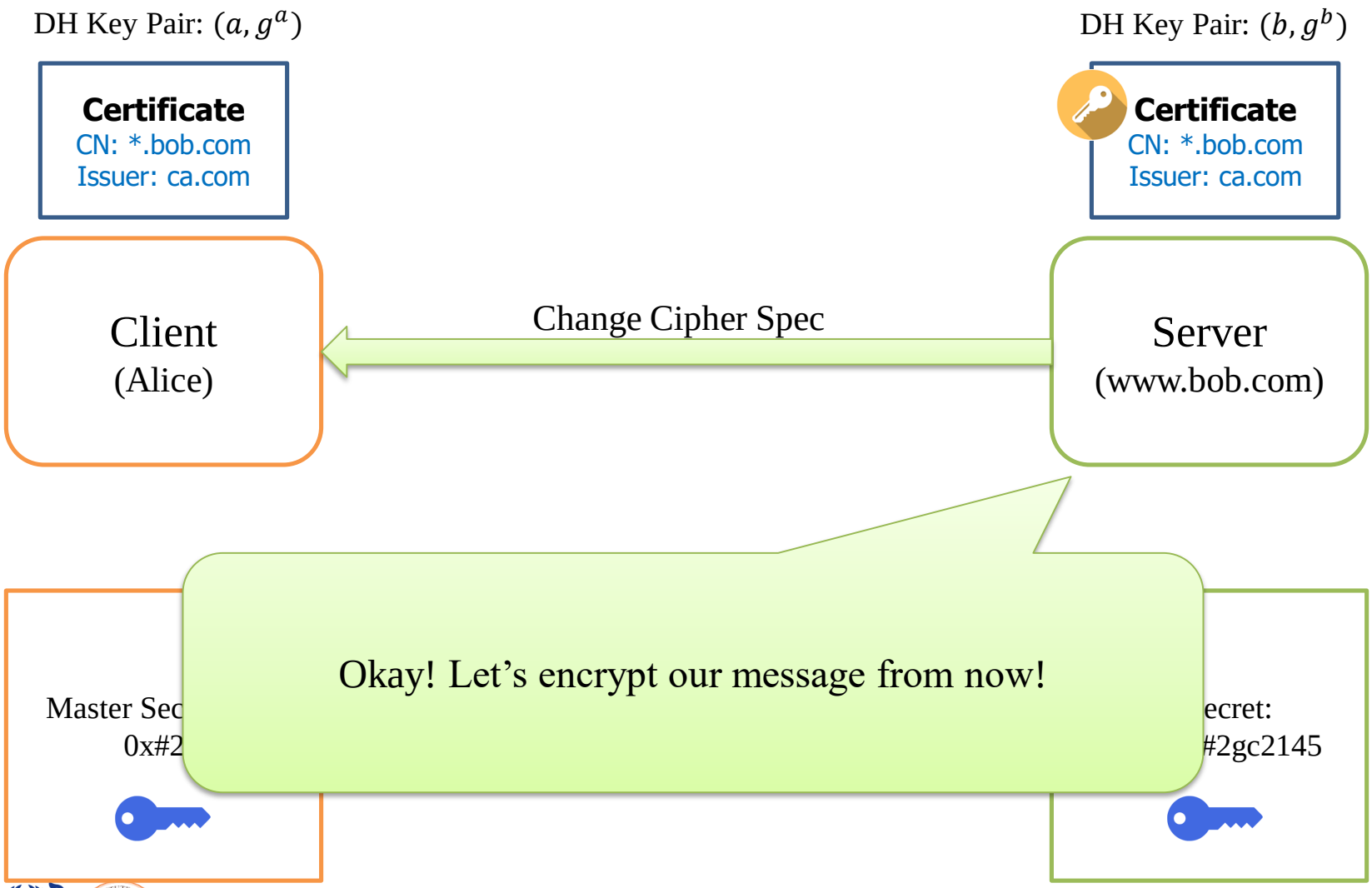


TLS Handshake Protocol in Detail

DH Key Pair: (a, g^a)

Certificate
CN: *.bob.com
Issuer: ca.com

DH Key Pair: (b, g^b)

Certificate
CN: *.bob.com
Issuer: ca.com

Client
(Alice)

Server Finished

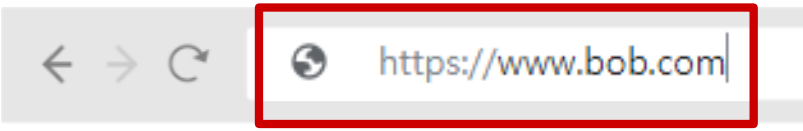
Server
(www.bob.com)

This is the **hash value** of our exchanged handshake messages (**Transcript**)
Please check if it is right!

Master Sec
0x#2

ecret:
#2gc2145

TLS Handshake Protocol in Detail



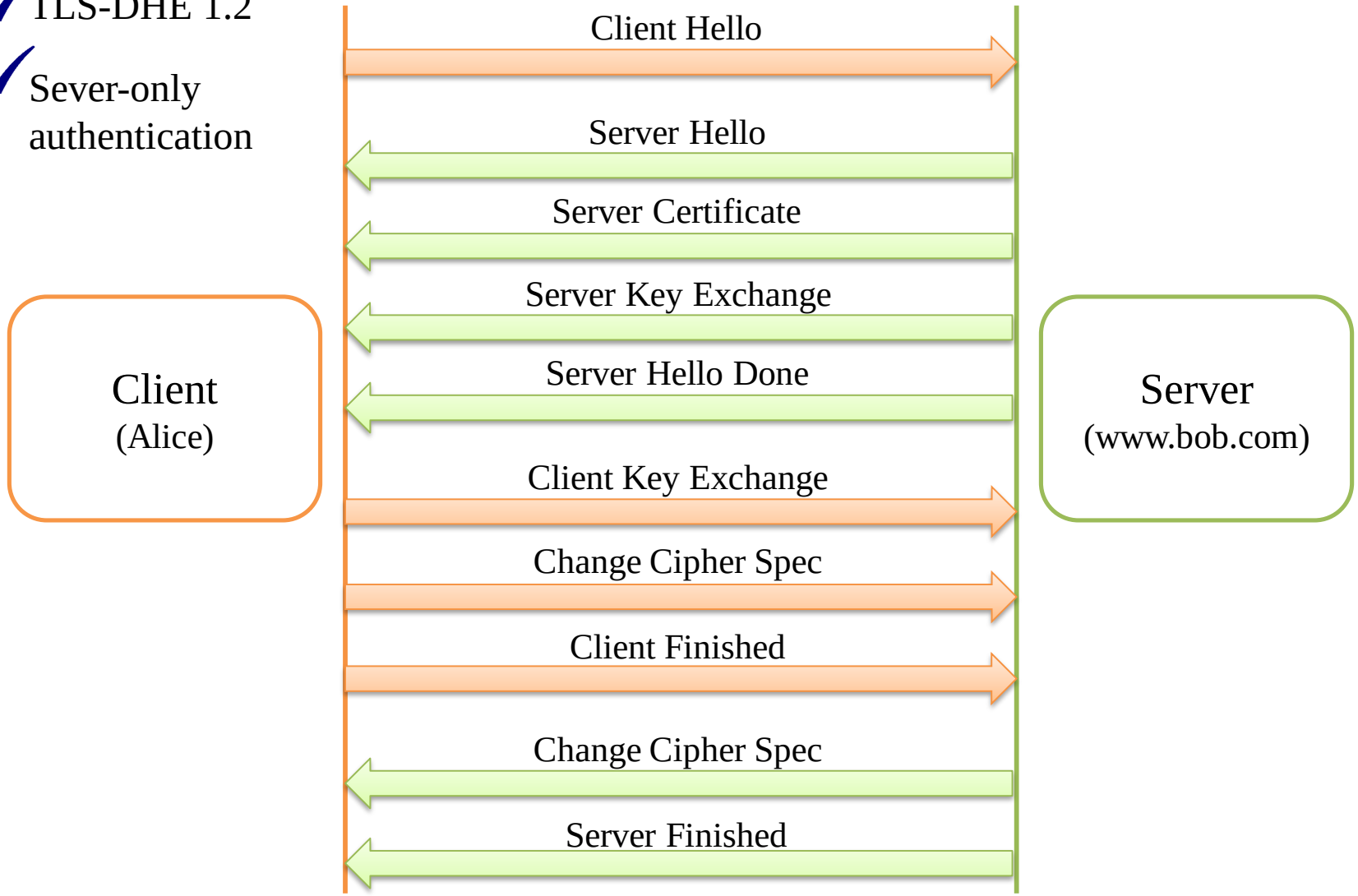
Client
(Alice)

Server
(www.bob.com)

TLS Handshake Protocol in Detail

Summary of TLS Handshake Protocol

- ✓ TLS-DHE 1.2
- ✓ Sever-only authentication



Summary of TLS Handshake Protocol

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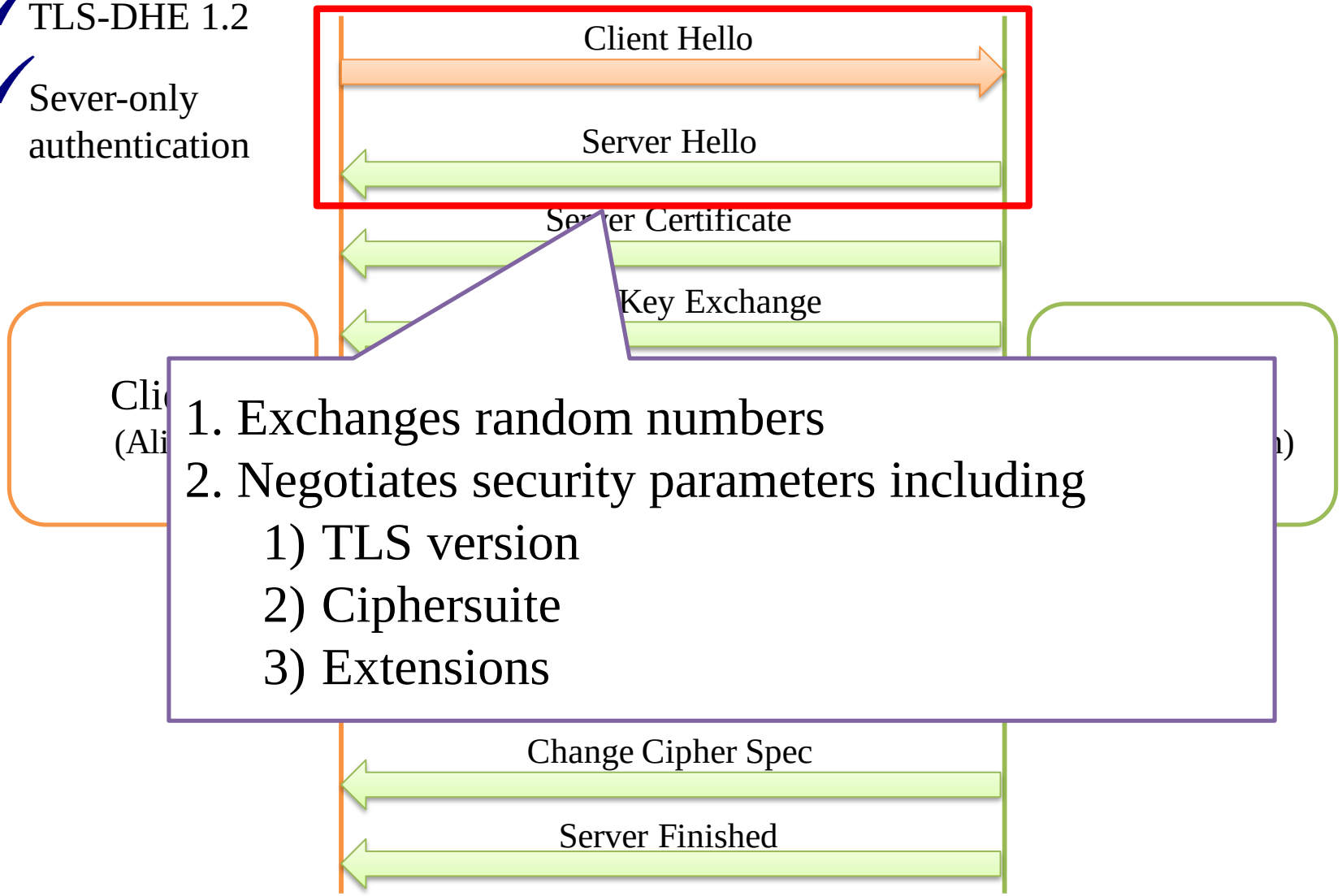
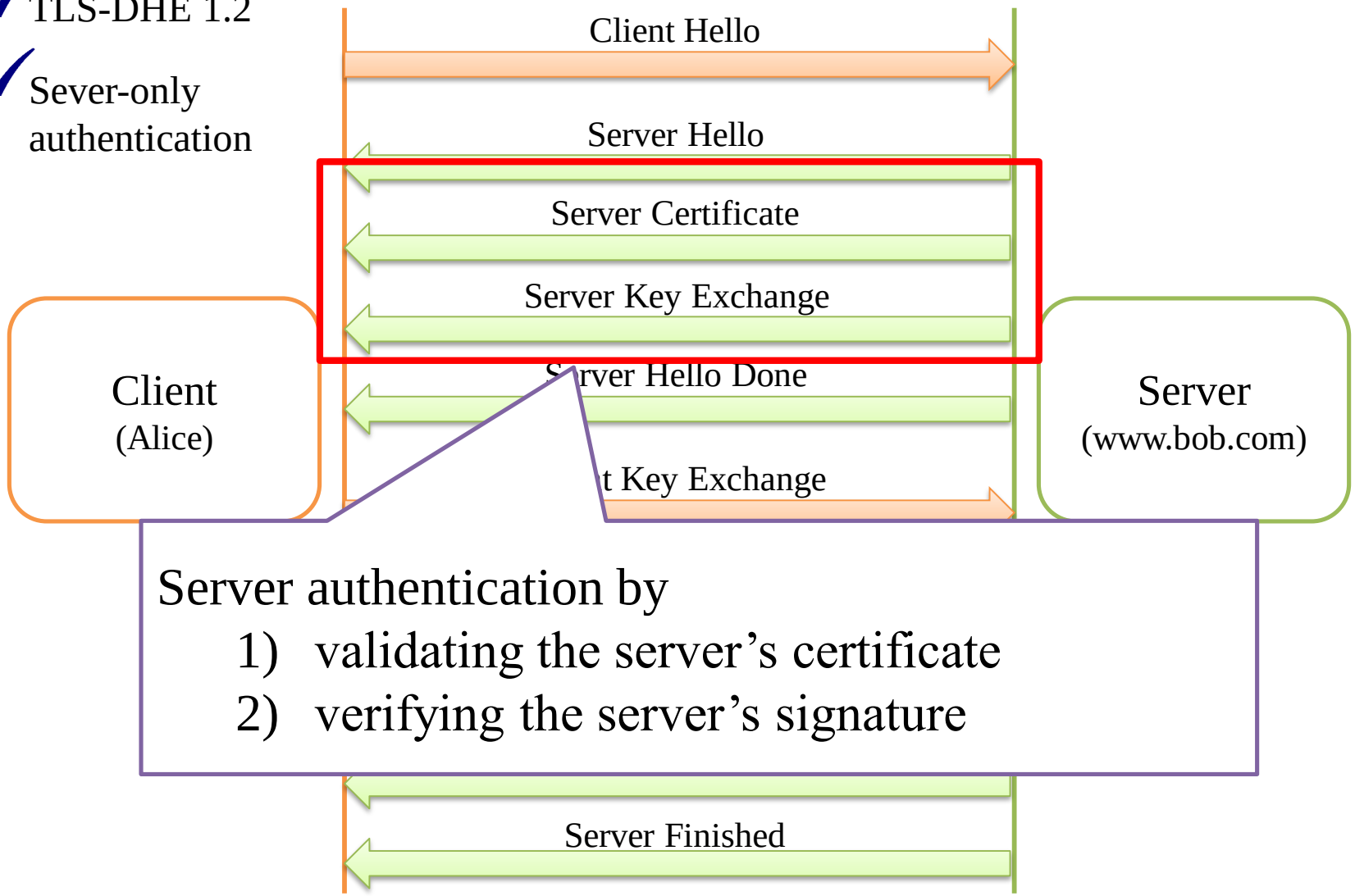


1. Exchanges random numbers
2. Negotiates security parameters including
   1) TLS version
   2) Ciphersuite
   3) Extensions

Summary of TLS Handshake Protocol

- ✓ TLS-DHE 1.2
- ✓ Sever-only authentication



Summary of TLS Handshake Protocol

- ✓ TLS-DHE 1.2
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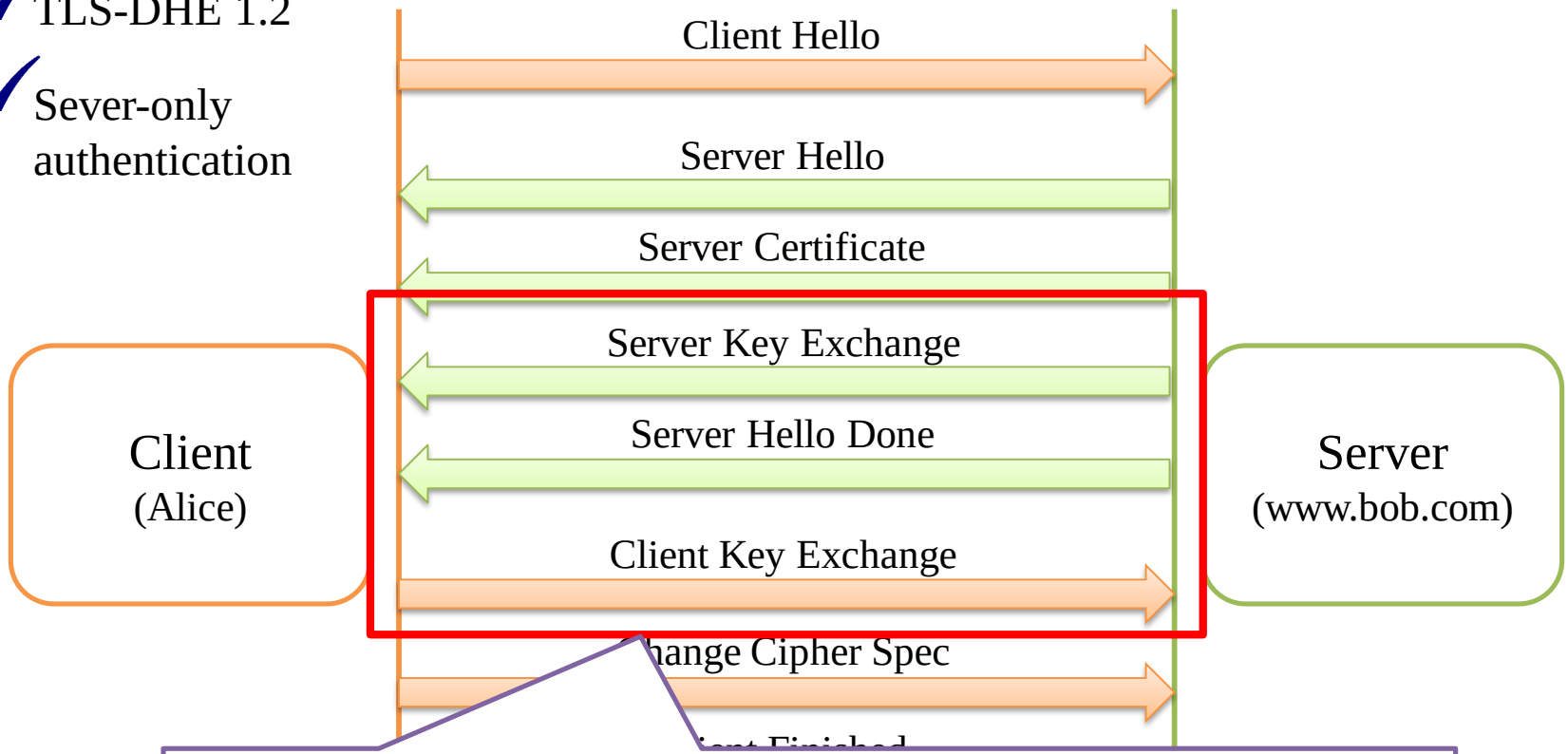
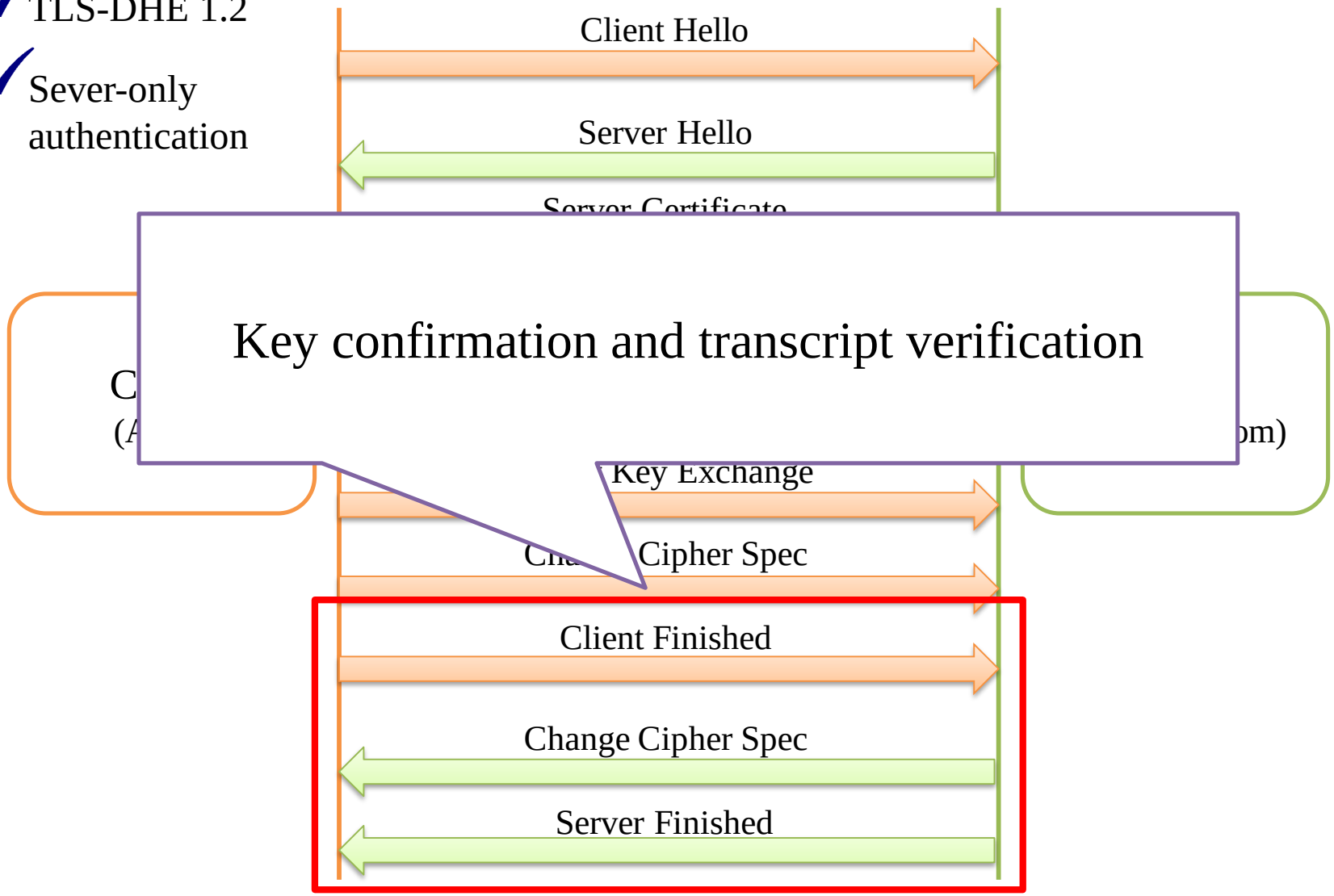


Key exchange and establishment
by using **Diffie-Hellman key exchange** algorithm

Summary of TLS Handshake Protocol

- ✓ TLS-DHE 1.2
- ✓ Sever-only authentication



TLS Record Protocol

Messages are ***authenticated encrypted*** with

- ✓ Confidentiality
- ✓ Integrity

2 Problems in TLS with Middleboxes

Middleboxes

Client
(Alice)

Server
(www.bob.com)

Middleboxes

- Web Application Firewalls
- Security Gateways
- Parental Controls

⋮

Middleboxes and Transport Layer Security

- Web Application Firewalls
- Security Gateways
- Parental Controls

⋮

Cannot work!

