Composition Kills:
A Case Study of Email Sender Authentication

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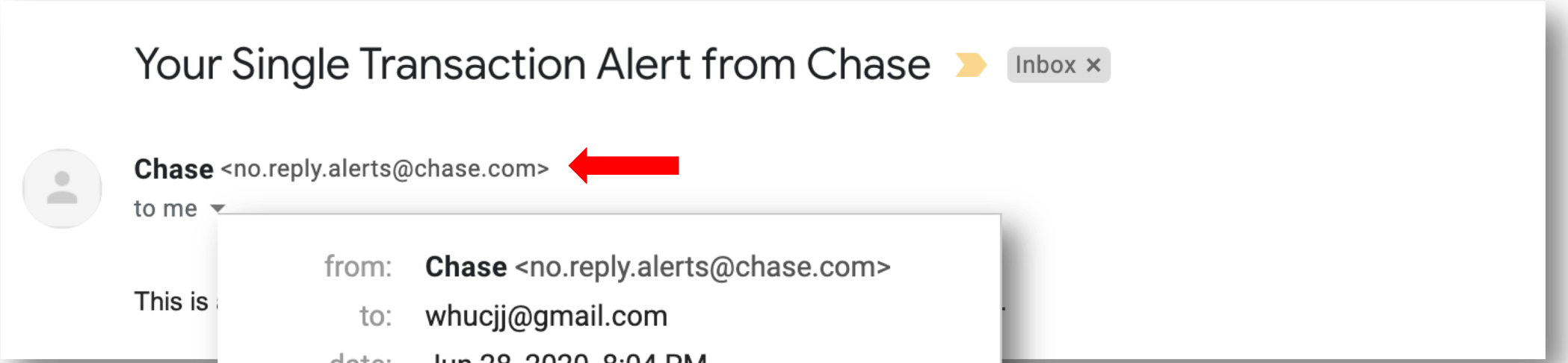