Motivation for SplitTLS

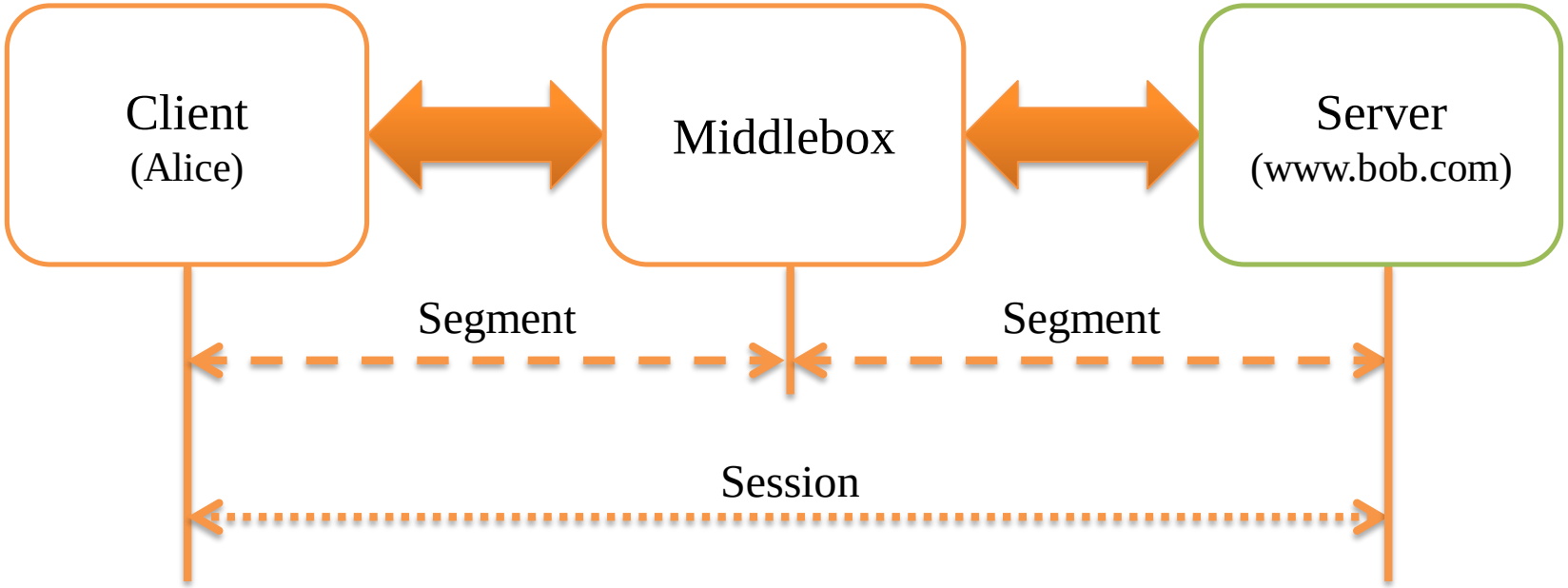
To perform their functions
Middleboxes **split** the TLS session

- Private key sharing
- Custom root certificate

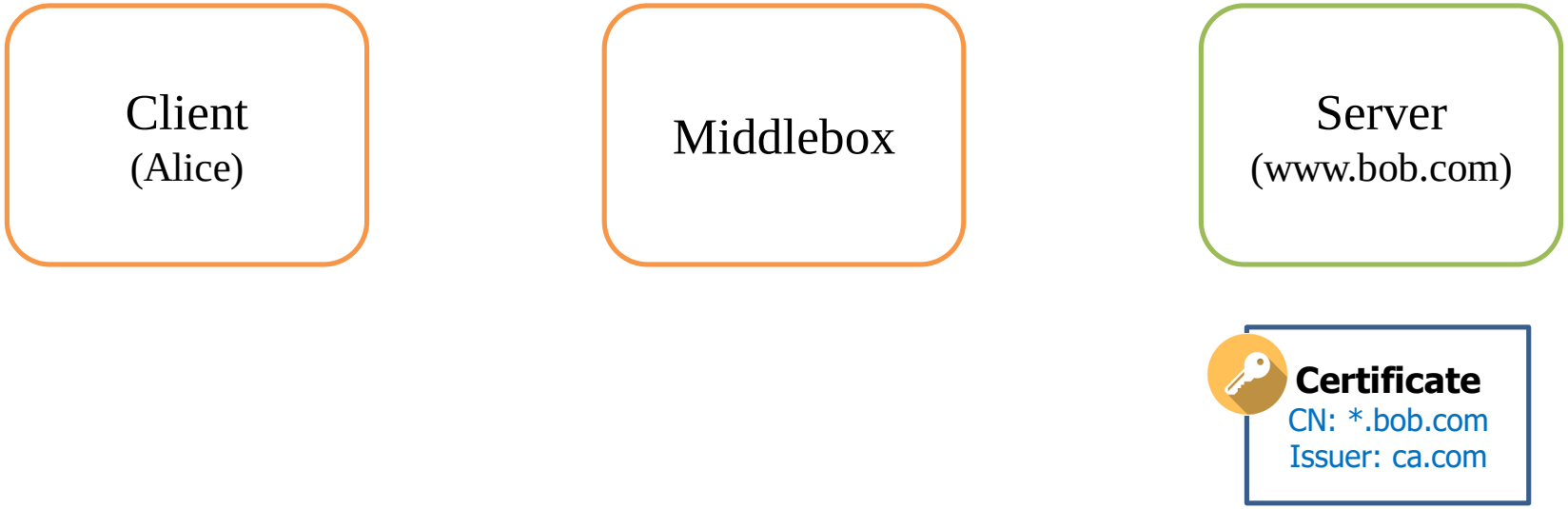
Session and Segment

To perform their functions
Middleboxes **split** the TLS session

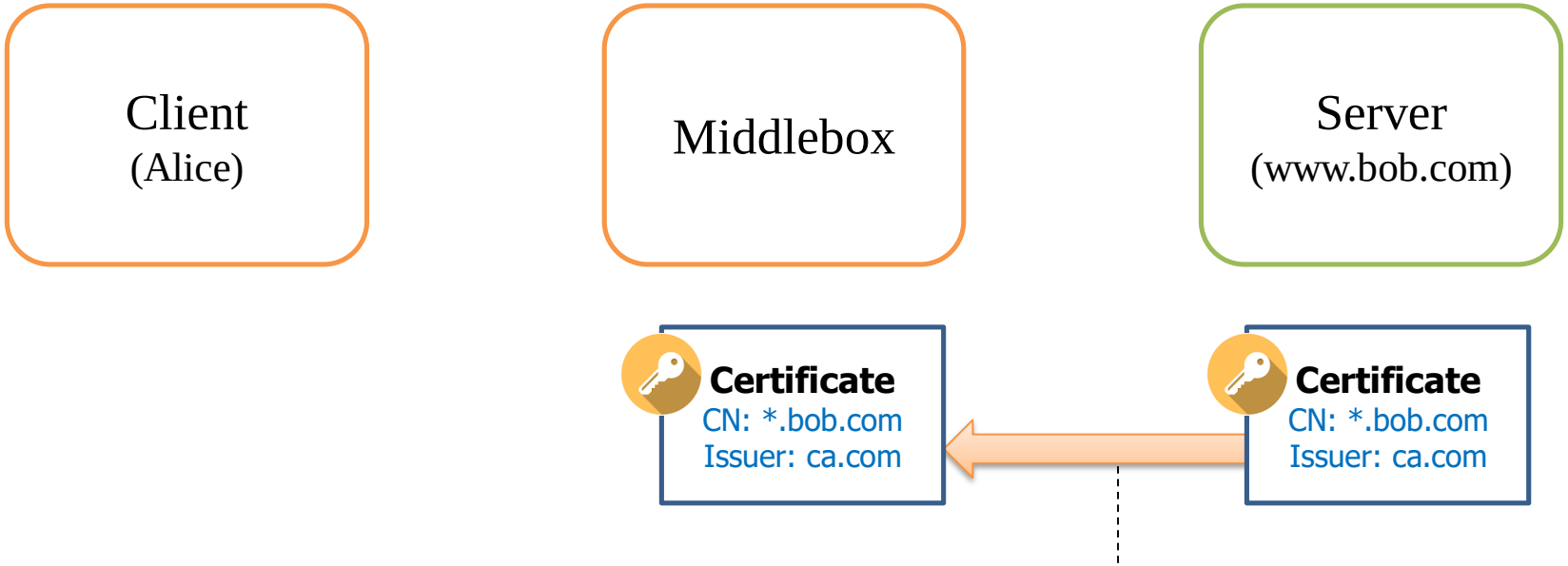
- Private key sharing
- Custom root certificate



SplitTLS (1) Private Key Sharing

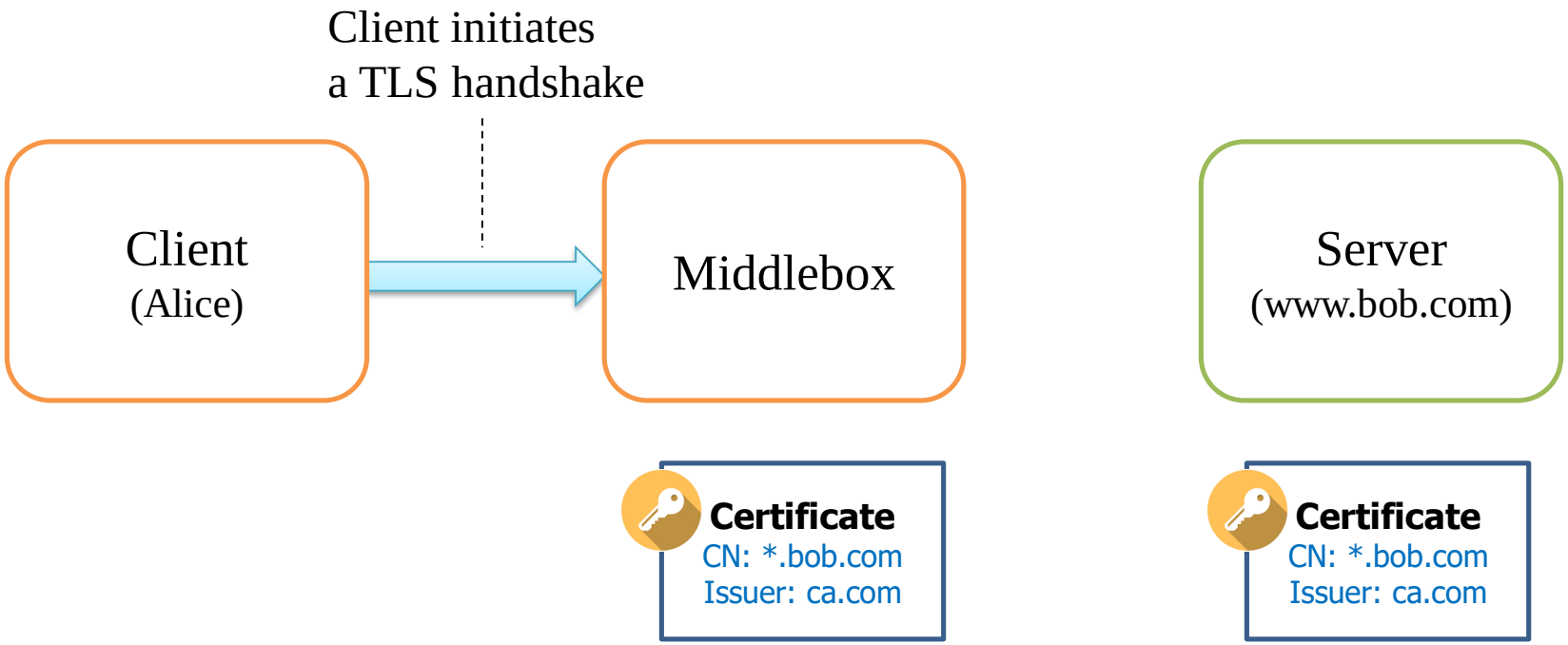


SplitTLS (1) Private Key Sharing

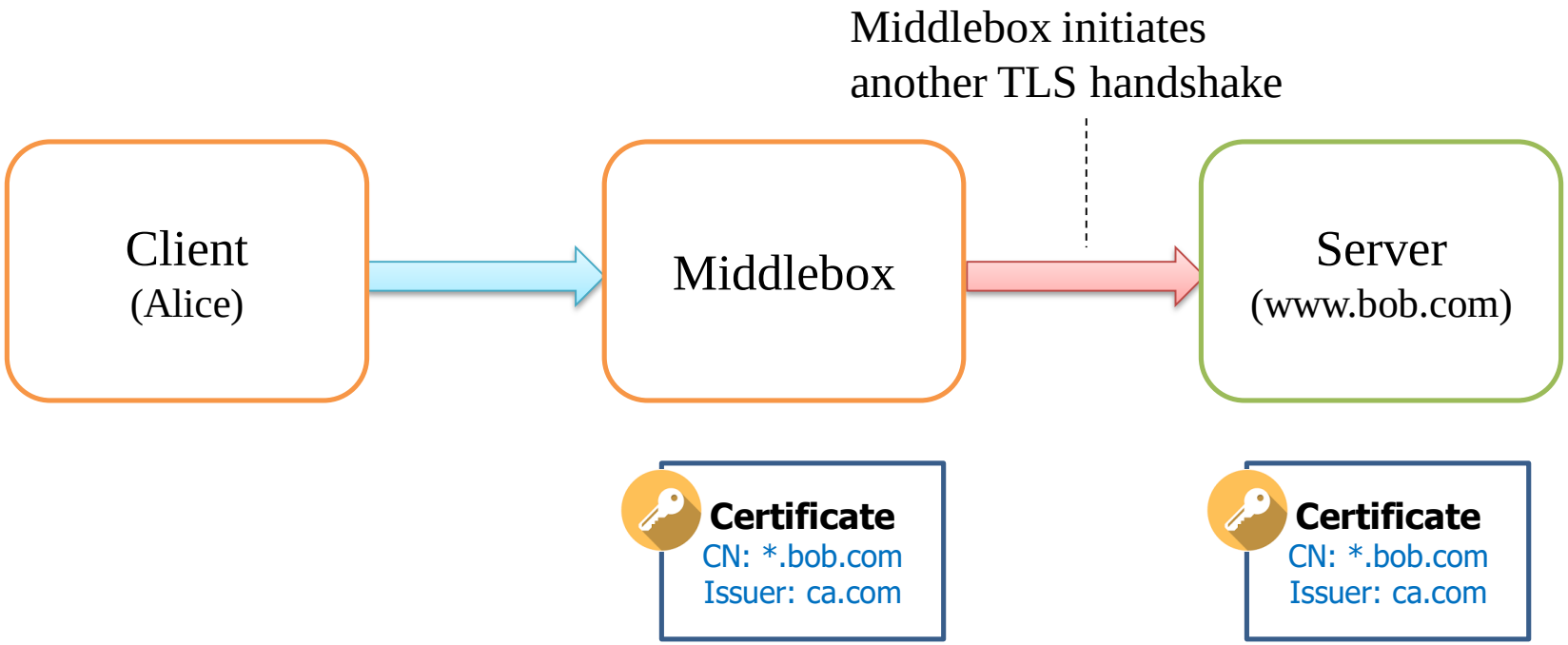


Server **transfers**
their private key and certificate

SplitTLS (1) Private Key Sharing

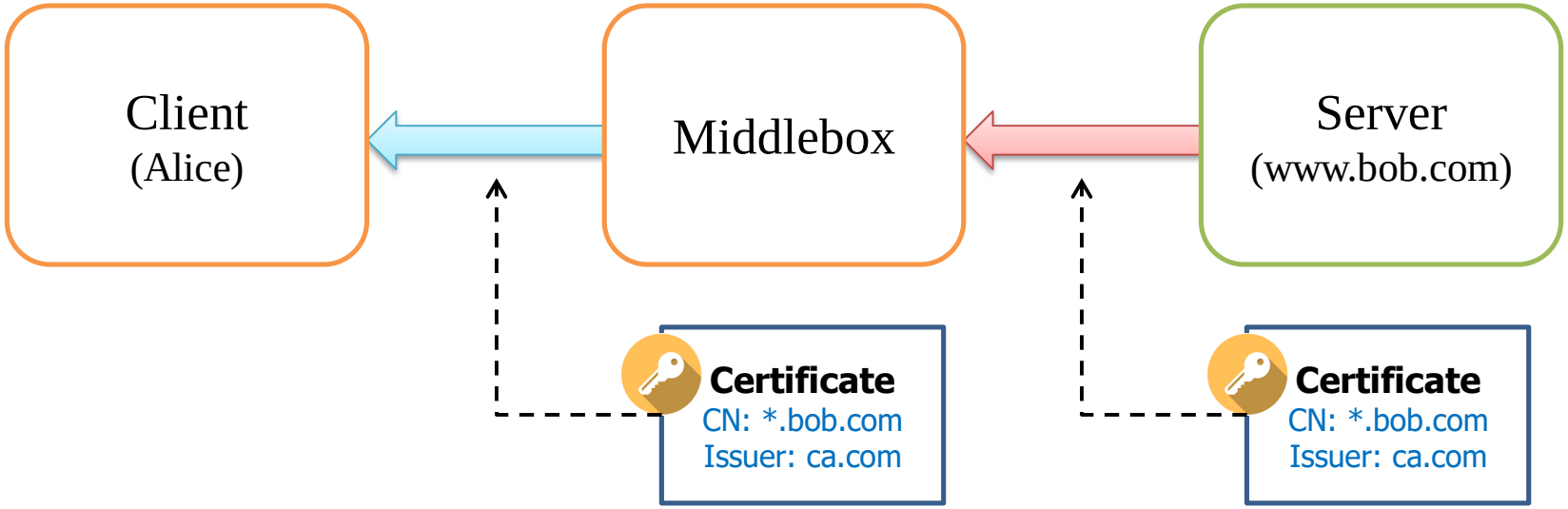


SplitTLS (1) Private Key Sharing



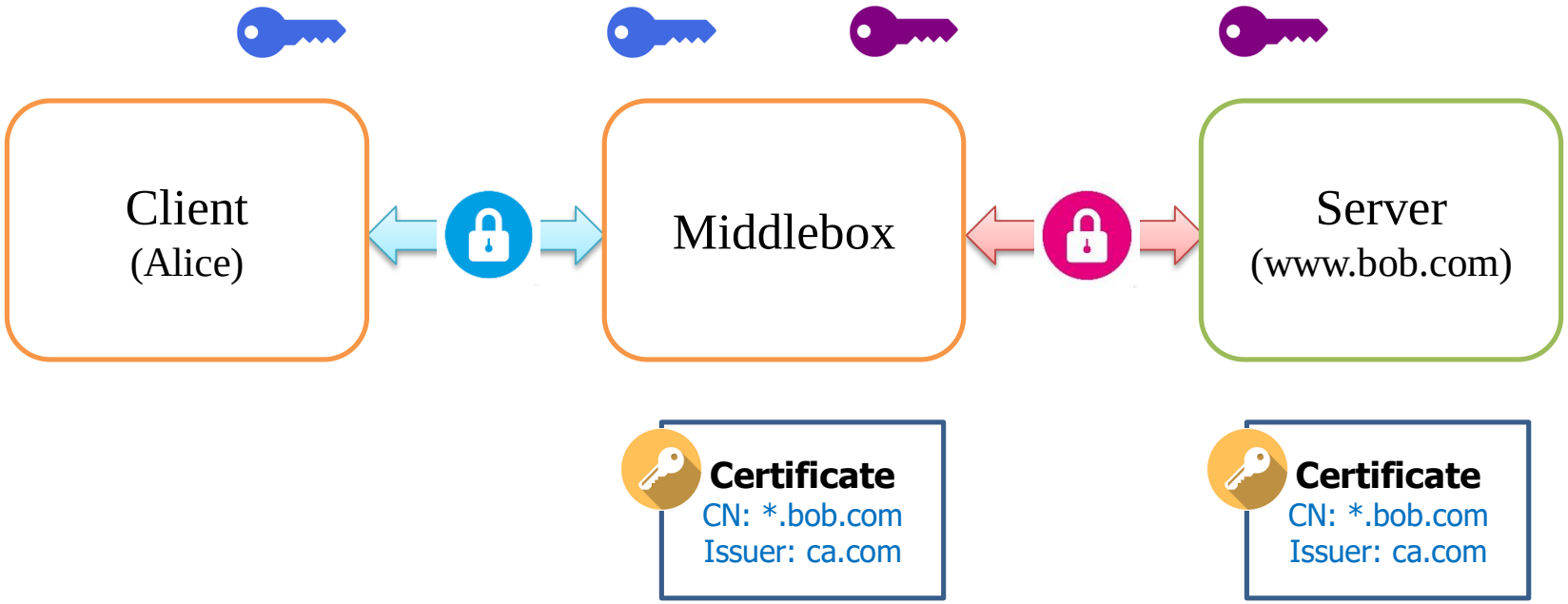
SplitTLS (1) Private Key Sharing

Middlebox **impersonates** Server with the **tranferred** key pair



SplitTLS (1) Private Key Sharing

Client believes they have established a TLS session **with Server**, **not Middlebox!**



SplitTLS (2) Custom Root Certificate

Client
(Alice)

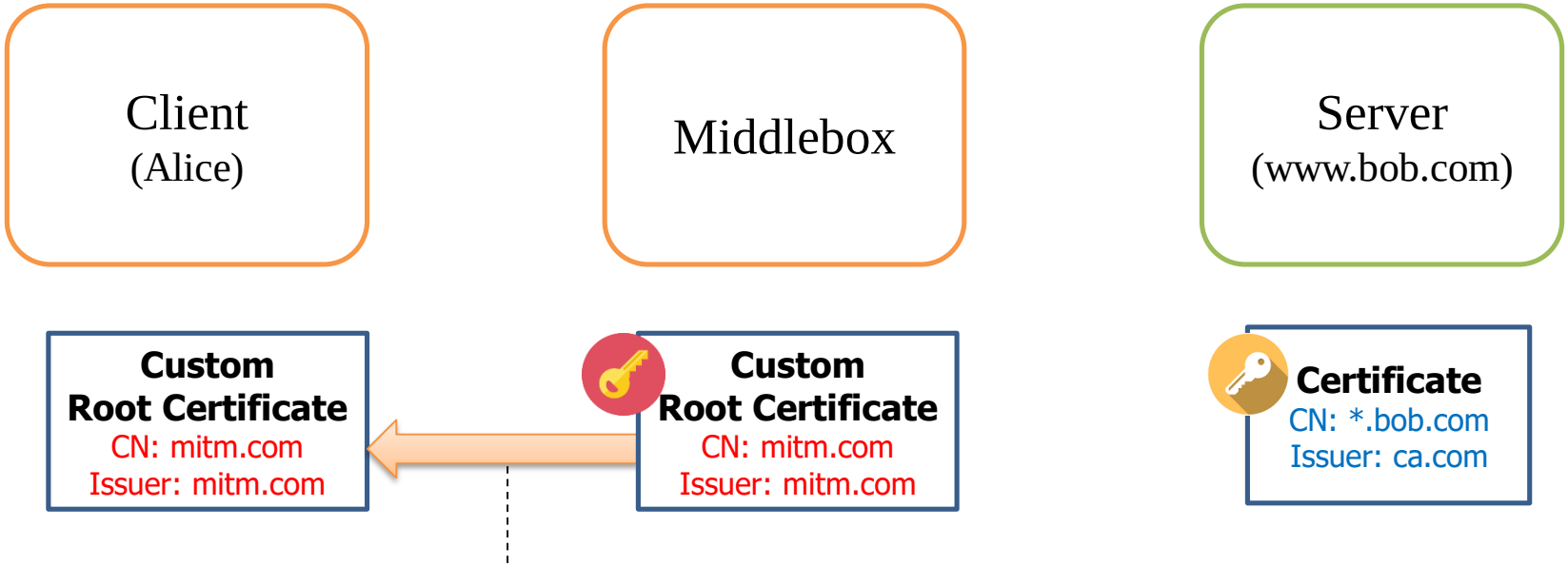
Middlebox

Server
(www.bob.com)

Custom Root Certificate
CN: mitm.com
Issuer: mitm.com

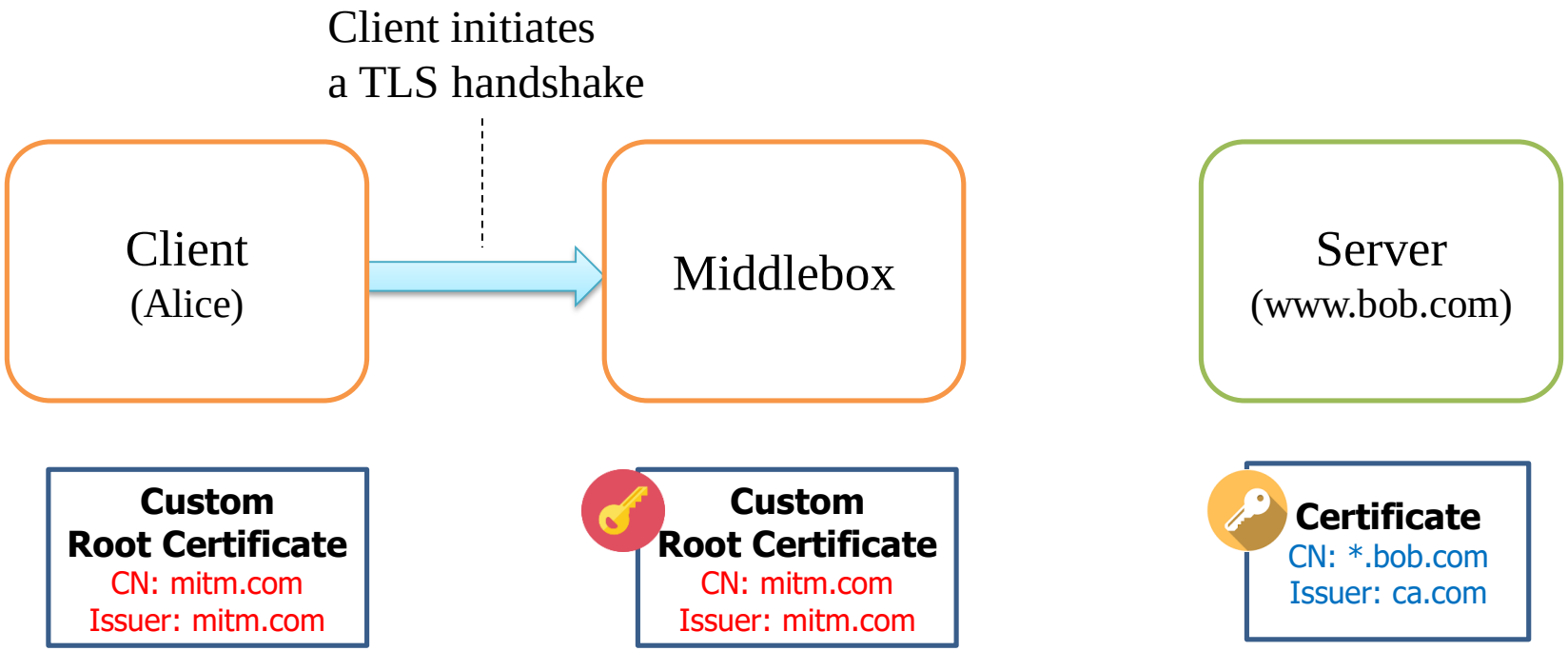
Certificate
CN: *.bob.com
Issuer: ca.com

SplitTLS (2) Custom Root Certificate

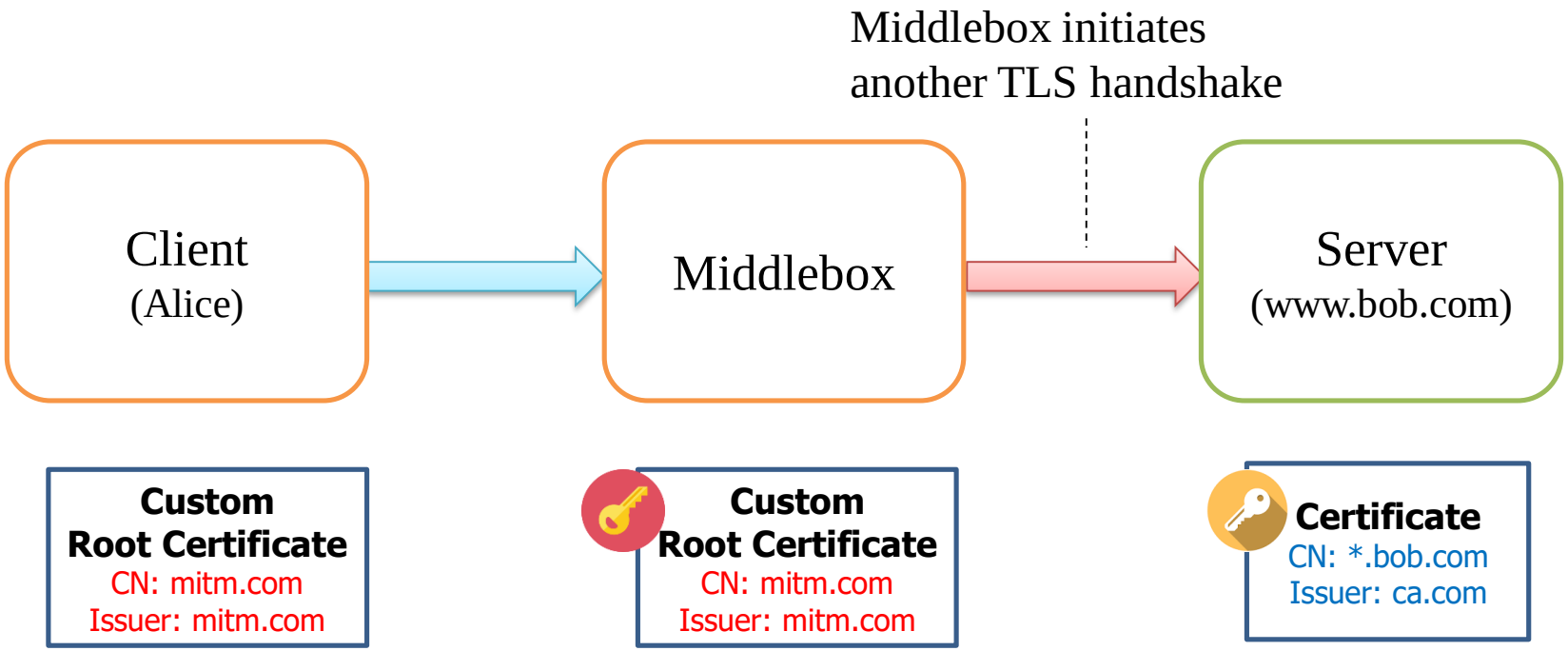


Middlebox **installs**
a root certificate in the client

SplitTLS (2) Custom Root Certificate

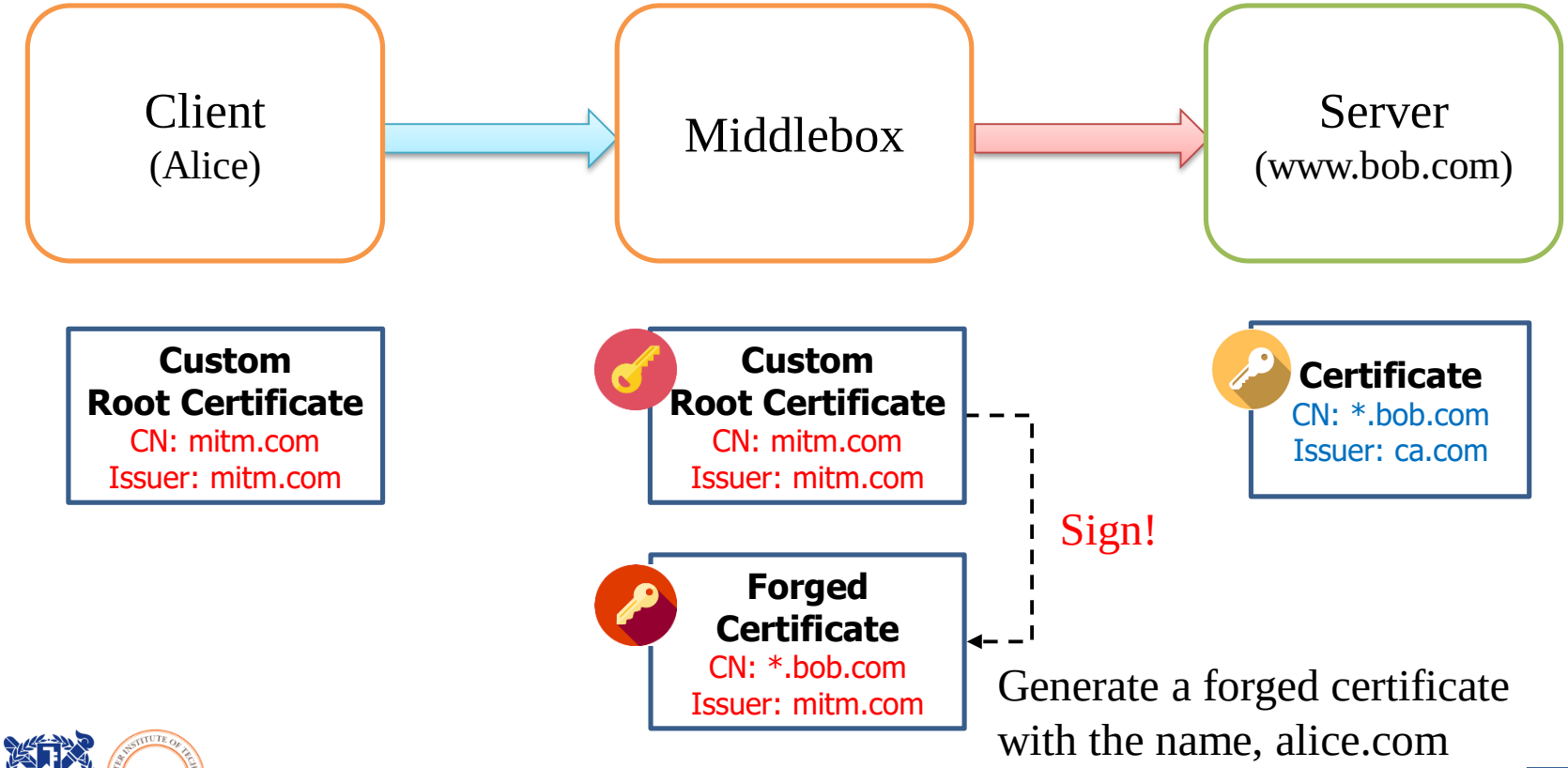


SplitTLS (2) Custom Root Certificate

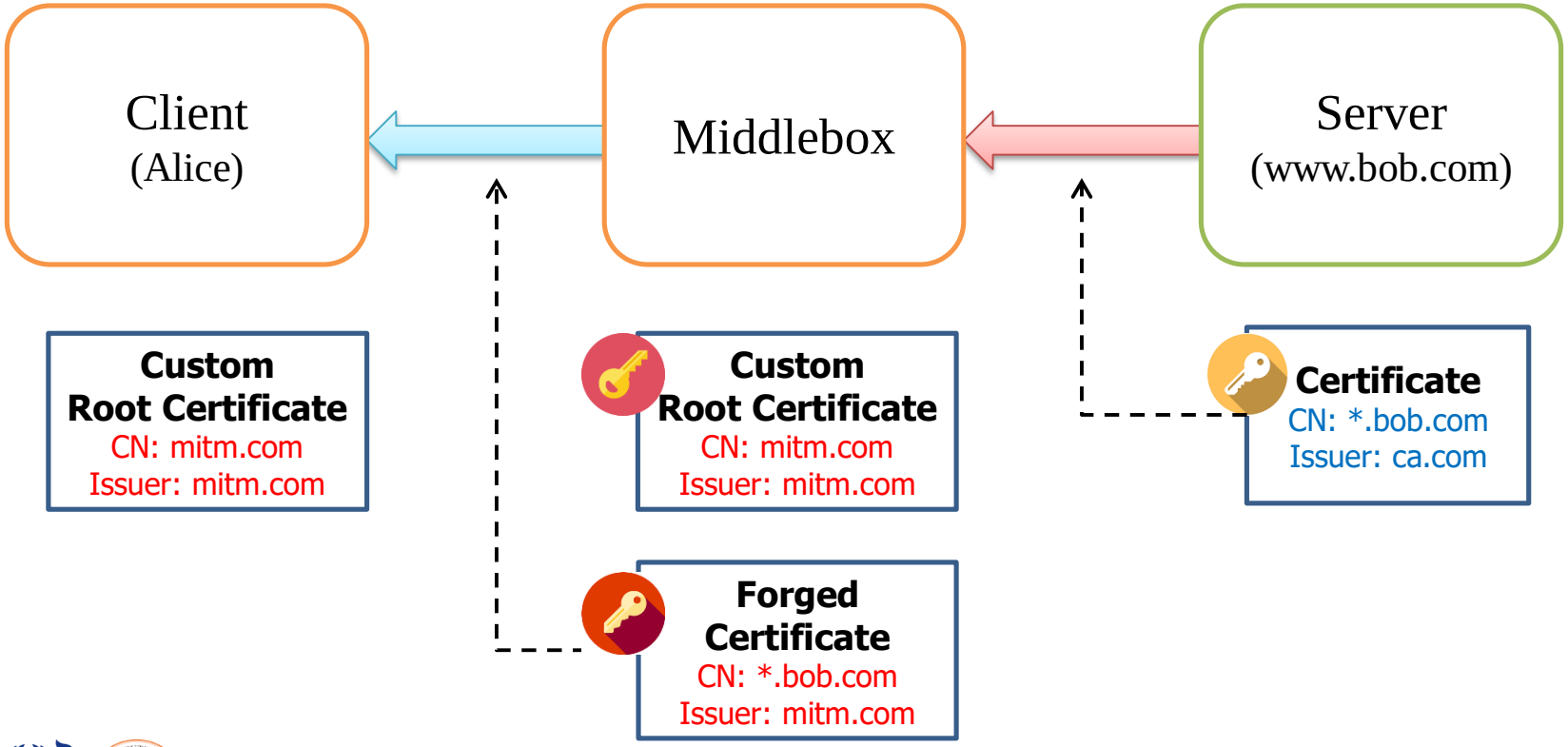


SplitTLS (2) Custom Root Certificate

Middlebox **impersonates** Server with the **forged** key pair

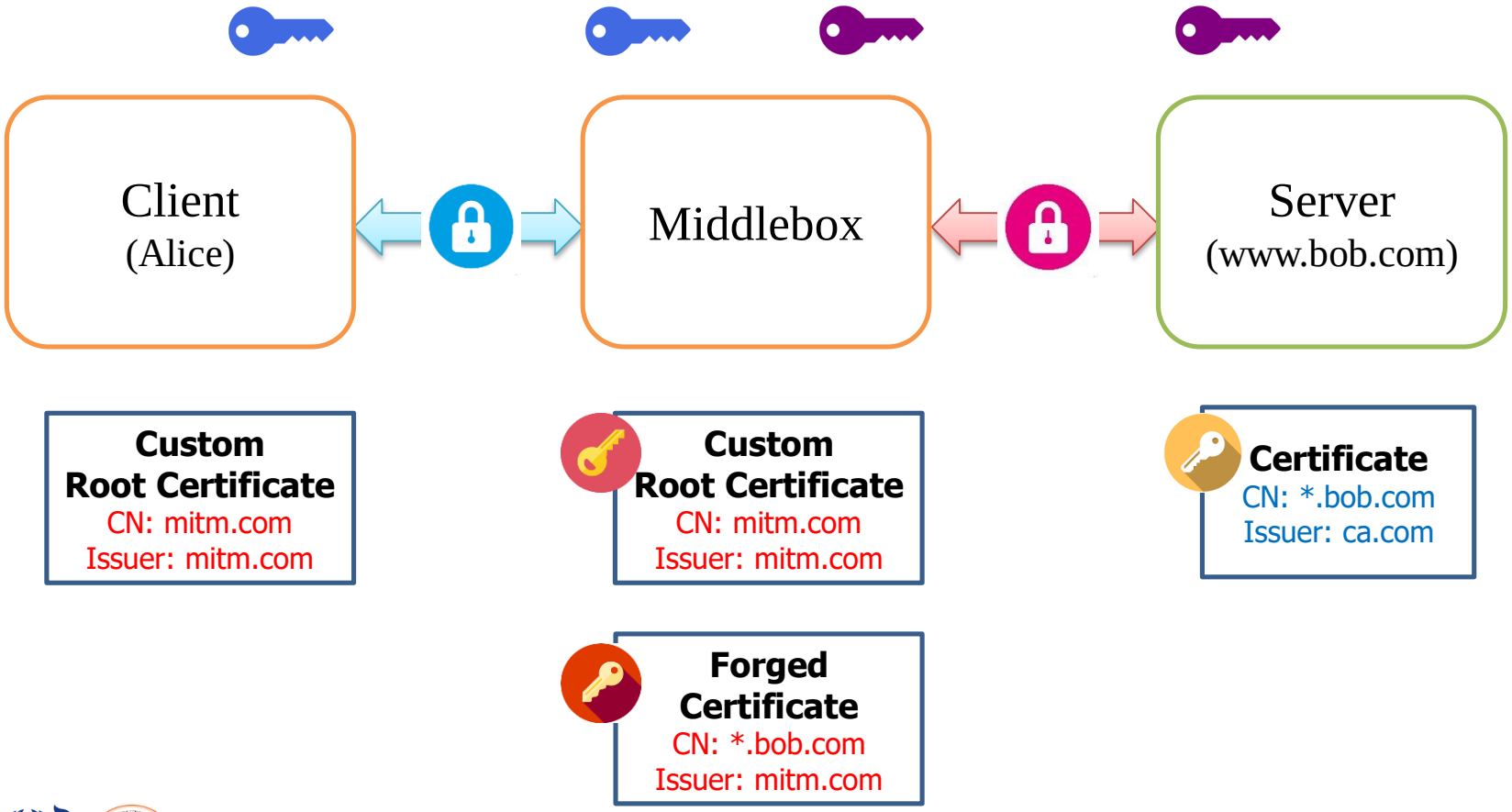


SplitTLS (2) Custom Root Certificate

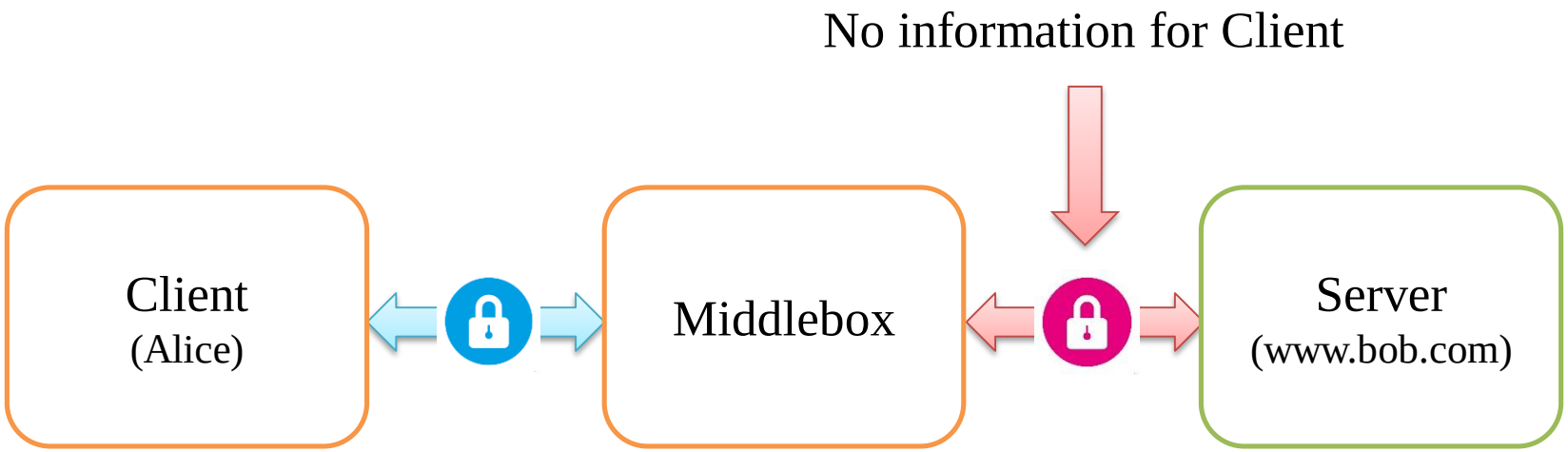


SplitTLS (2) Custom Root Certificate

Client believes they have established a TLS session **with Server**, **not Middlebox!**



Problems in SplitTLS

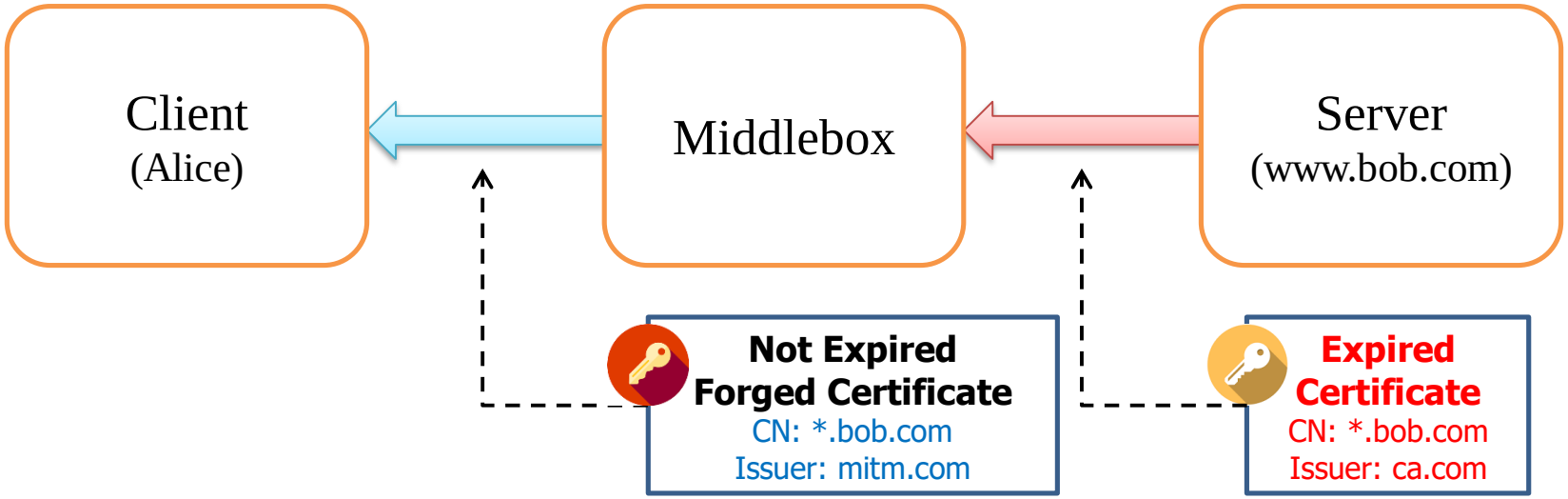


- Killed by Proxy: Analyzing Client-end TLS Interception Software (NDSS `16)
- The Security Impact of HTTPS Interception (NDSS `17)
- To Intercept or Not to Intercept: Analyzing TLS Interception in Network Appliances (AsiaCCS `18)

Problems in SplitTLS - Authentication

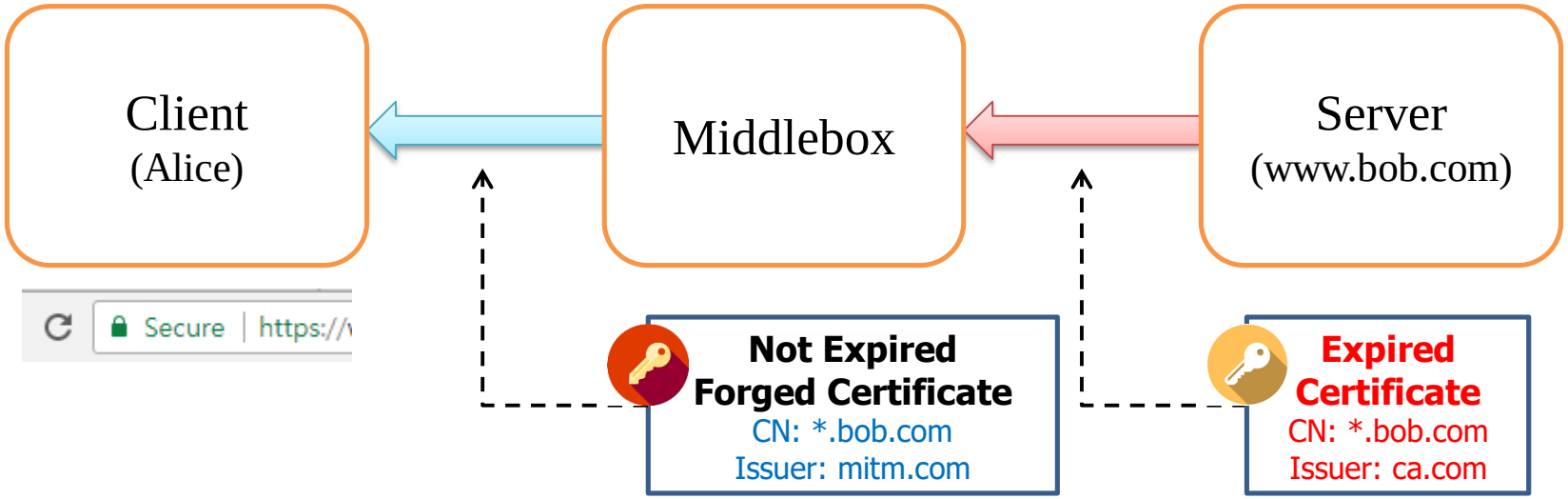
Authentication Client does not authenticate Server

Problems in SplitTLS - Authentication



Authentication Client does not authenticate Server

Problems in SplitTLS - Authentication



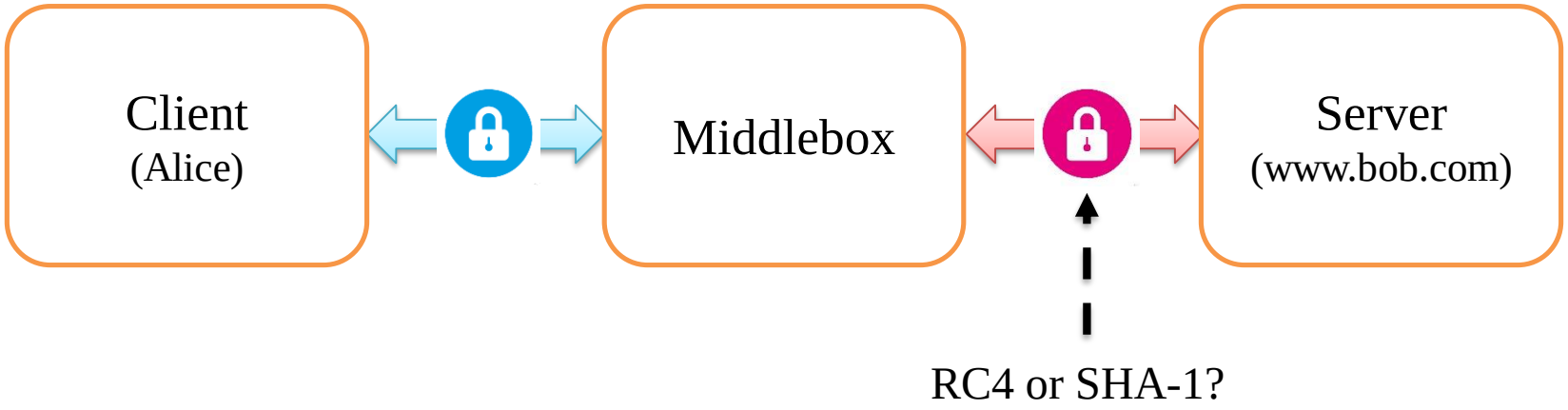
Authentication Client does not authenticate Server

Problems in SplitTLS - Confidentiality

Authentication Client does not authenticate Server

Confidentiality Client does not know whether or not the segment is encrypted with a strong ciphersuite

Problems in SplitTLS - Confidentiality



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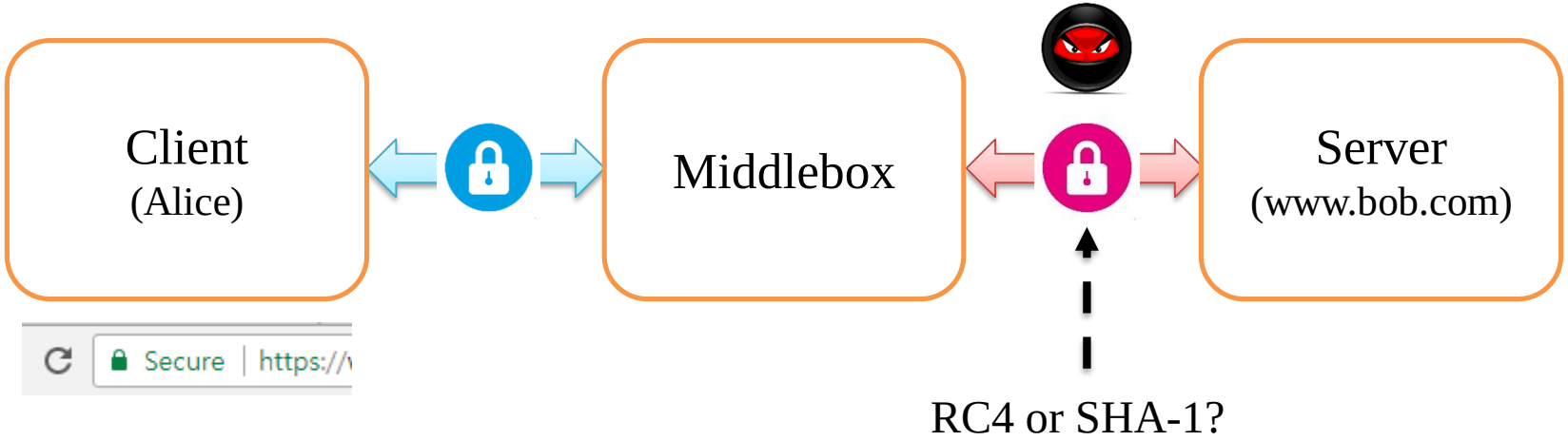
Problems in SplitTLS - Confidentiality



Authentication Client does not authenticate Server

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Problems in SplitTLS - Integrity

Authentication — Client does not authenticate Server

Confidentiality — Client does not know whether or not the segment is encrypted with a strong ciphersuite

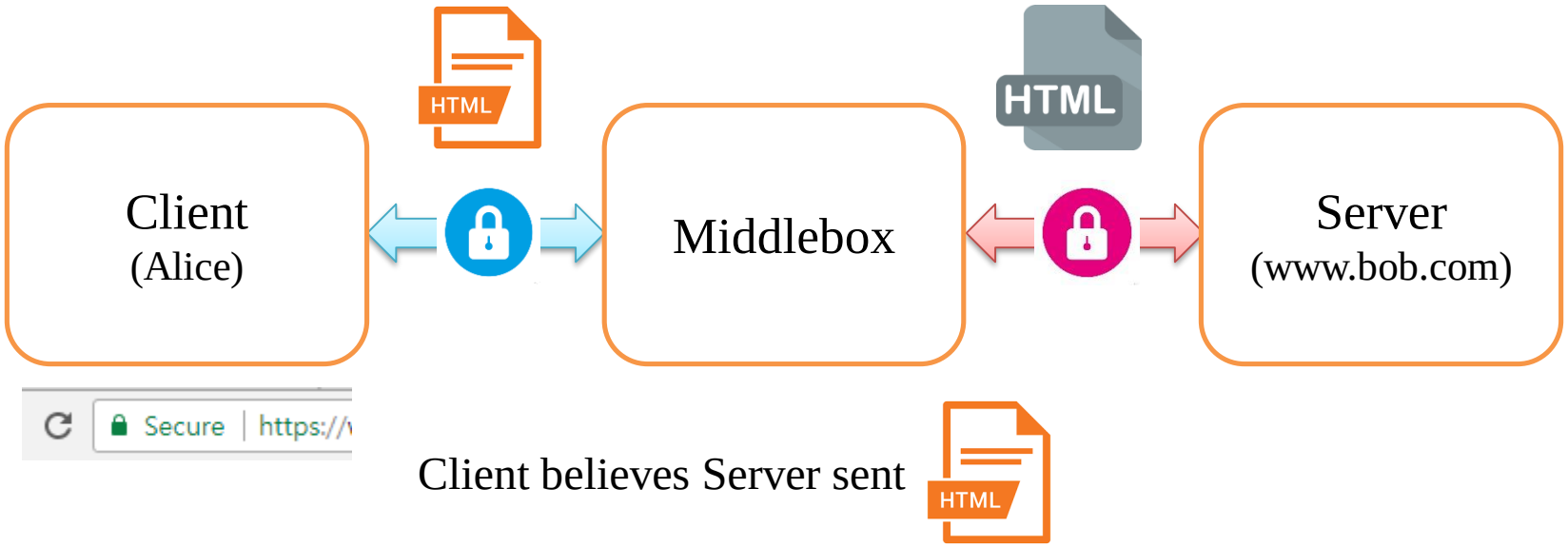
Integrity — Client cannot confirm that Server sent the message, or which middleboxes have modified it

Problems in SplitTLS - Integrity

Middlebox inserts the unwanted script!

Authentication	Client does not authenticate Server
Confidentiality	Client does not know whether or not the segment is encrypted with a strong ciphersuite
Integrity	Client cannot confirm that Server sent the message, or which middleboxes have modified it

Problems in SplitTLS - Integrity



Authentication — Client does not authenticate Server

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3 Middlebox-aware TLS (maTLS) with Auditable Middleboxes

Goal: Middlebox-aware TLS (maTLS)

Establish a secure session *with middleboxes*
as well as overcoming the challenges in SplitTLS

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	Problems in SplitTLS	Solution in maTLS
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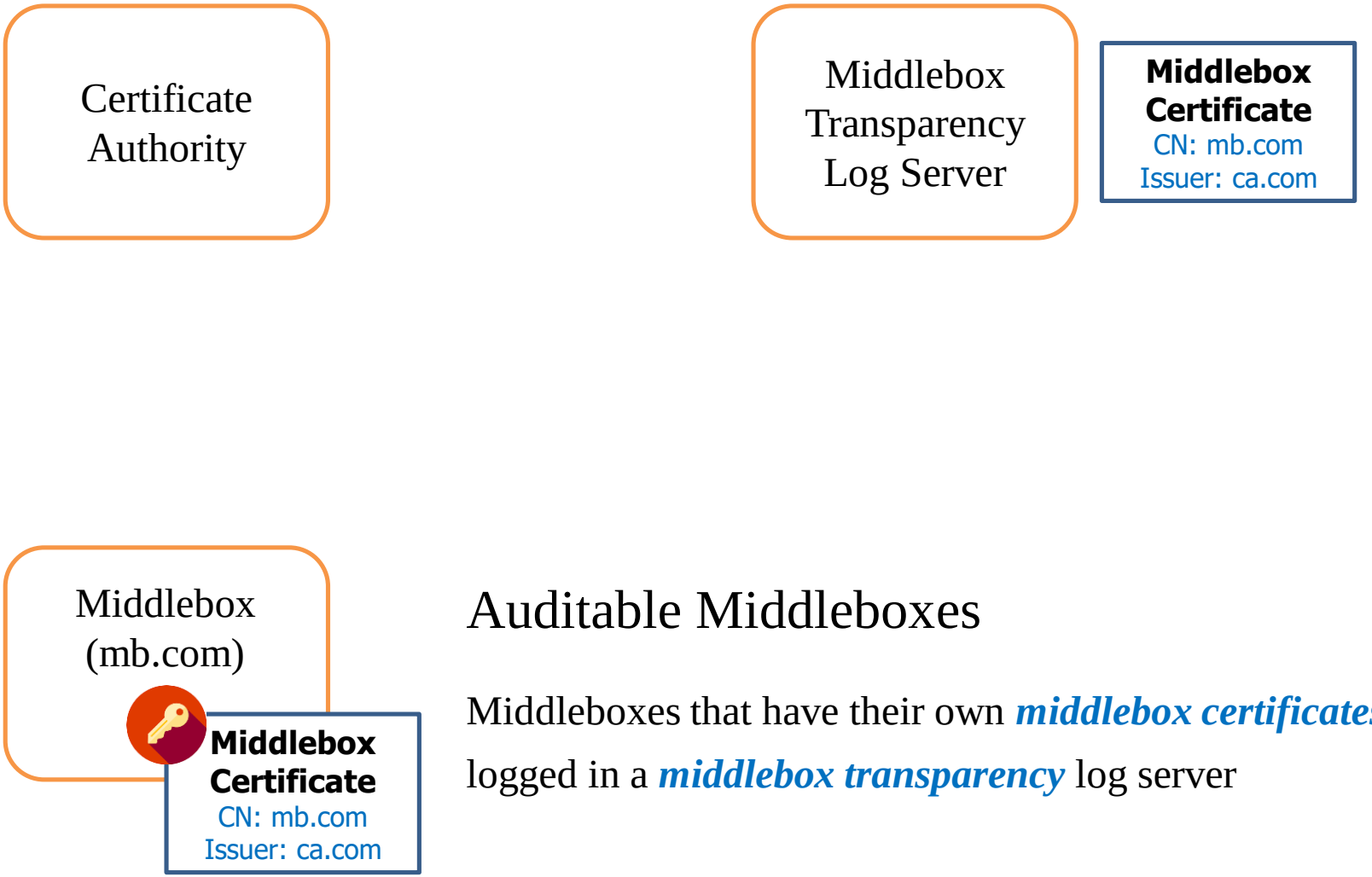
Authentication	Client cannot authenticate Server (as well as Middlebox)	Explicit Authentication
Confidentiality	Client cannot know if each of the segments has been encrypted with strong ciphersuites	Security Parameter Verification
Integrity	Client cannot confirm (1) who actually sent the message (2) and whether it has been modified	Valid Modification Checks

Auditable Middleboxes



Auditable Middleboxes

Middleboxes that have their own ***middlebox certificates*** logged in a ***middlebox transparency*** log server

Auditable Middleboxes

Certificate Authority

Middlebox Certificate
CN: mb.com
Issuer: ca.com

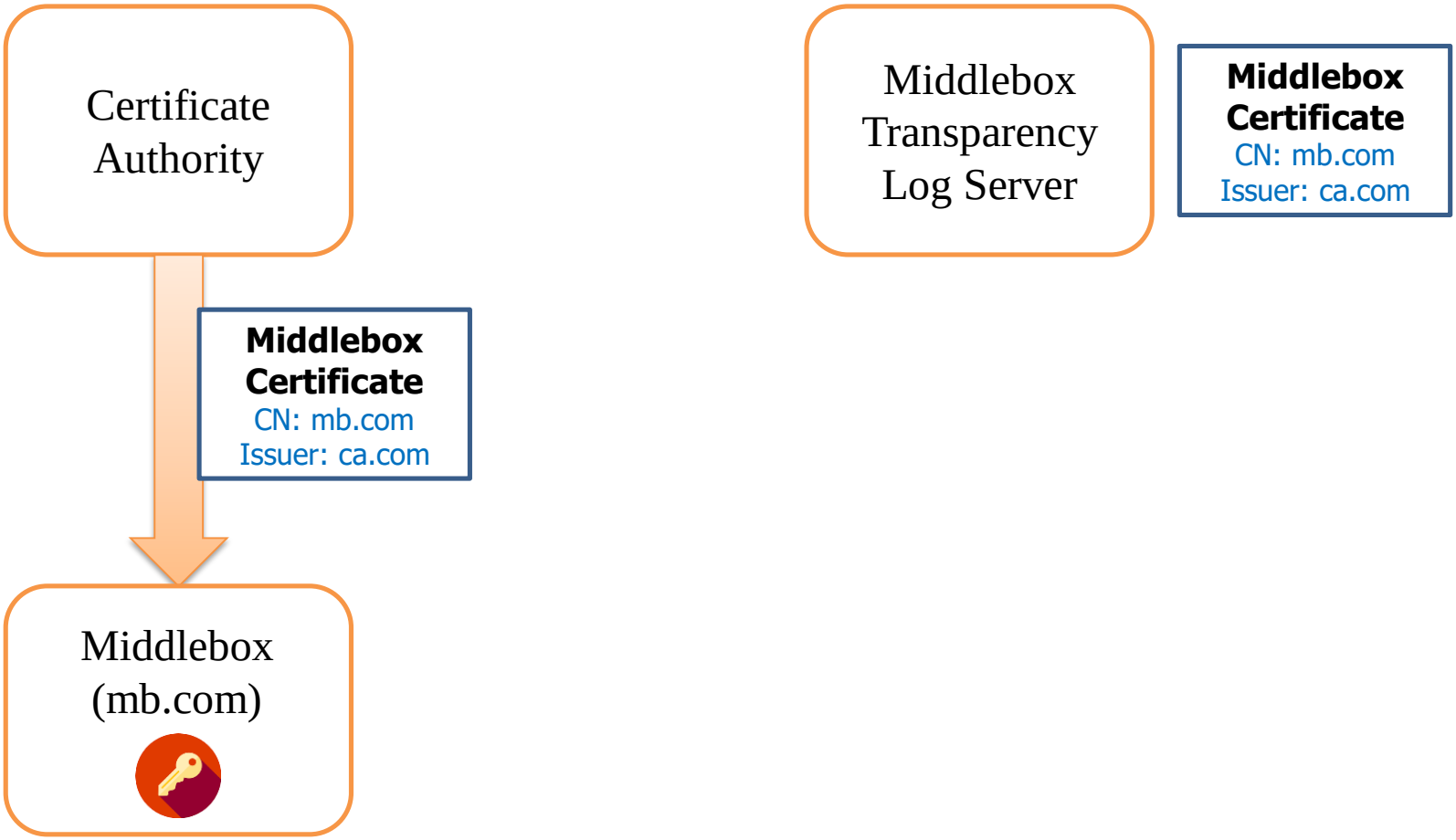
Middlebox Transparency Log Server

Information about Middlebox

- Type of Service
- URL
- Permission

Middlebox (mb.com)

Auditable Middleboxes



Advantages of Auditable Middleboxes

- No impersonation
- Awareness
- Auditability
- Revocability

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- No impersonation

  Middleboxes now have their ***own key pairs*** and do not need to impersonate others (in TLS)

- Awareness

- Auditability

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  Anyone can know the name and properties of a middlebox from its ***middlebox certificate***

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  Any interested parties can check for fraudulent certificates using the ***middlebox transparency*** system

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Awareness

Anyone can know the name and properties of a middlebox from its ***middlebox certificate***

Auditability

Any interested parties can check for fraudulent certificates using the ***middlebox transparency*** system

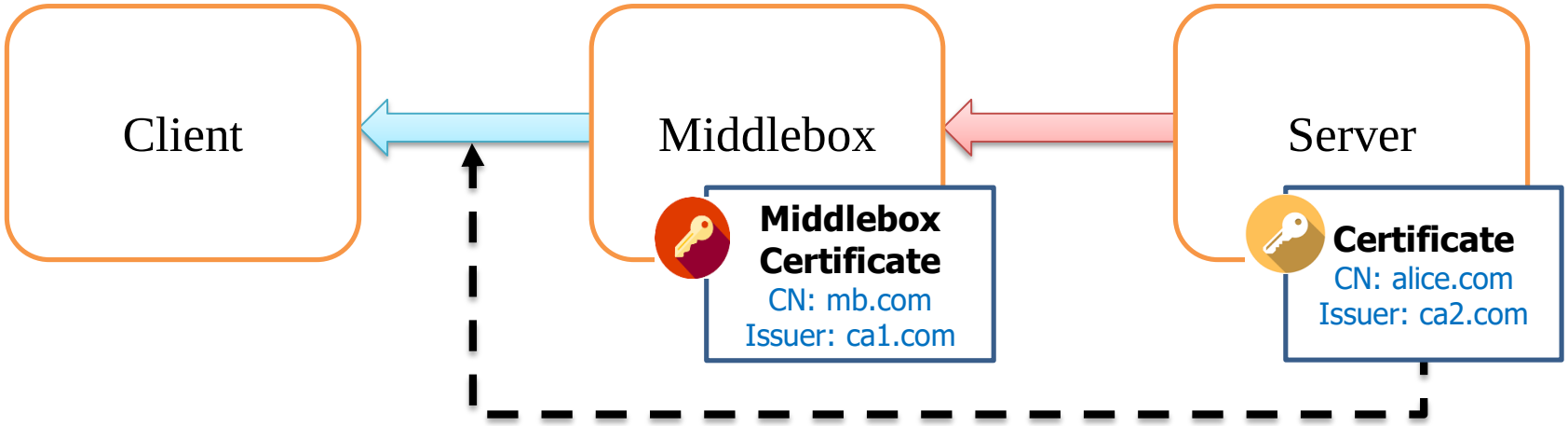
Revocability

Any incorrect middleboxes can be blocked following the ***certificate revocation mechanisms*** (e.g., CRL or OCSP)

Security Goals of maTLS

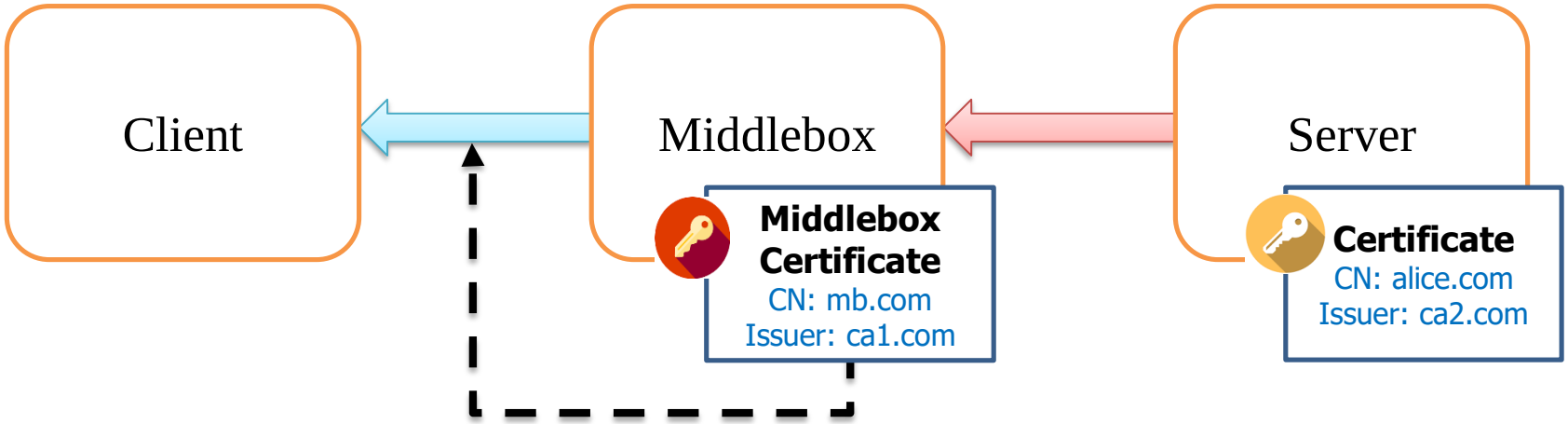
- ✓ Server Authentication
- ✓ Middlebox Authentication
- ✓ Segment Secrecy
- ✓ Individual Secrecy
- ✓ Data Source Authentication
- ✓ Modification Accountability
- ✓ Path Integrity

Security Goals of maTLS - Authentication



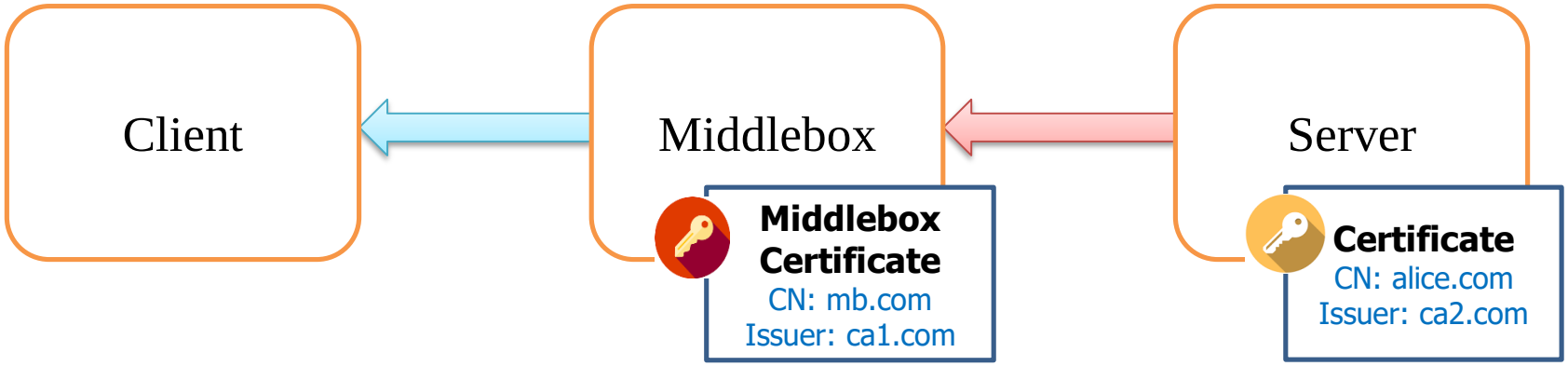
✓ Server Authentication

Security Goals of maTLS - Authentication



- ✓ Server Authentication
- ✓ Middlebox Authentication

Audit Mechanism for Authentication



- ✓ Server Authentication
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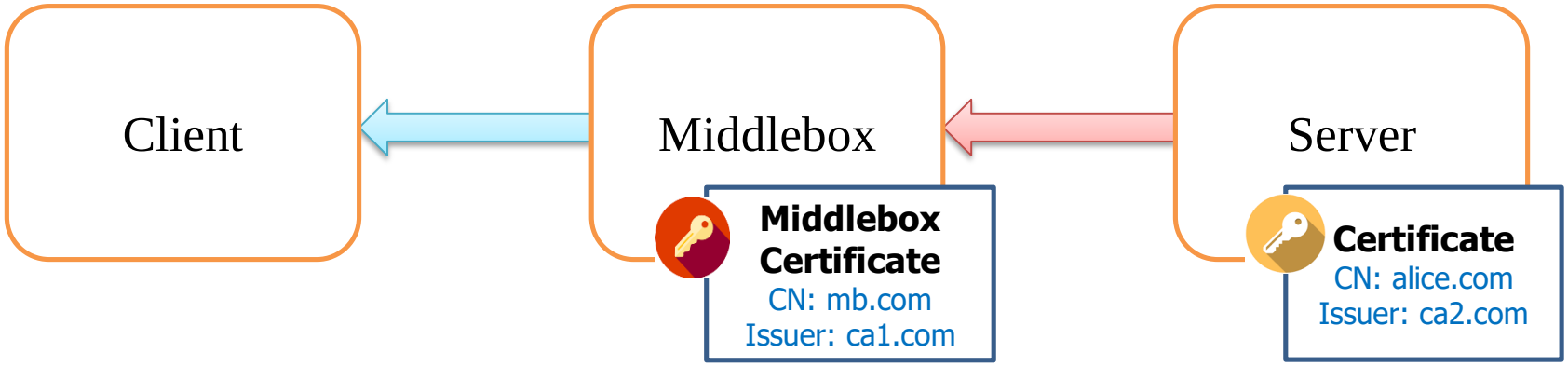
→ Explicit Authentication

Explicit Authentication

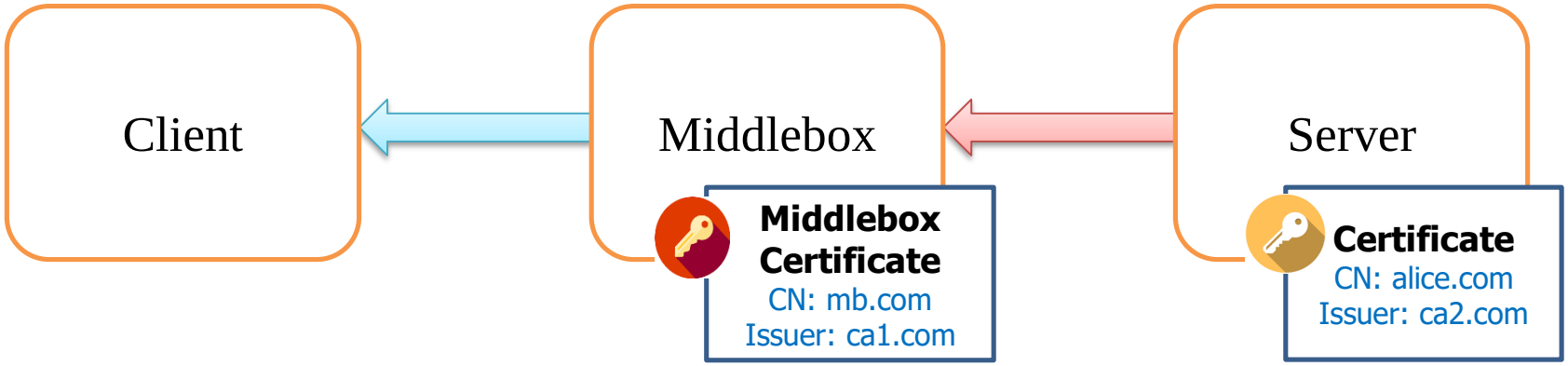


Certificate Blocks

Each entity sends its certificate (with its signed certificate timestamp)

No impersonation

Explicit Authentication



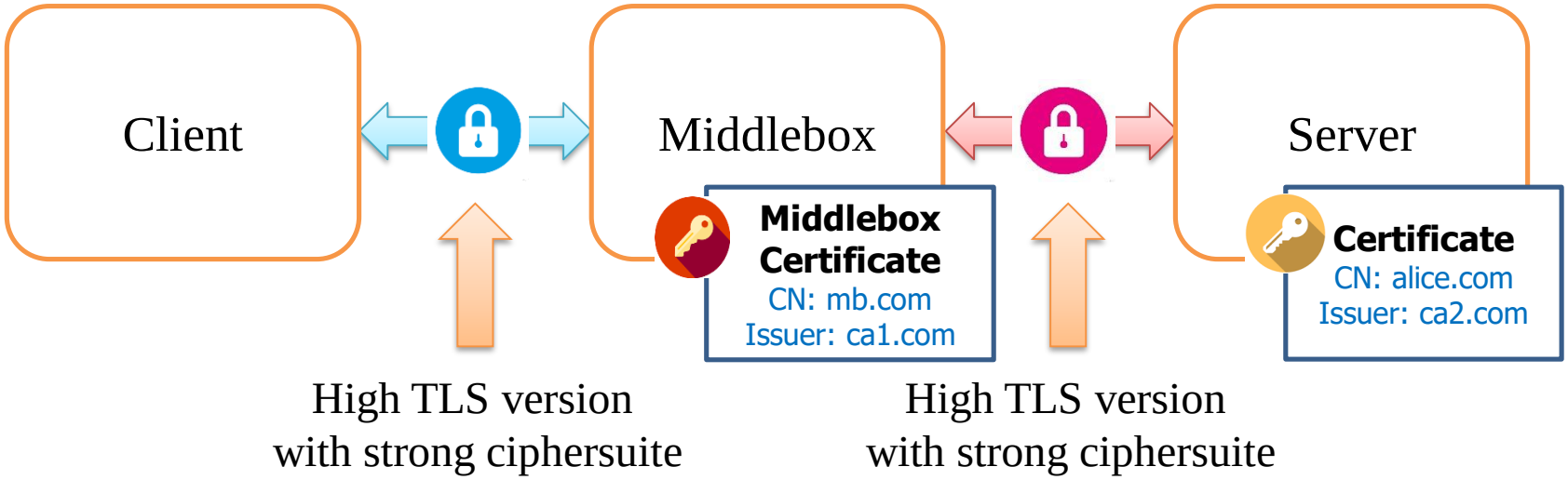
Certificate Blocks

Each entity sends its certificate (with its signed certificate timestamp)

- No impersonation
- EV certificates, DANE, and CT can be supported

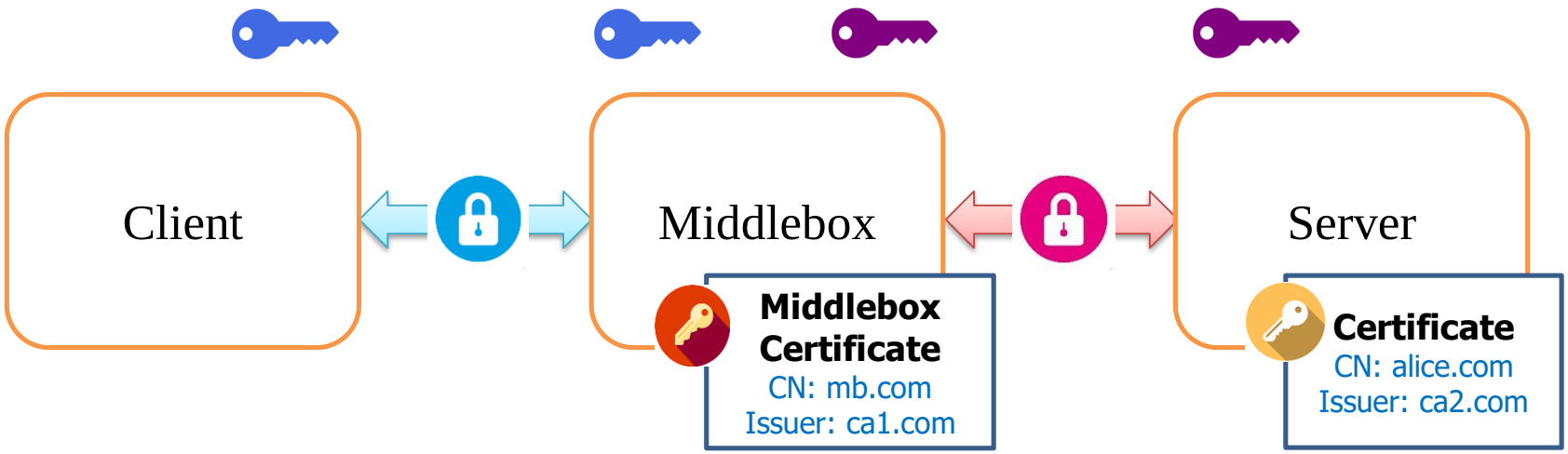
EV certificates: extended validation certificates
DANE: DNS-based Authentication of Named Entities (RFC 6698)
CT: Certificate Transparency (RFC 6962)

Security Goals of maTLS - Confidentiality



✓ Segment Secrecy

Security Goals of maTLS - Confidentiality



- ✓ Segment Secrecy
- ✓ Individual Secrecy

Why Individual Secrecy?

- It is known that initialization vector should not be reused
- Without Individual Secrecy, confidentiality is undermined

This happened when the same keystream is used across the session and the middlebox modified the message

$$C_1 = P_1 \oplus F(Key, IV)$$

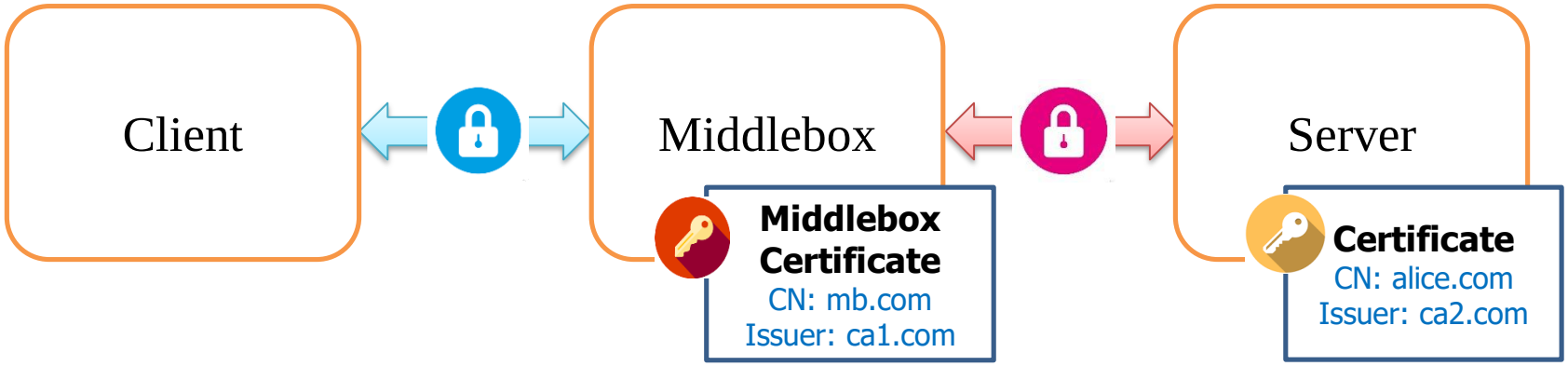
$$C_2 = P_2 \oplus F(Key, IV)$$

$$C_1 \oplus C_2 = P_1 \oplus P_2$$

The same keystream with the different message

- It is desirable to use different segment keys across the session

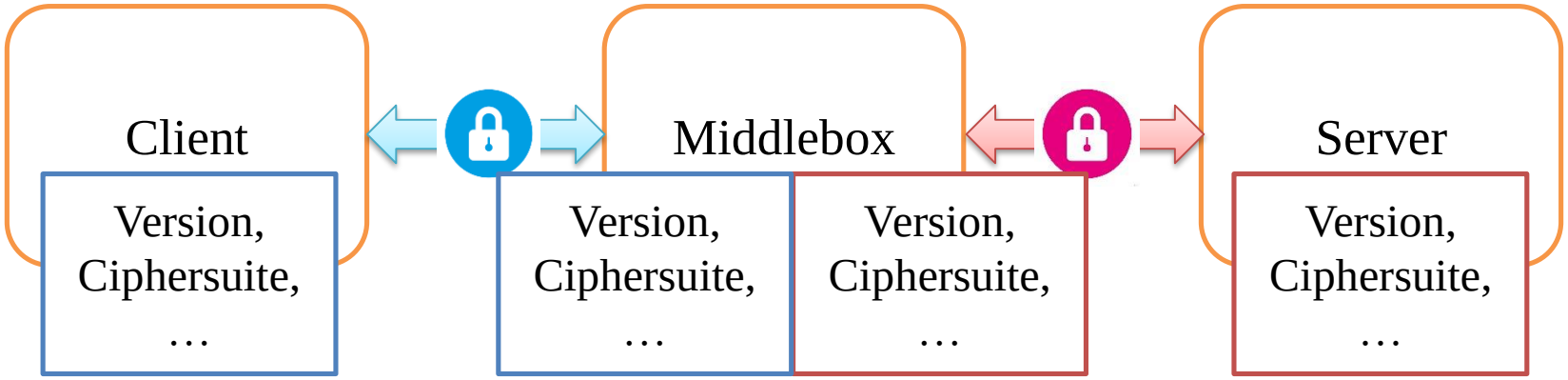
Audit Mechanism for Confidentiality



- ✓ Segment Secrecy
- ✓ Individual Secrecy

→ Security Parameter Verification

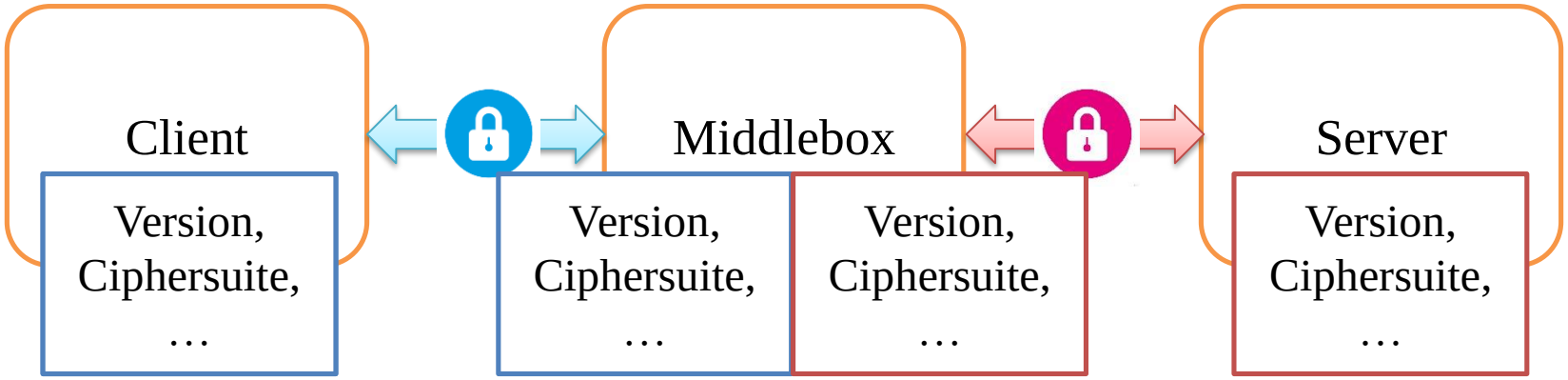
Security Parameter Verification



Security Parameter Blocks

Each entity describes information about its related segment(s)

Security Parameter Verification



Security Parameter Blocks

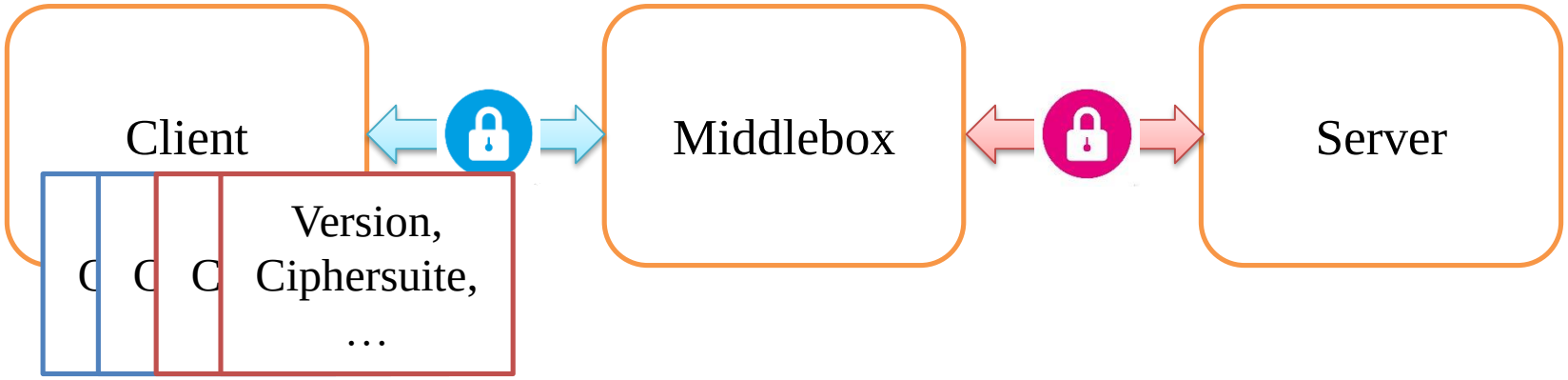
Each entity describes information about its related segment(s)

TLS version Ciphersuite
Transcript of Handshake Hash of Master Secret

→ Segment Secrecy

→ Individual Secrecy

Security Parameter Verification



Security Parameter Blocks

Each entity describes information about its related segment(s)

Report

TLS version
Ciphersuite

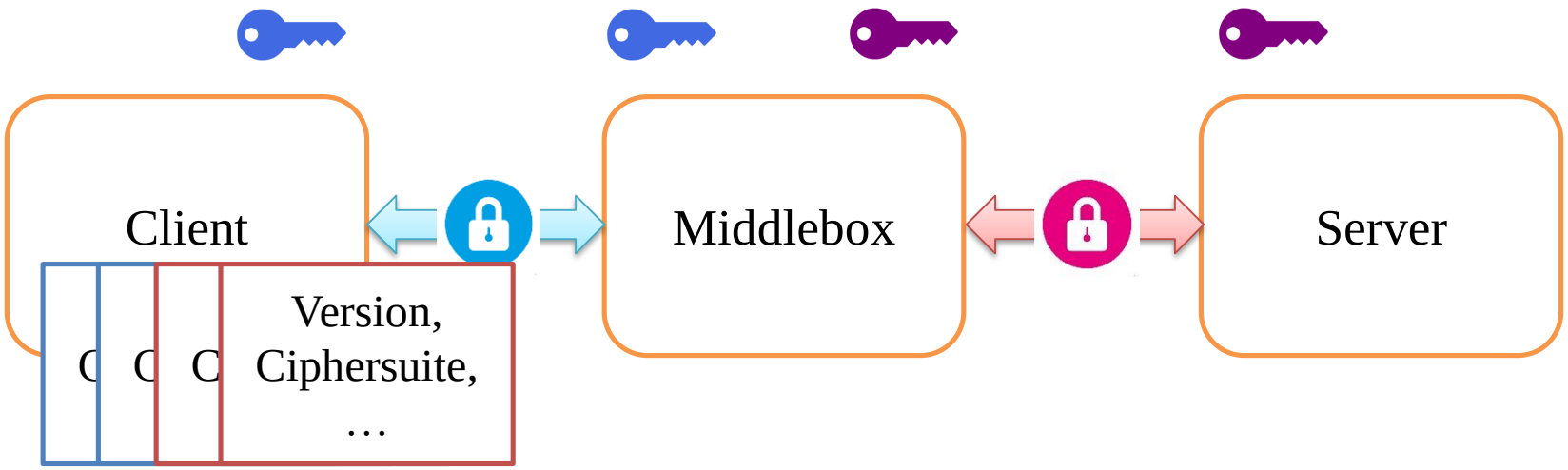
Transcript of Handshake
Hash of Master Secret

Segment Secrecy

Individual Secrecy

No low TLS versions and weak ciphersuites

Security Parameter Verification



Security Parameter Blocks

Each entity describes information about its related segment(s)

Report

TLS version
Ciphersuite

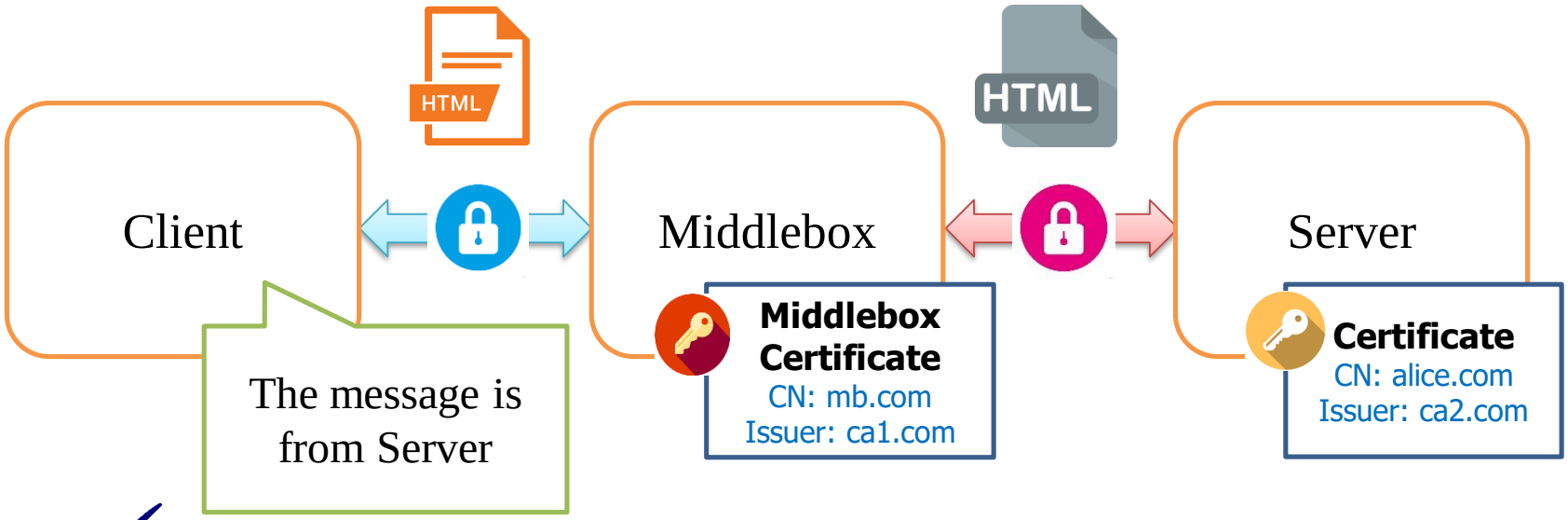
Transcript of Handshake
Hash of Master Secret

Segment Secrecy

Individual Secrecy

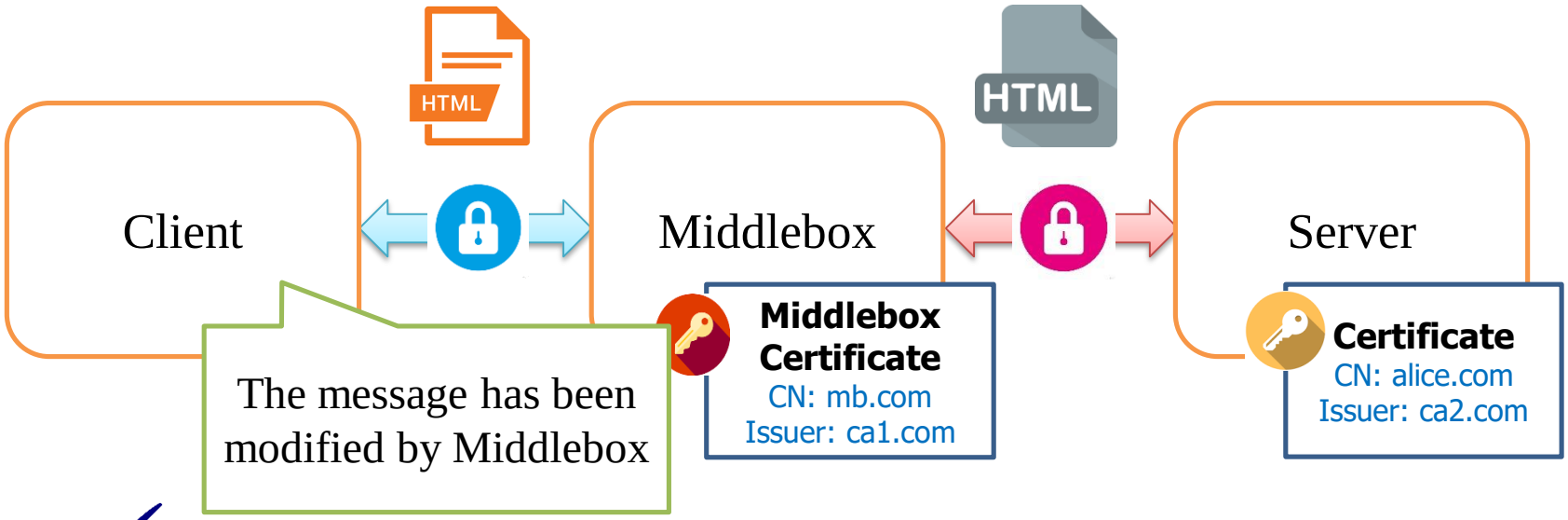
- ✓ No low TLS versions and weak ciphersuites
- ✓ Confirmation of different segment keys

Security Goals of maTLS - Integrity



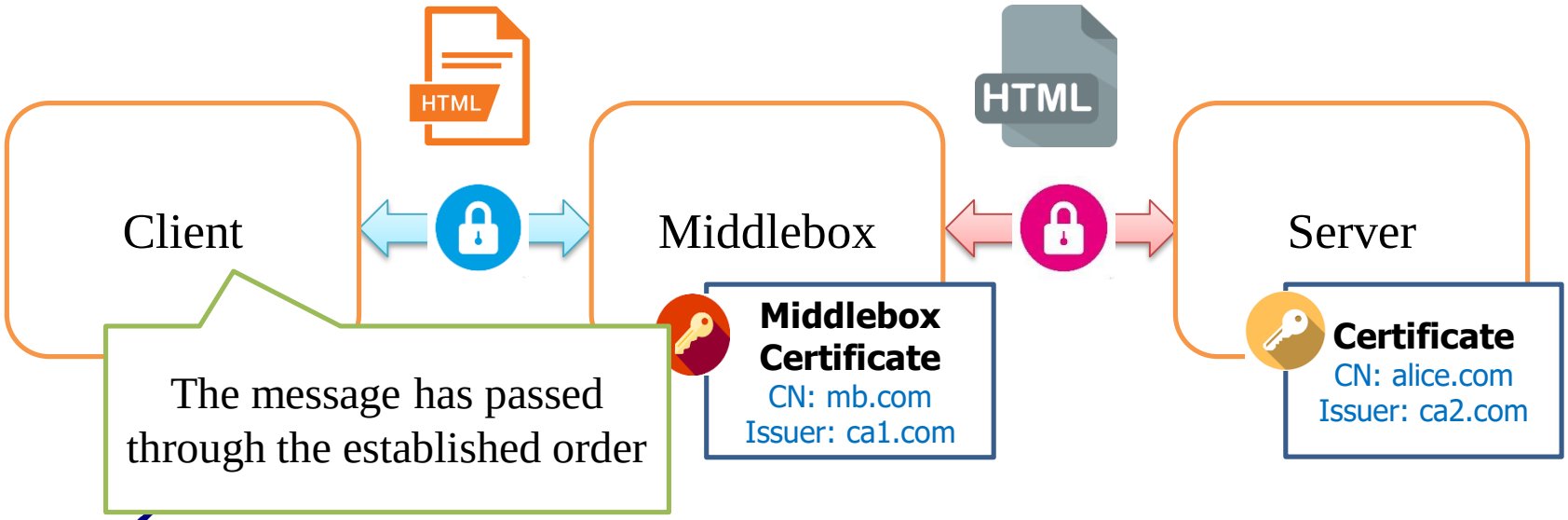
✓ Data Source Authentication

Security Goals of maTLS - Integrity



- ✓ Data Source Authentication
- ✓ Modification Accountability

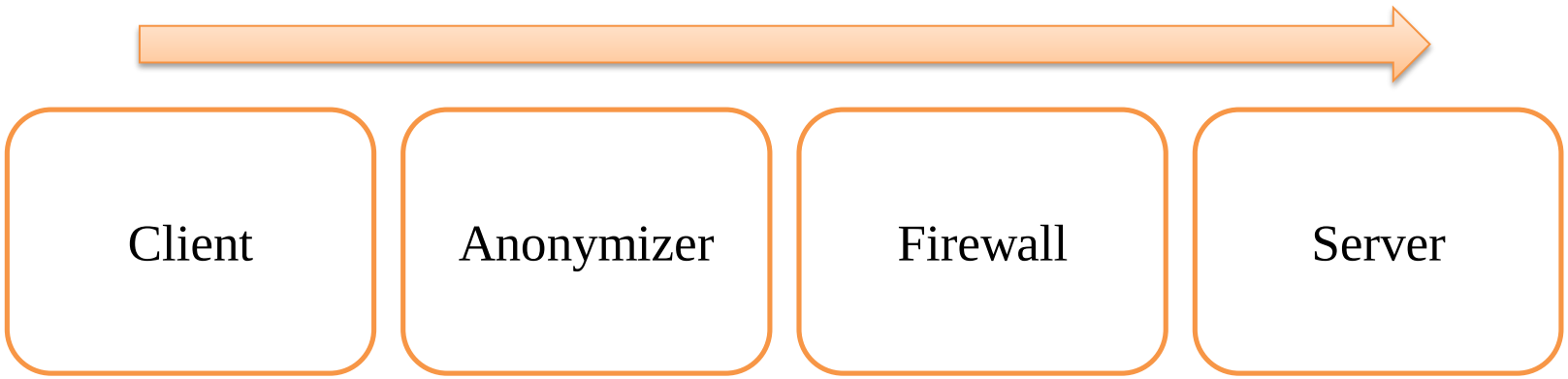
Security Goals of maTLS - Integrity



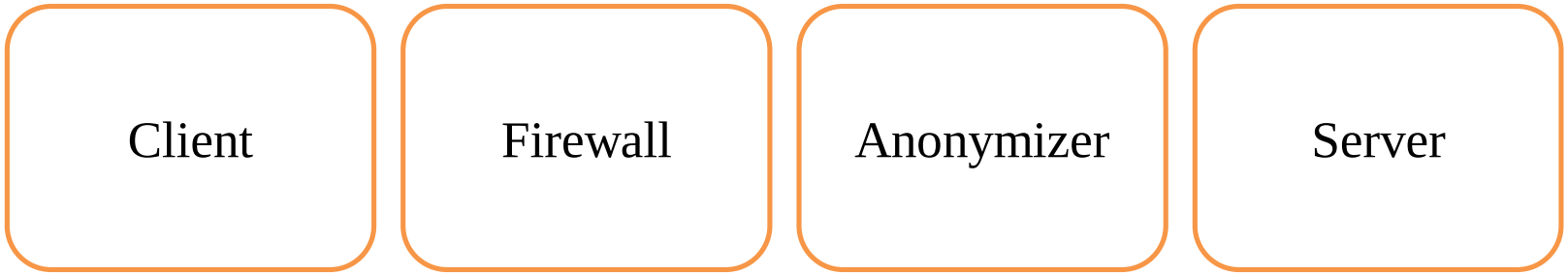
- ✓ Data Source Authentication
- ✓ Modification Accountability
- ✓ Path Integrity

Why Path Integrity?

Message Flow



The data is anonymized and then the firewall read it



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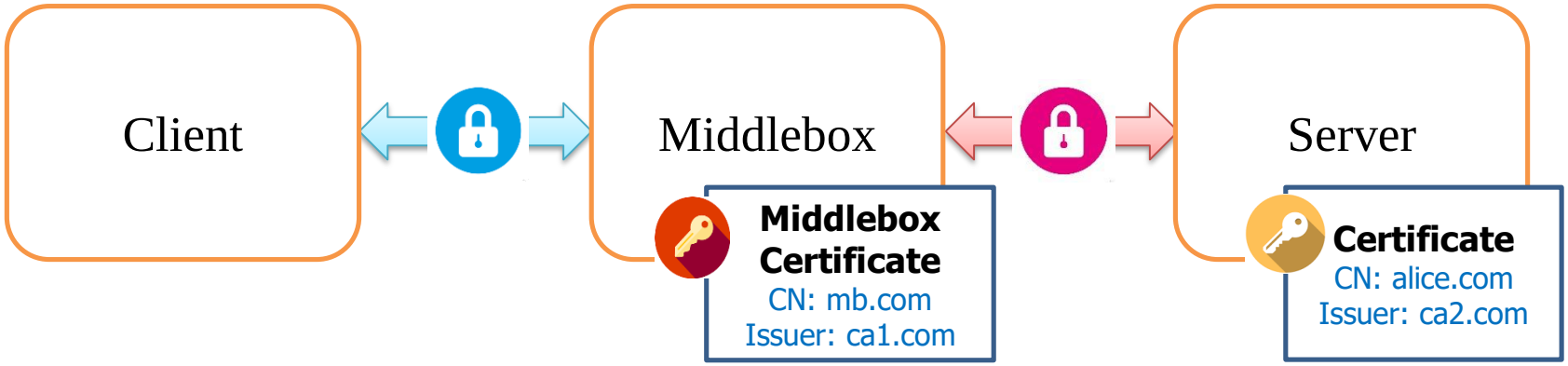
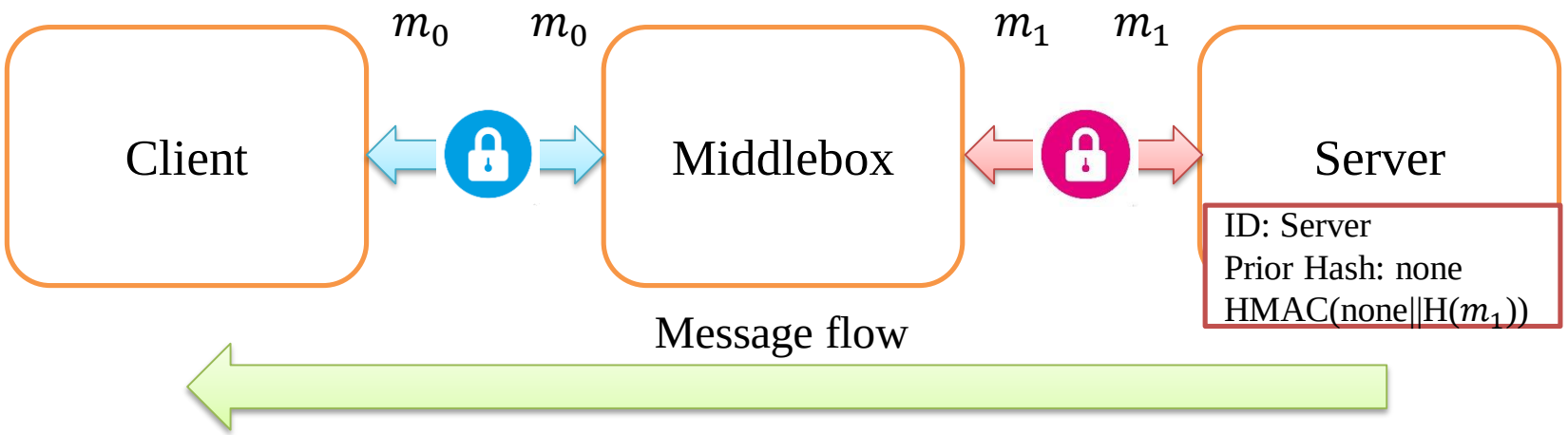
Audit Mechanism for Integrity



- ✓ Data Source Authentication
- ✓ Modification Accountability → Valid Modification Checks
- ✓ Path Integrity

Valid Modification Checks



Modification Log Blocks

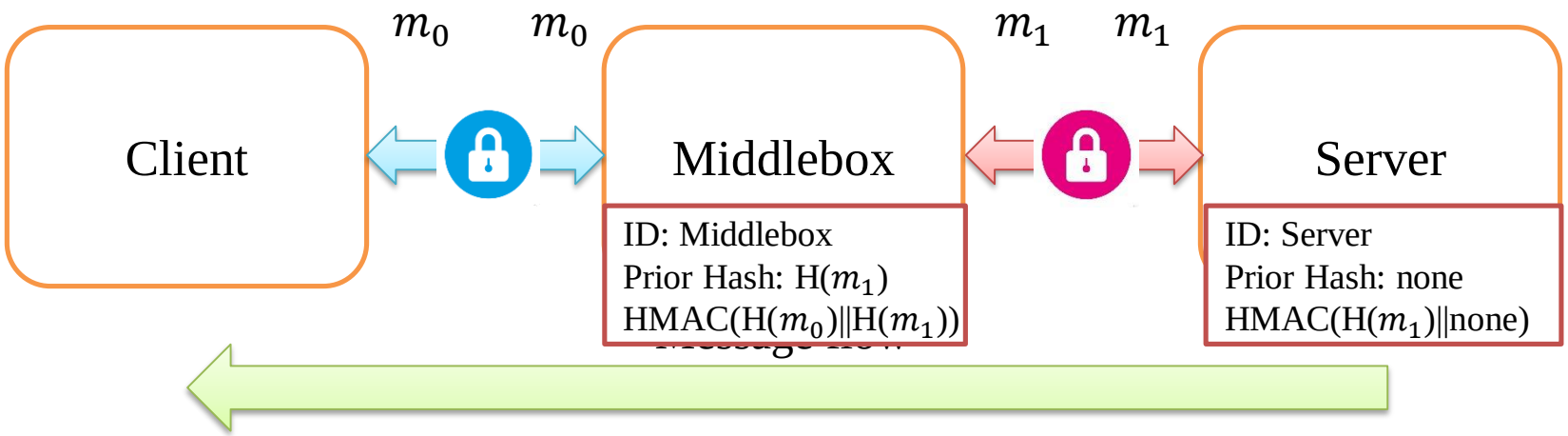
Each entity describes information about its modification by using HMAC (The HMAC key is called an ***accountability key***)

$m \rightarrow m'$

ID	$H(m)$	$HMAC(H(m')\|\|H(m))$

* Optimization on a Modification Log is described in the paper

Valid Modification Checks



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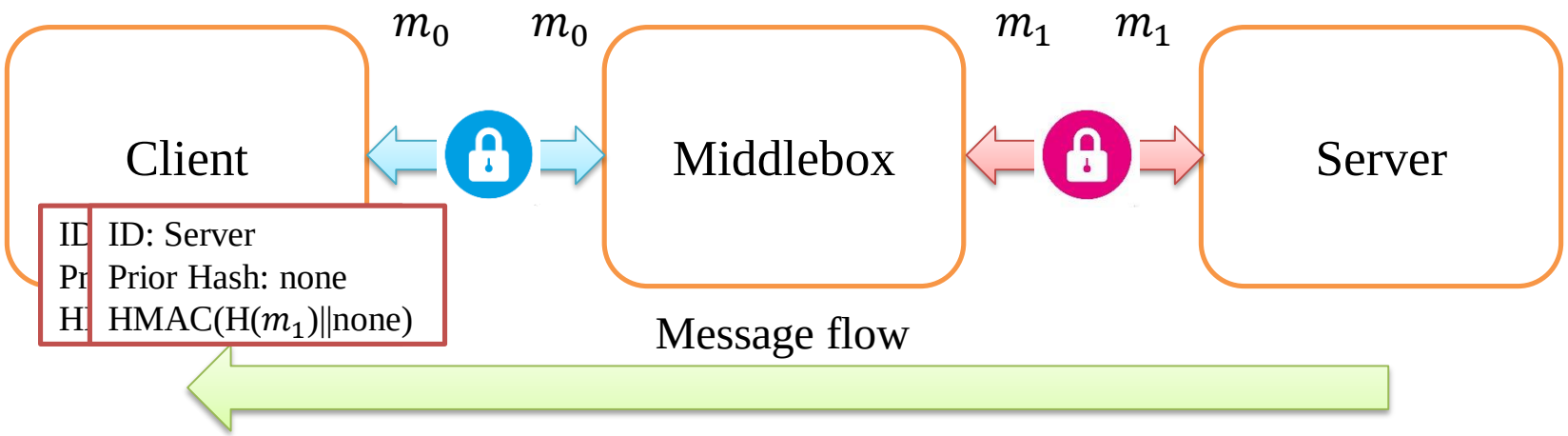

Modification Log Blocks

Each entity describes information about its modification by using HMAC (The HMAC key is called an ***accountability key***)

Report

$m \rightarrow m'$

ID	$H(m)$	$HMAC(H(m')\|\|H(m))$

Confirmation of who sends and who modifies the message

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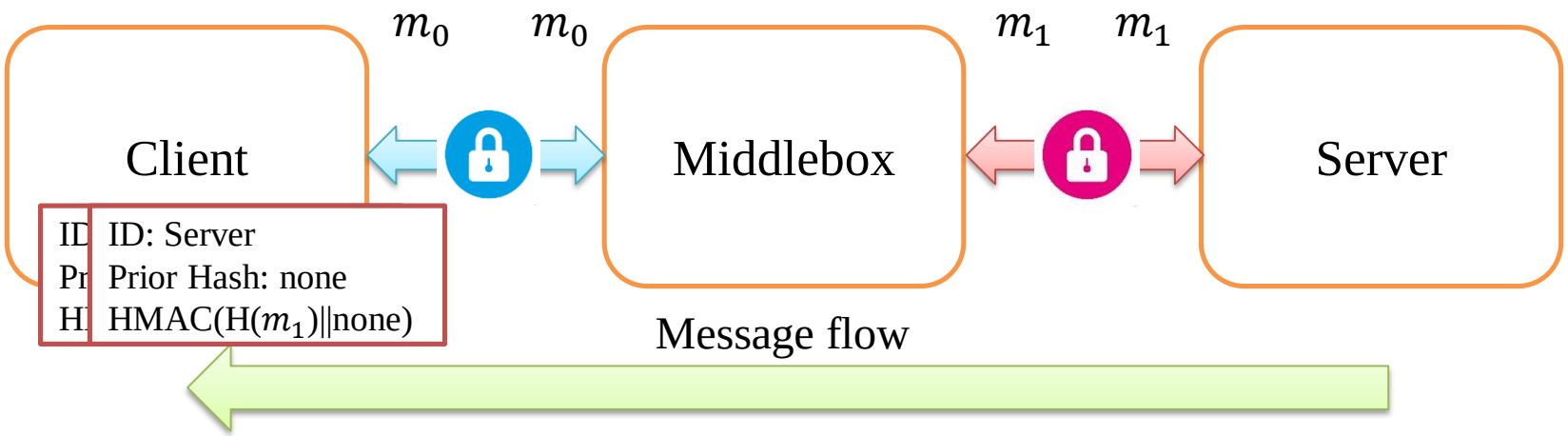
Valid Modification Checks



Modification Log Blocks

Each entity describes information about its modification by using HMAC (The HMAC key is called an ***accountability key***)

Report

$m \rightarrow m'$

ID	$H(m)$	$HMAC(H(m')\|\|H(m))$

- ✓ Confirmation of who sends and who modifies the message
- ✓ Confirmation of the order of middleboxes

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Summary of Audit Mechanisms

Explicit Authentication

Server Authentication
Middlebox Authentication

Server Certificate and Middlebox Certificates (with their signed certificate timestamps)

Summary of Audit Mechanisms

Explicit Authentication

Server Authentication
Middlebox Authentication

Server Certificate and Middlebox Certificates (with their signed certificate timestamps)

Security Parameter Verification

Segment Secrecy
Individual Secrecy

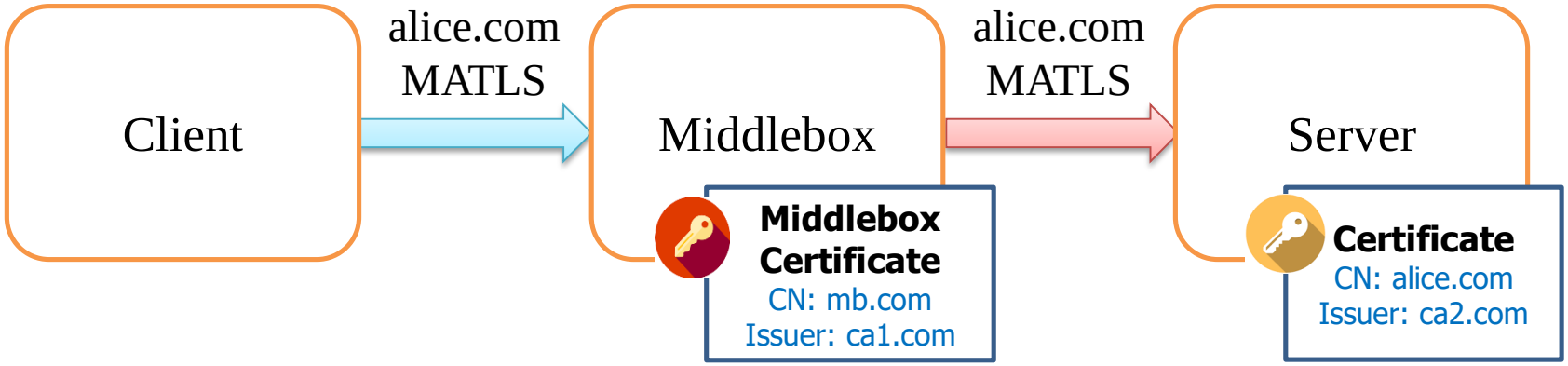
Security Information Blocks

Summary of Audit Mechanisms

Explicit Authentication	Server Authentication Middlebox Authentication	Server Certificate and Middlebox Certificates (with their signed certificate timestamps)
Security Parameter Verification	Segment Secrecy Individual Secrecy	Security Information Blocks
Valid Modification Checks	Data Source Authentication Modification Accountability Path Integrity	Modification Log Blocks

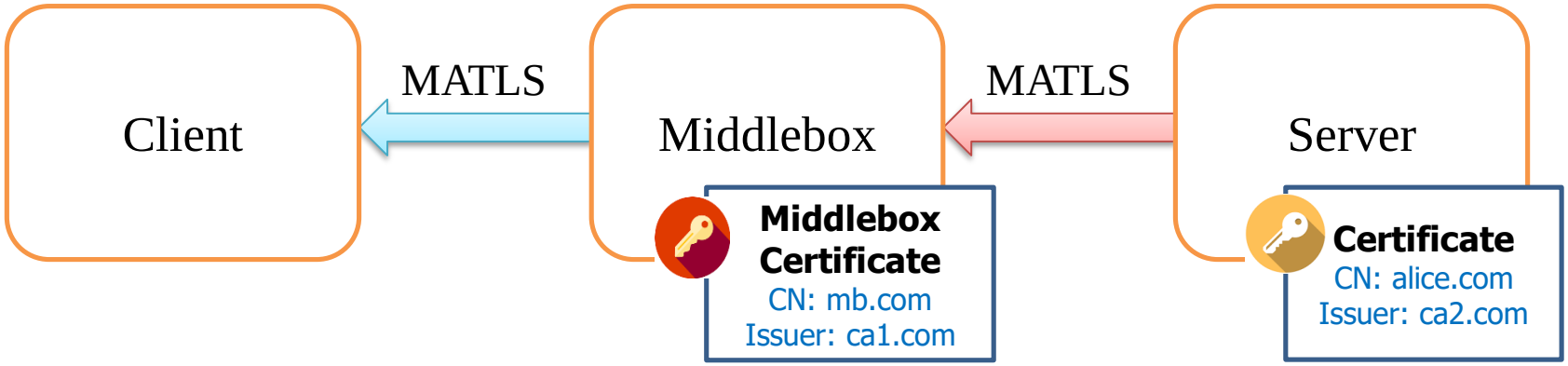
maTLS Handshake

maTLS Handshake



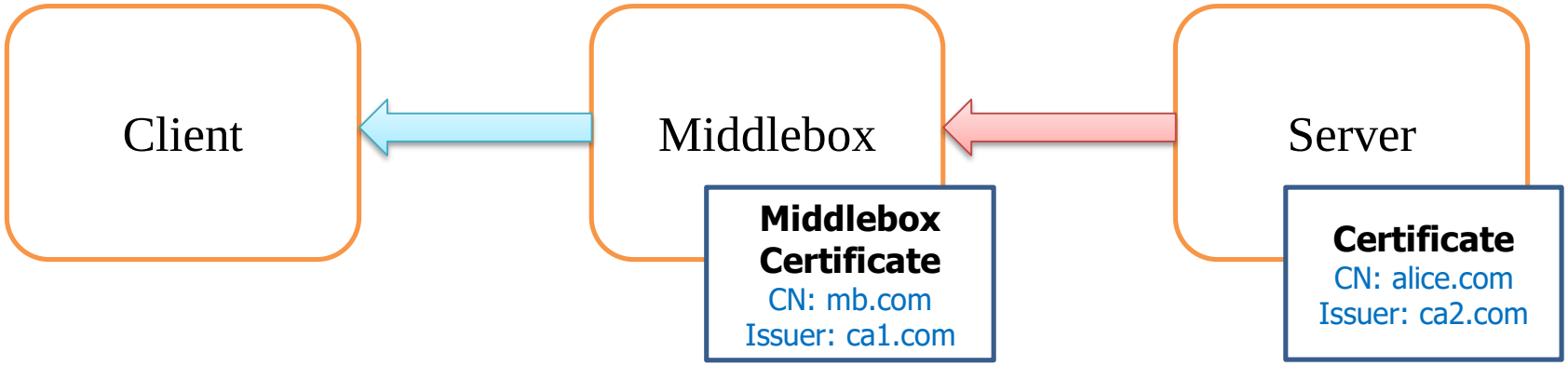
- ✓ ClientHello and ServerHello,

maTLS Handshake



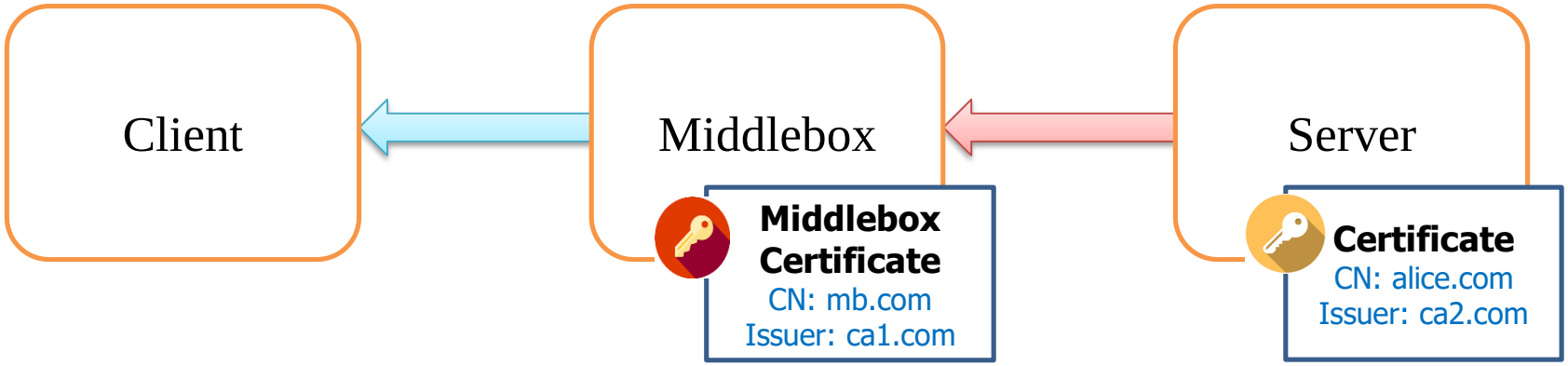
- ✓ ClientHello and ServerHello,
  - Each segment negotiates its TLS version and ciphersuite
  - Each entity establishes HMAC keys (accountability keys)

maTLS Handshake



- ✓ ClientHello and ServerHello,
  - Each segment negotiates its TLS version and ciphersuite
  - Each entity establishes HMAC keys (accountability keys)
- ✓ Certificate, ⇒ Explicit Authentication

maTLS Handshake



- ✓ ClientHello and ServerHello,

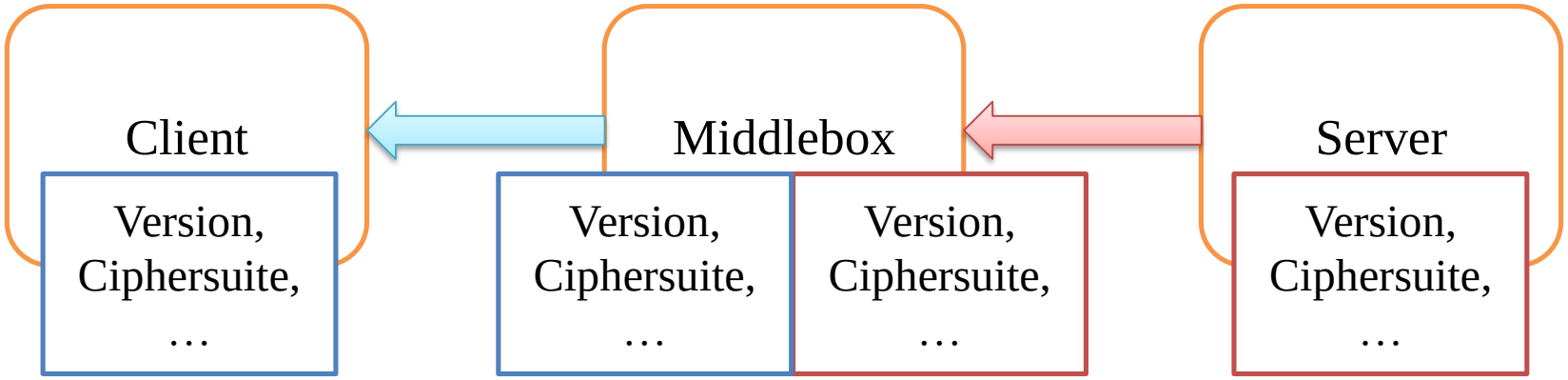
  Each segment negotiates its TLS version and ciphersuite
  Each entity establishes HMAC keys (accountability keys)

- ✓ Certificate, ⇒ Explicit Authentication

- ✓ ServerKeyExchange and ClientKeyExchange,

  Each segment establishes its master secret

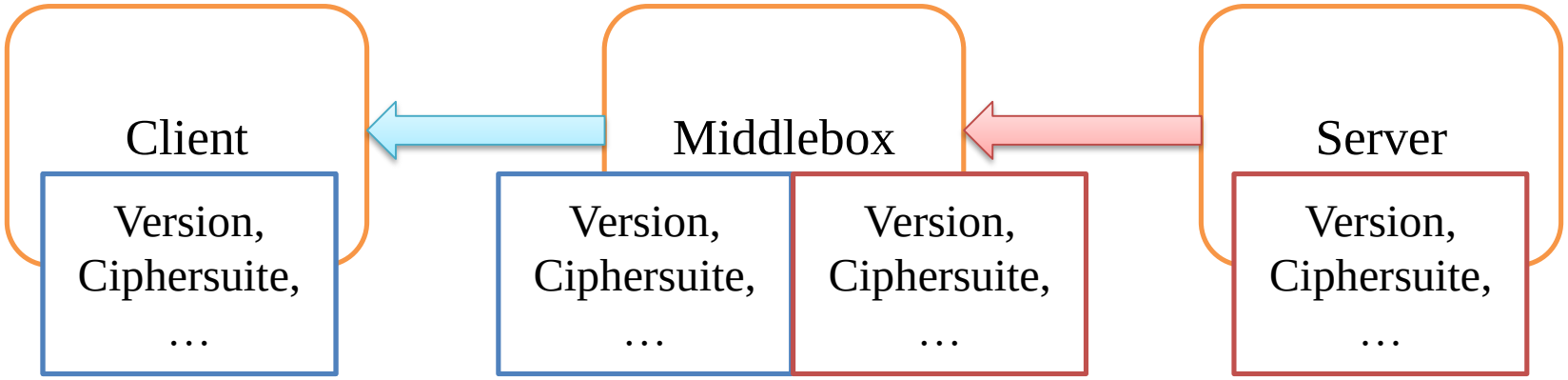
maTLS Handshake



✓ Finished

Each segment confirms the transcript of their handshake

maTLS Handshake

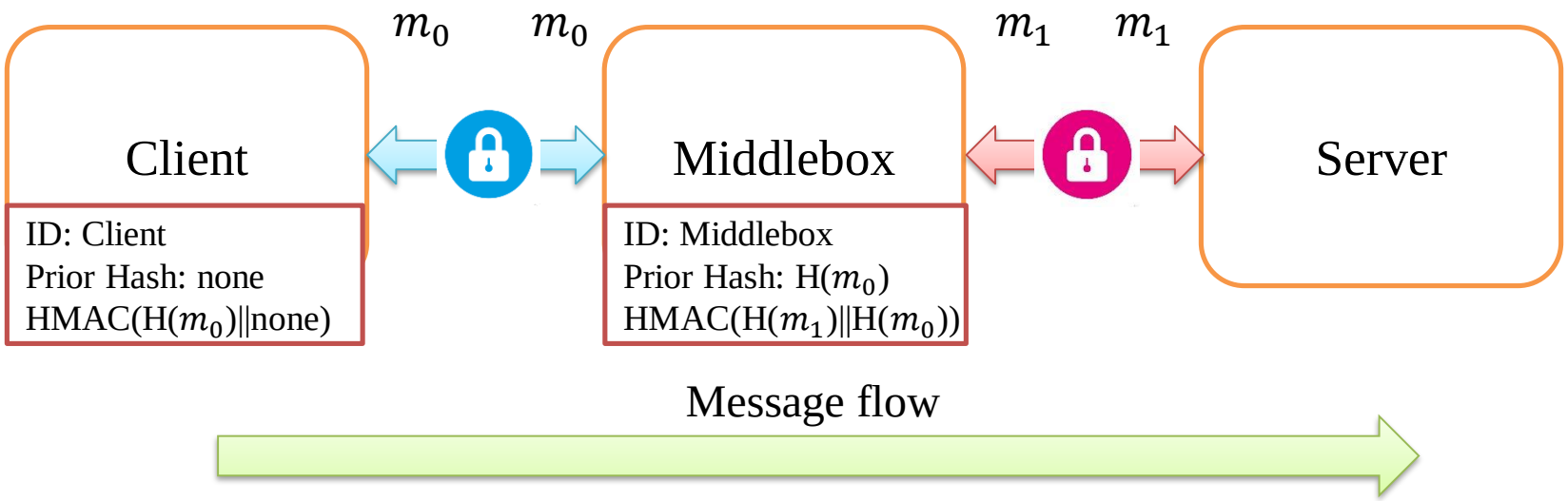


- ✓ Finished

  Each segment confirms the transcript of their handshake

- ✓ ExtendedFinished → Security Parameter Verification

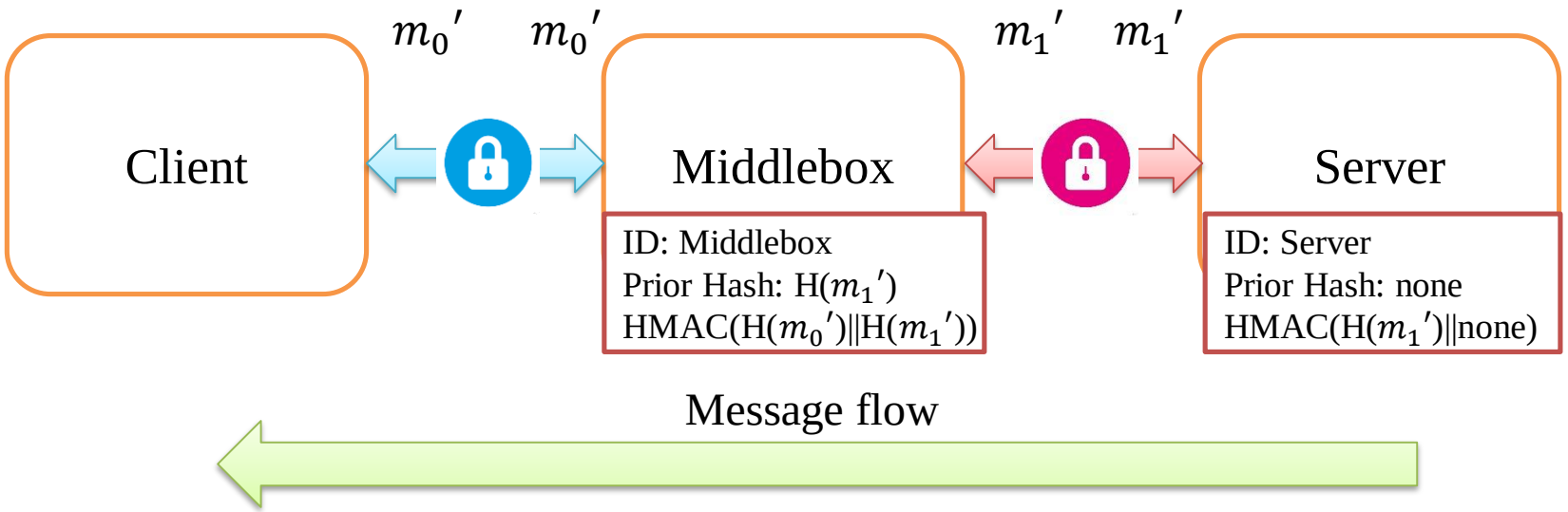
maTLS Record



✓ Data Exchange → Valid Modification Checks

* Optimization on a Modification Log is described in the paper

maTLS Record



✓ Data Exchange → Valid Modification Checks

* Optimization on a Modification Log is described in the paper

Security Verification

- Security verification of maTLS through Tamarin
- Dolev-Yao adversary
  - Can capture all the messages delivered on the air
  - Can insert/drop/alter/reorder messages
  - Can corrupt long-term keys
- Seven lemmas (security goals in first-order logic)

Example of
Server Authentication

```
All C S nonces #tc.
  C_HandshakeComplete(C, S, nonces)@tc
==>
Ex #ts.
  S_HandshakeComplete(C, S, nonces)@ts &
  (#ts < #tc)
```

- The result shows that the maTLS protocol is secure

* The implementation can be found at https://github.com/middlebox-aware-tls/matls-tamarin.git

Evaluation Setting

All the applications are implemented in C with OpenSSL (for maTLS)

Client

Client-side Middlebox

Located in
Seoul National University

Client: Intel Broadwell CPU at 3.30GHz with 1GB Memory
Client-side Middlebox: Intel Core i7 at 2.30GHz with 1GB Memory

---

Located in
1) AWS Seoul (Intra-Country)
2) AWS Tokyo (Intra-Region)
3) AWS Virginia (Inter-Region)

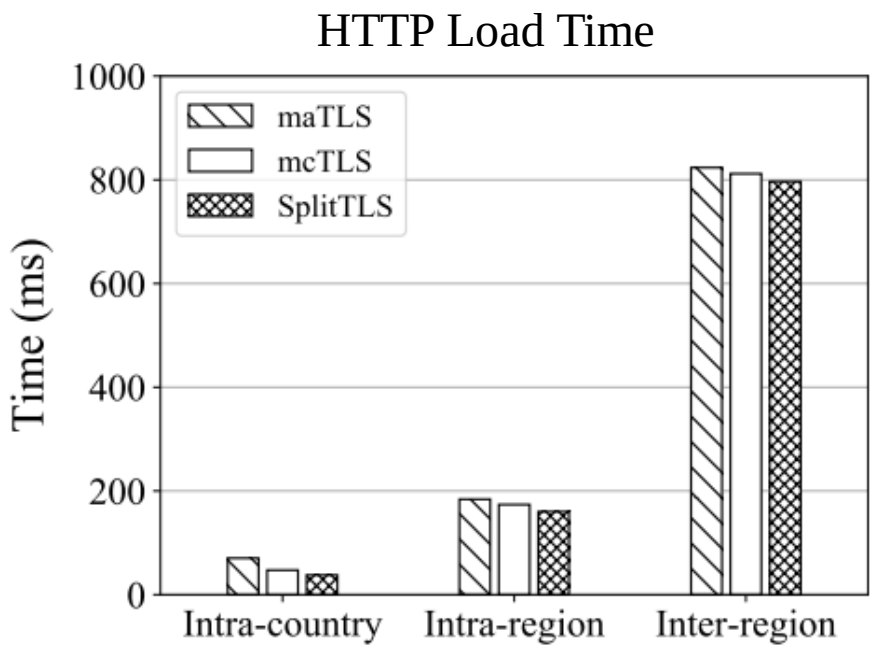
Server-side Middlebox

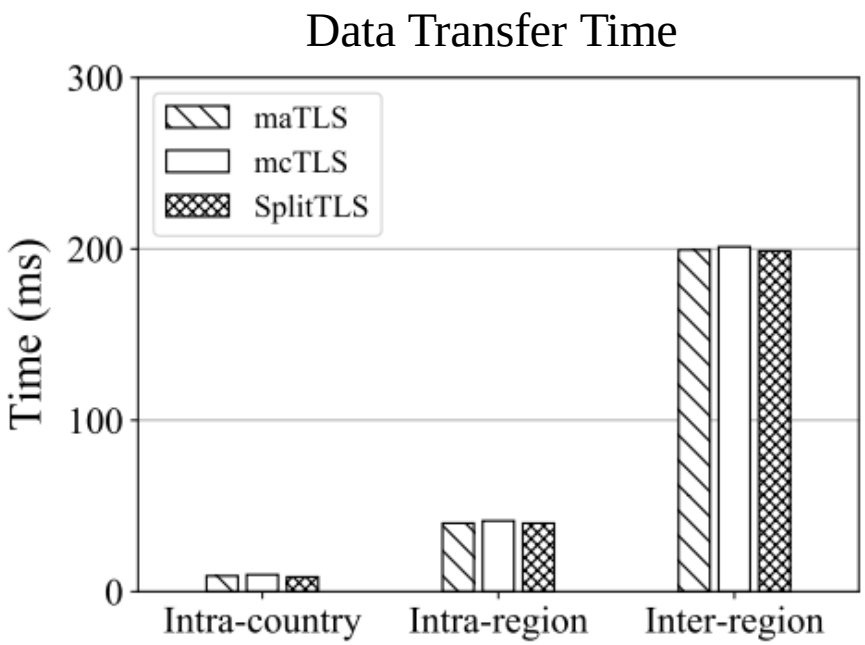
Server

Server and Server-side Middlebox: Intel Xeon CPU E5-3676 at 2.40GHz with 1GB Memory

* The implementation can be found at https://github.com/middlebox-aware-tls/matls-implementation.git

Evaluation – HTTP Load Time

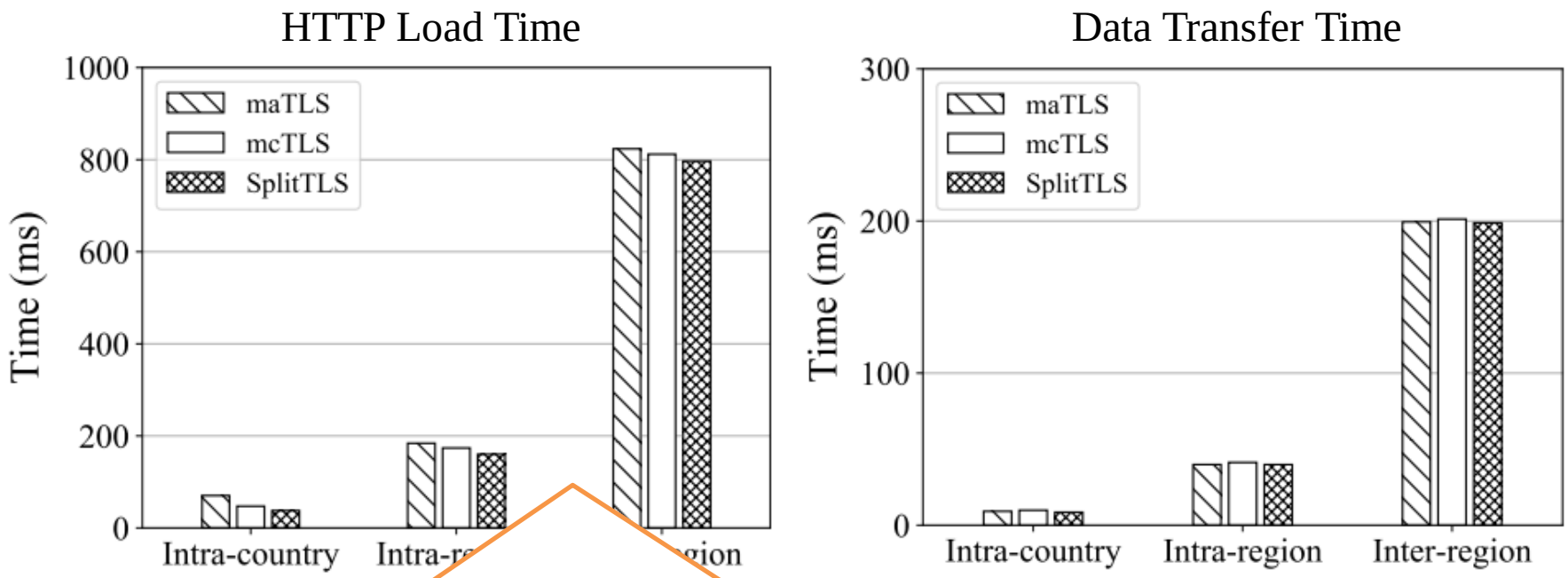




Testbed	$C\text{-}MB_C$	$MB_C\text{-}MB_S$	$MB_S - S$
Intra-country	1.136ms	4.944ms	0.551ms
Intra-region	1.136ms	35.896ms	0.537ms
Inter-region	1.136ms	192.818ms	0.610ms

- HTTP Load Time: The TLS handshake and the HTTP message exchange (GET and RESPONSE)
- Data Transfer Time: Only the HTTP message exchange (GET and RESPONSE)

Evaluation – HTTP Load Time



The maTLS protocol introduces a slight delay (10.22ms – 32.52ms) compared to SplitTLS and mcTLS

- HTTP Load Time: The TLS handshake and the HTTP message exchange (GET and RESPONSE)
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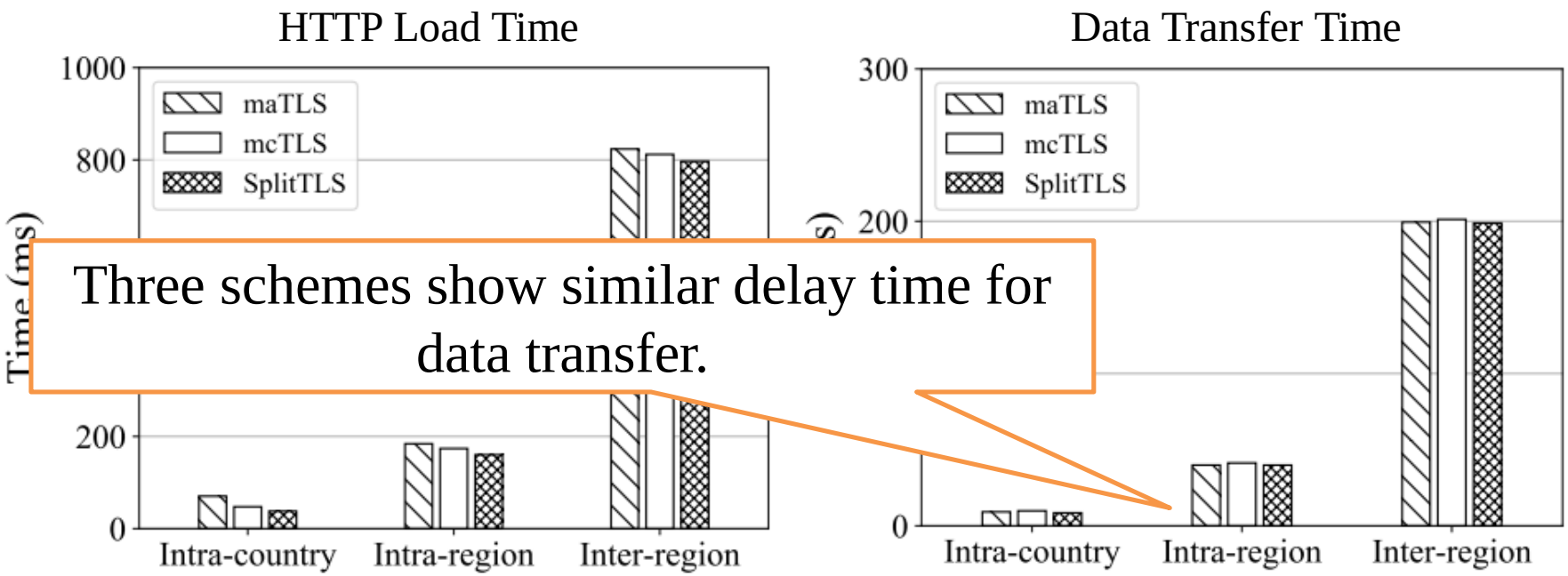
Evaluation – HTTP Load Time



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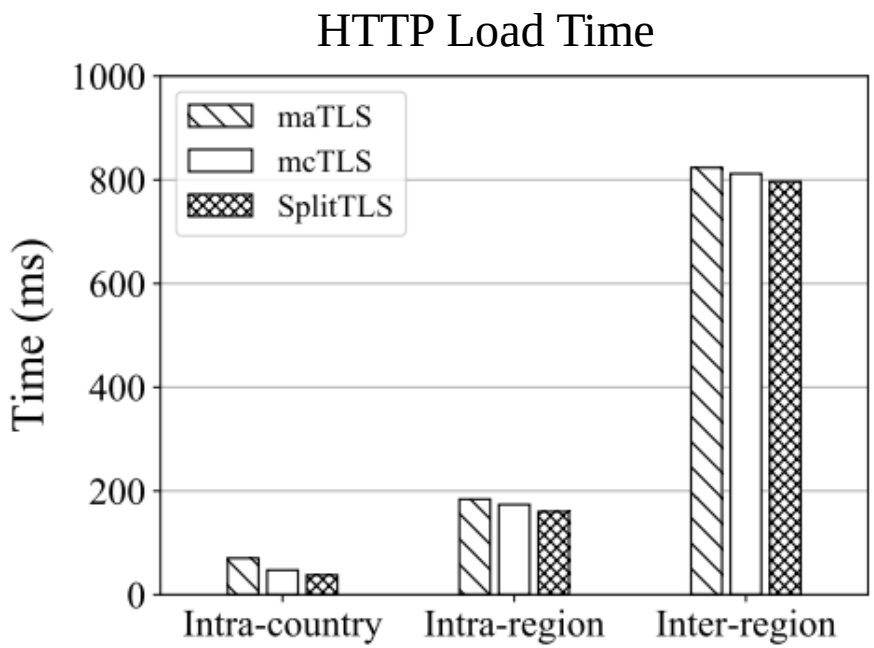

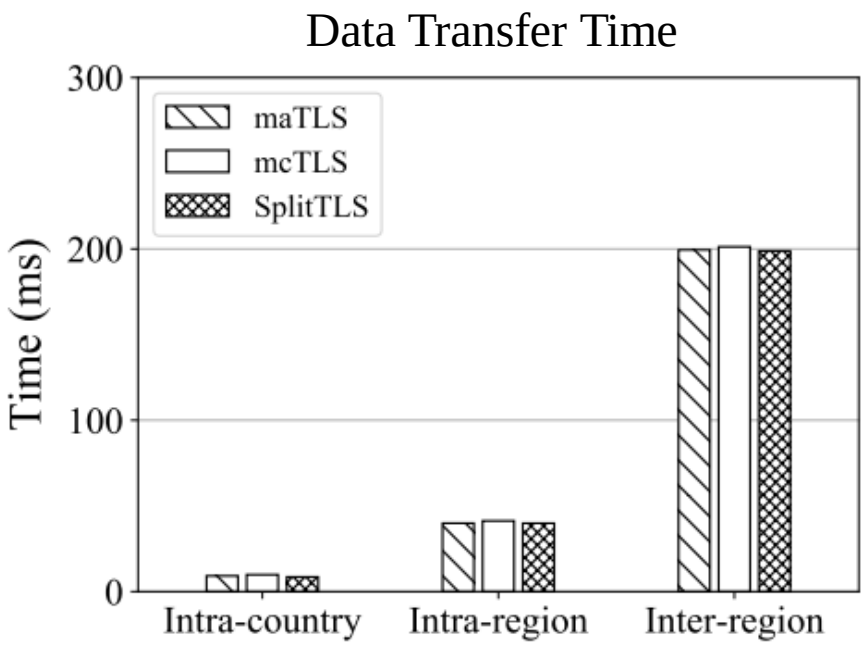

We conclude that the maTLS overhead is mainly due to the setup of an maTLS session

Inter-region	1.136ms	192.818ms	0.610ms

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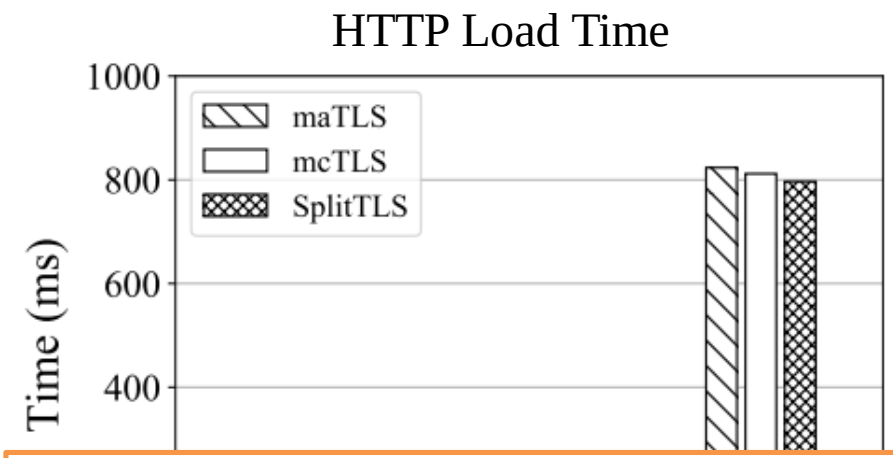
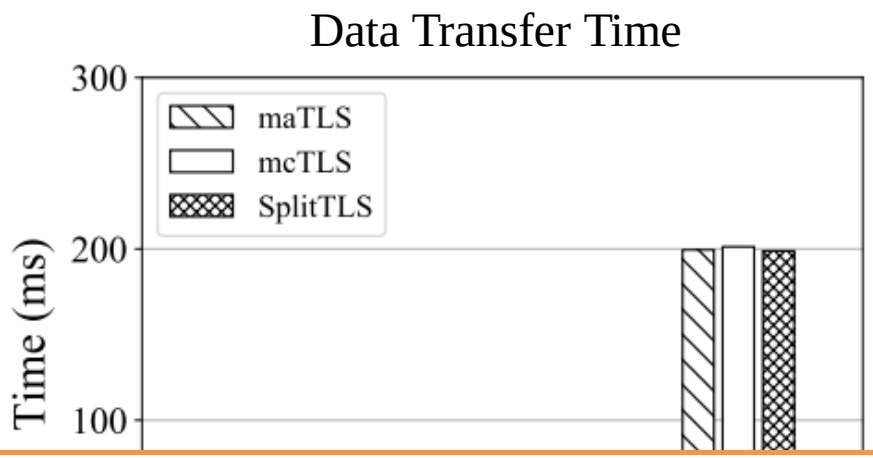
- Data Transfer Time: Only the HTTP message exchange (GET and RESPONSE)

Evaluation – HTTP Load Time





Once the session is established,
maTLS provides similar performance to the others
while preserving all security merits that we have discussed

Intra-country	1.136ms	4.944ms	0.551ms
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- HTTP Load Time: The TLS handshake and the HTTP message exchange (GET and RESPONSE)
- Data Transfer Time: Only the HTTP message exchange (GET and RESPONSE)

Summary of maTLS

- SplitTLS is risky
  - Client is not aware of the middleboxes involved
  - Client is forced to fully trust behavior of middleboxes
- Auditable Middlebox
  - Middlebox Certificate
  - Middlebox Transparency System
- Middlebox-aware TLS (maTLS)
  - Explicit Authentication
  - Security Parameter Verification
  - Valid Modification Checks

fin.

email: hwlee2014@mmlab.snu.ac.kr

project webpage: https://middlebox-aware-tls.github.io

source code: https://github.com/middlebox-aware-tls

Backup Slides

Why Middleboxes?

- Acceptable Use Policy
- Marware and Threat Protection
- IoT Endpoint Protection
- Unpatched Endpoint Protection
- Crypto Security Audit

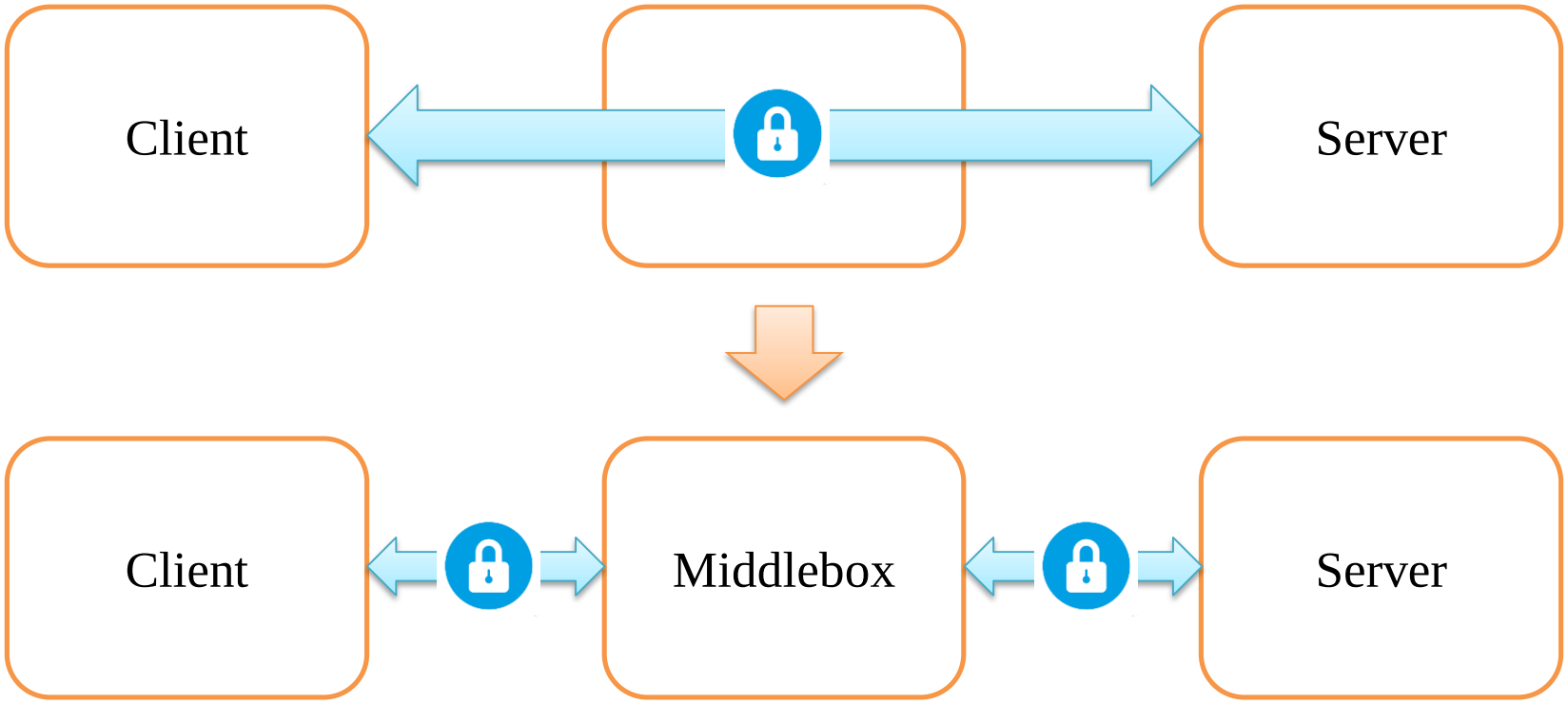
⋮

* I get the use cases from a draft of the RFC document titled “TLS 1.3 Impact on Network-Based Security”

Session Establishment Approach (1)

Top-down approach

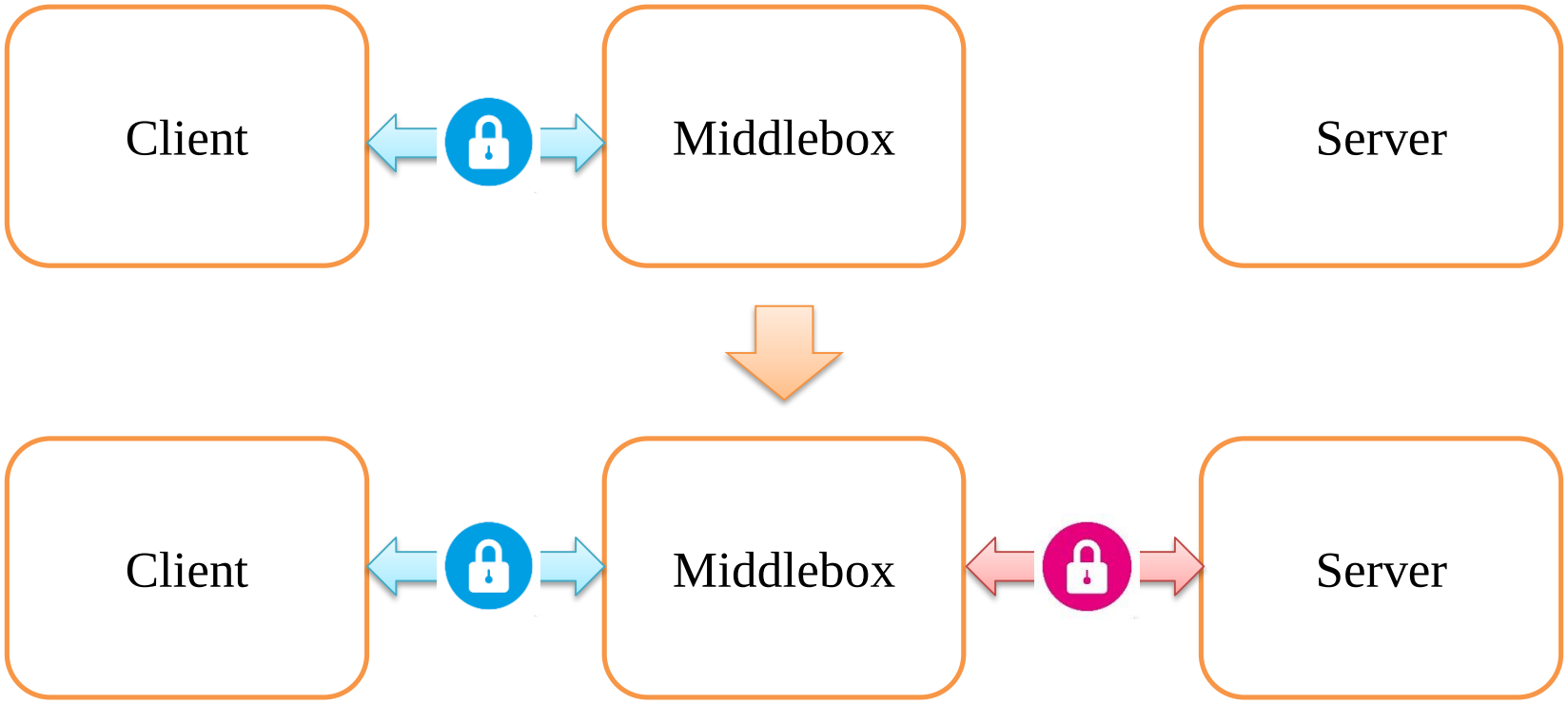
Server determines a TLS version, a ciphersuite, and extensions



Session Establishment Approach (2)

Bottom-up approach

A TLS version, a ciphersuite, and extensions are selected on a segment basis



Difference from mcTLS

- ✗ mcTLS does not achieves Individual Secrecy

  The same keystream is used across the session, which might undermine the confidentiality of the session

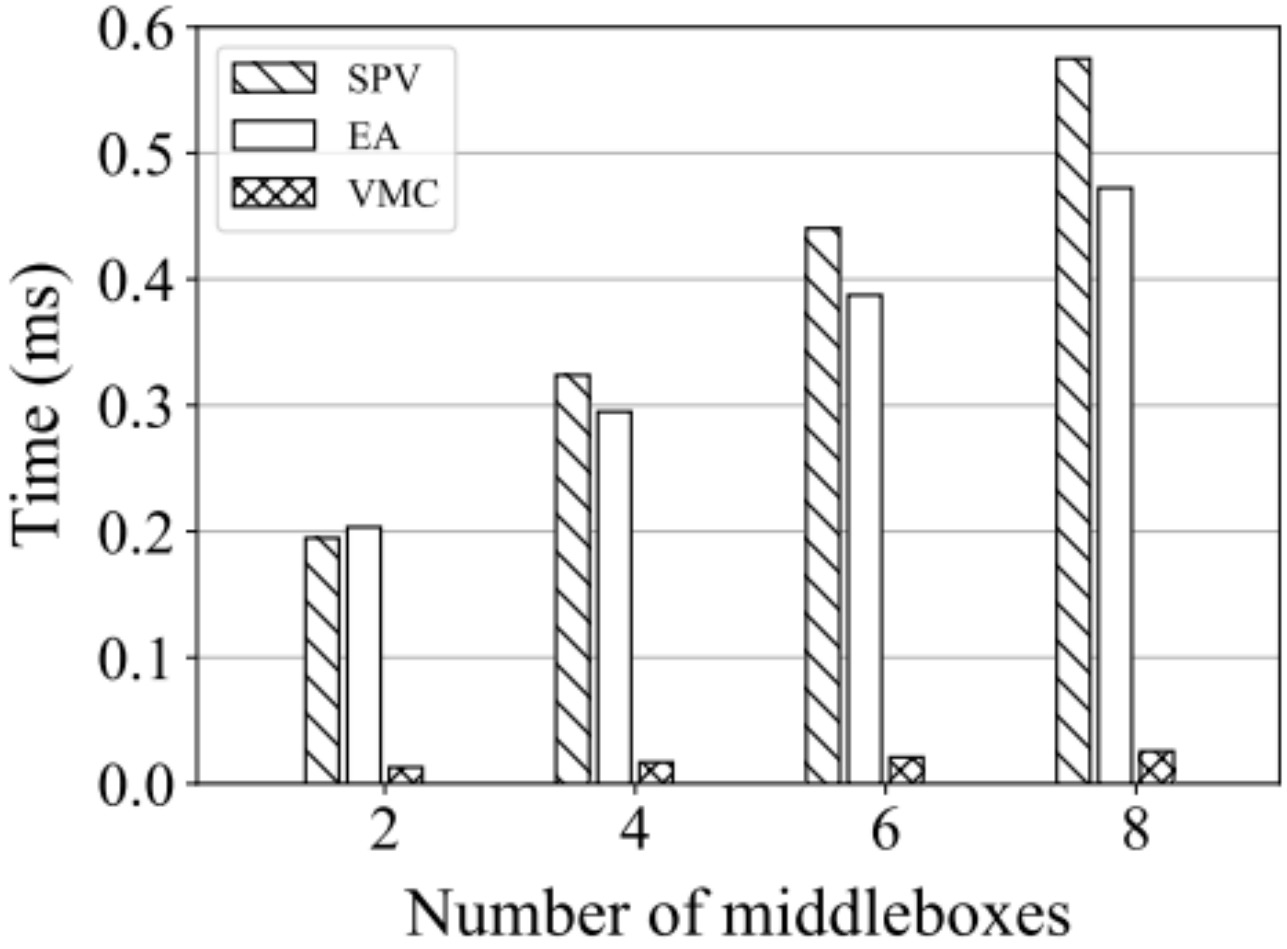
- ✓ maTLS establishes different segment keys in different segments

- ✗ mcTLS requires all the entities support the protocol

  Since the server determines the extensions among the “intersection” of the supported extensions by all the entities

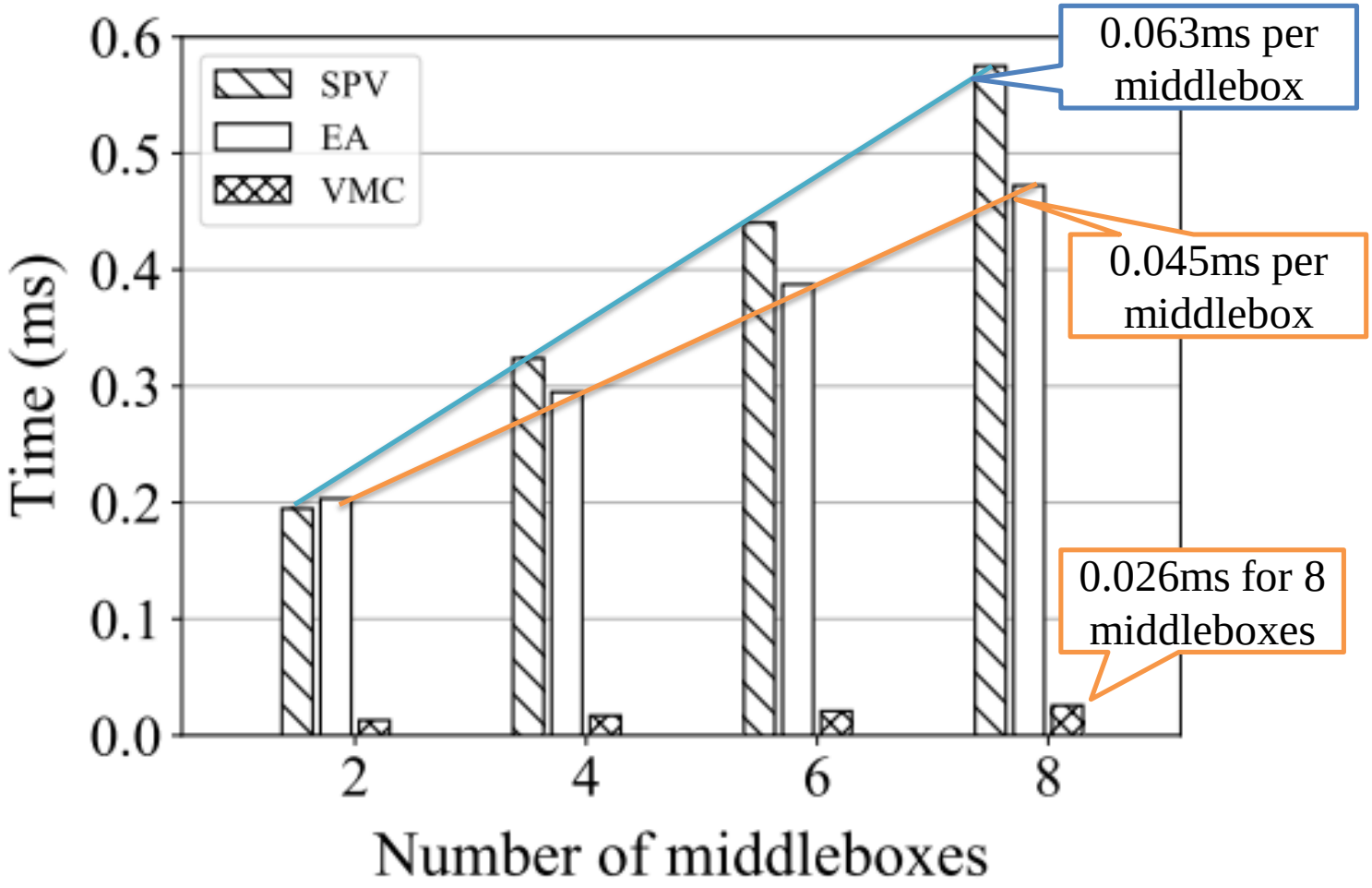
- ✓ maTLS allows a partial maTLS session

Evaluation – Scalability of Three Audit Mechanisms



SPV: Security Parameter Verification / EA: Explicit Authentication / VMC: Valid Modification Checks

Evaluation – Scalability of Three Audit Mechanisms



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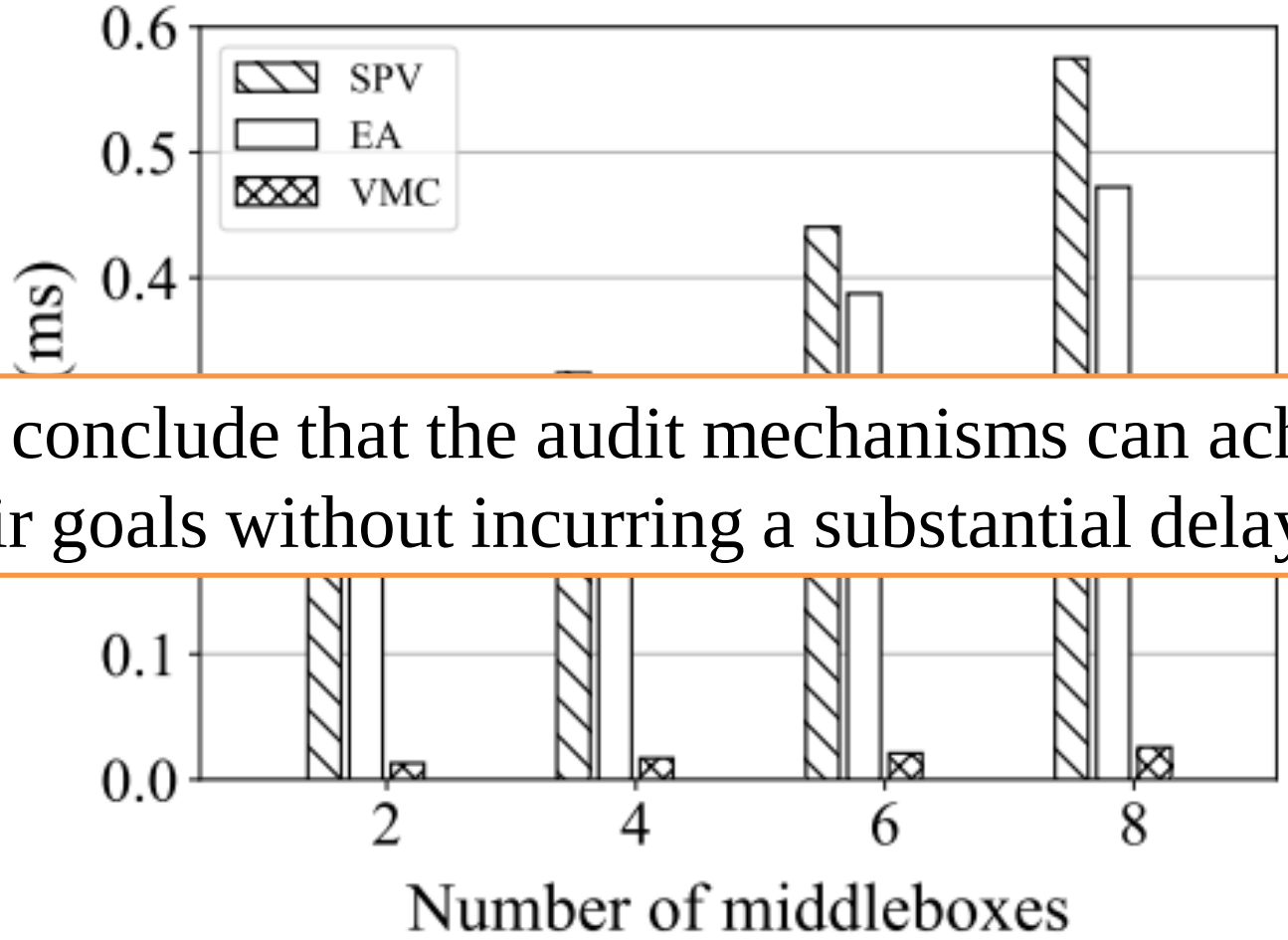
Evaluation – Scalability of Three Audit Mechanisms



We conclude that the audit mechanisms can achieve their goals without incurring a substantial delay

SPV: Security Parameter Verification / EA: Explicit Authentication / VMC: Valid Modification Checks

Modification Log

$ak_{s,c}$: Server's accountability key
$ak_{m,c}$: MB's accountability key (with client)

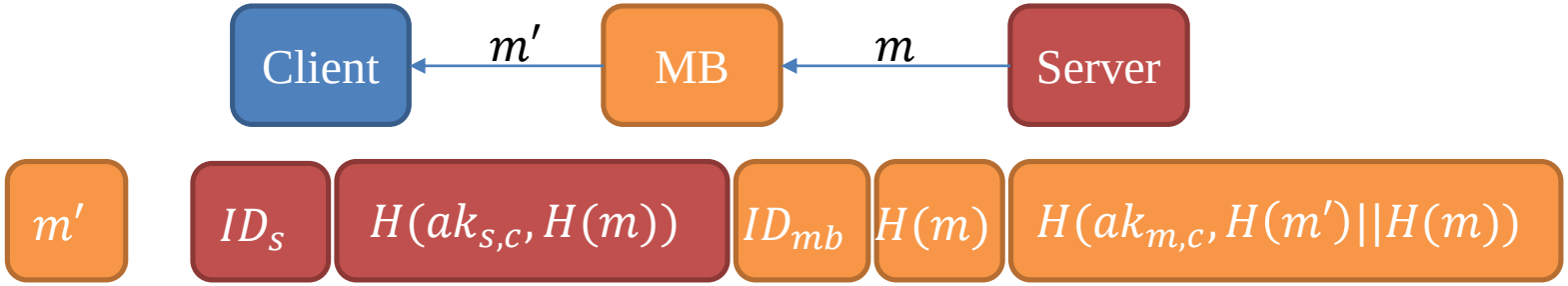
$H(k, m)$: The keyed hash function with k, applying to m
$H(m)$: The hash function, applying to m

- A series of HMACs
- End point: Server, Client, or a valid end-point middlebox such as a cache proxy

- Writer: HTTP Header Enrichment, Optimizer (adding JavaScript) ($m \rightarrow m'$)

ID_{mb} modifies m into m'

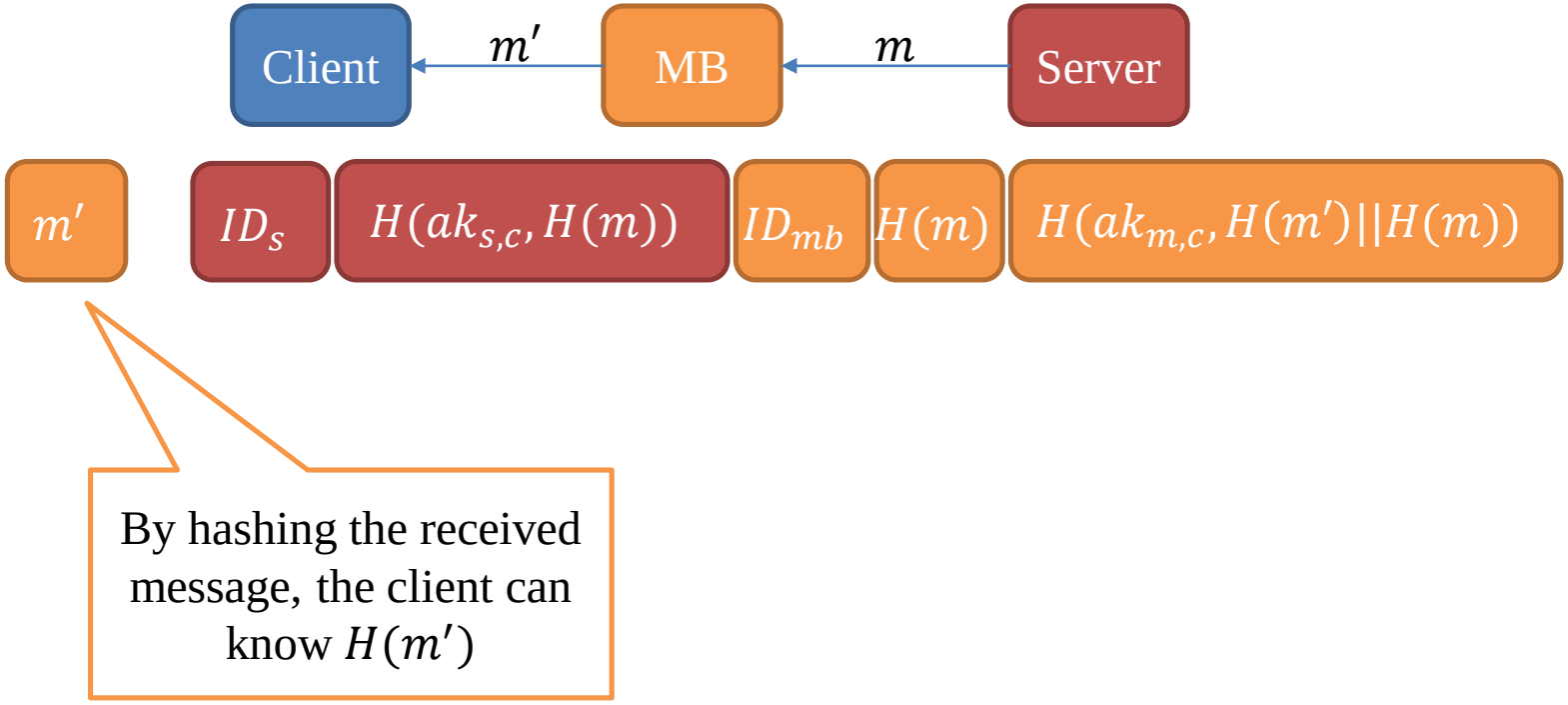
Modification Log Verification



Client knows

- $ak_{s,c}$: The accountability key with the server
- $ak_{m,c}$: The accountability key with the MB

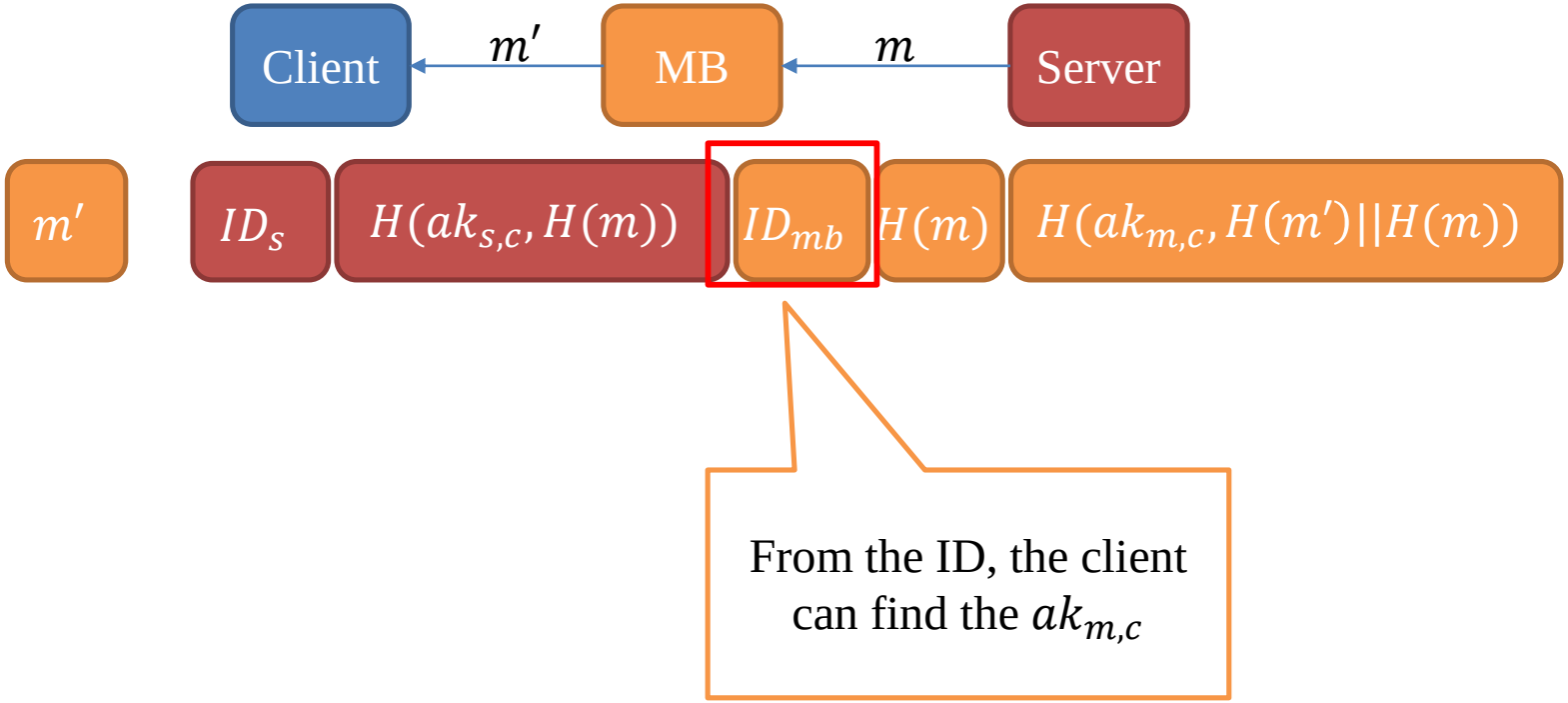
Modification Log Verification



Client knows

- $ak_{s,c}$: The accountability key with the server
- $ak_{m,c}$: The accountability key with the MB
- $H(m')$: The hash value of the received message

Modification Log Verification



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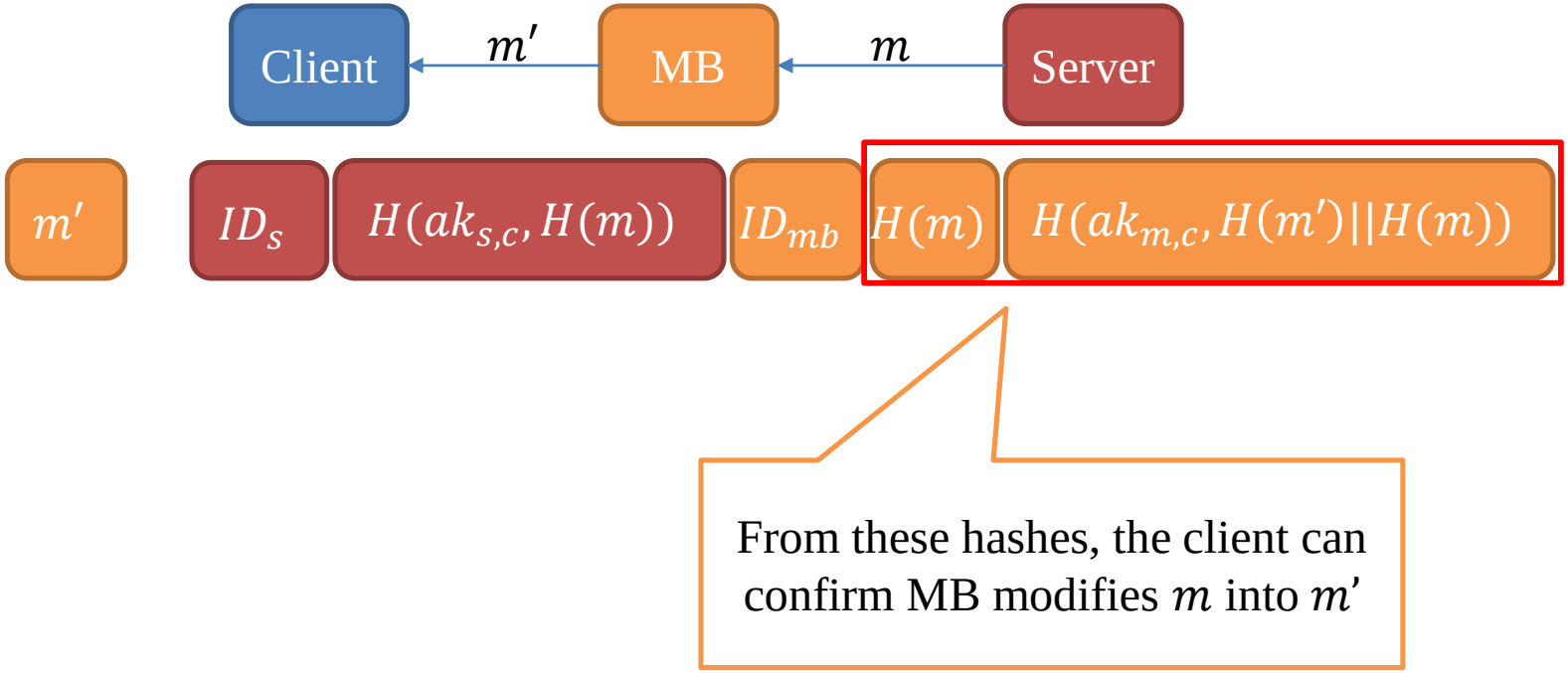

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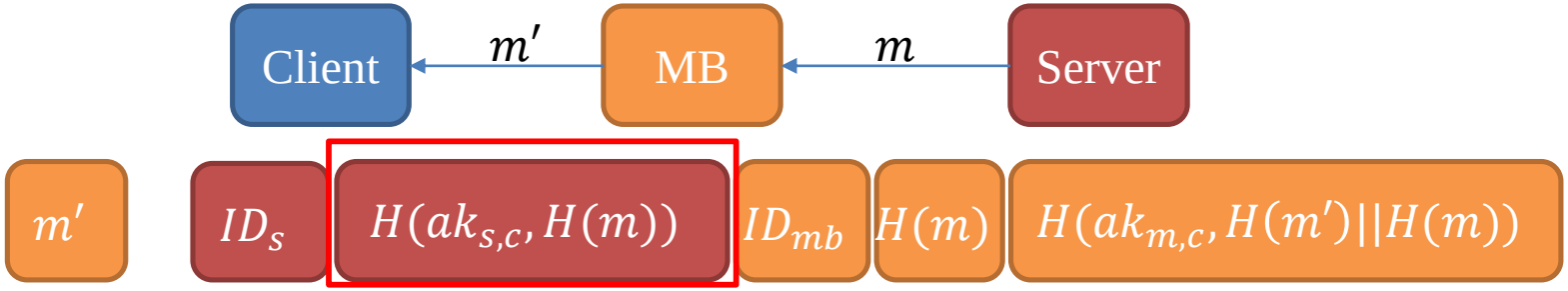

From this hash, the client can confirm the server generates m,
even though the client cannot confirm m itself

Client knows

- $ak_{s,c}$: The accountability key with the server
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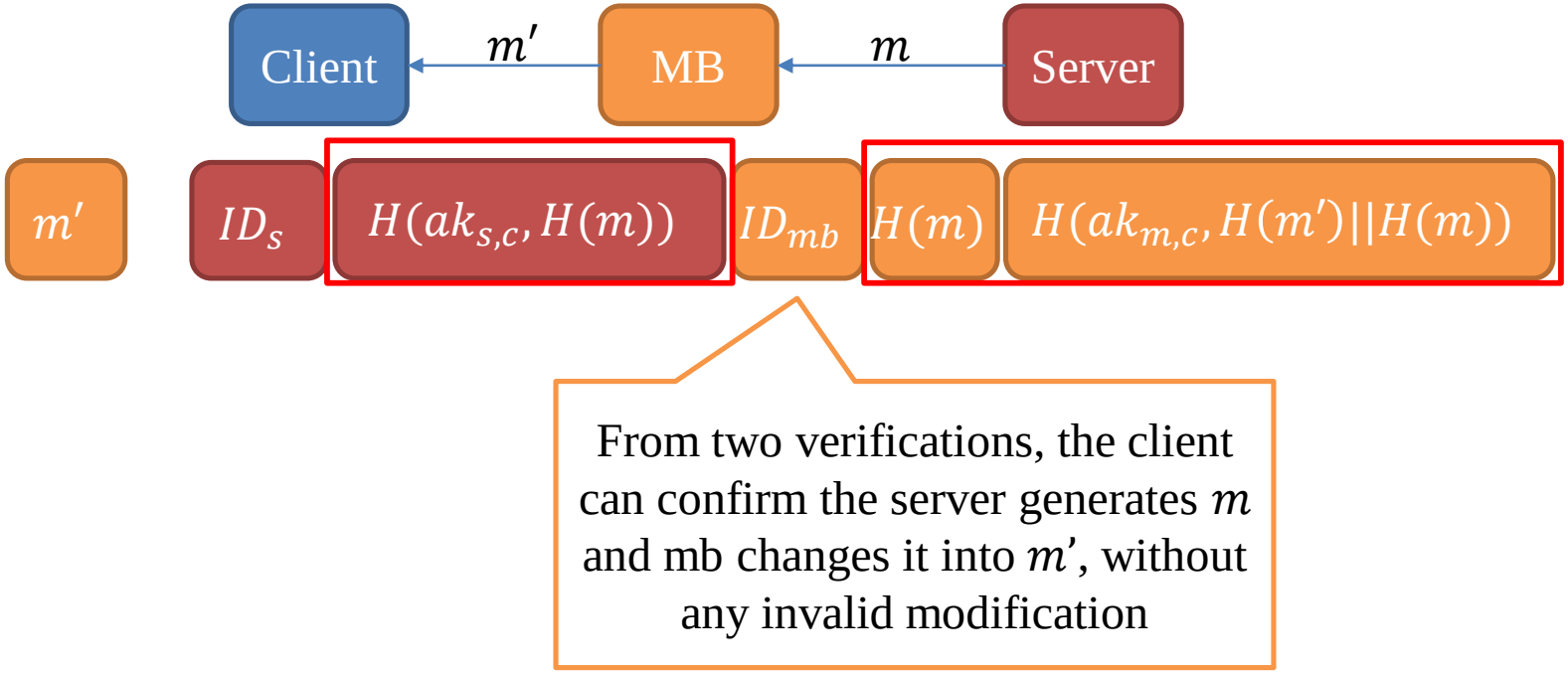

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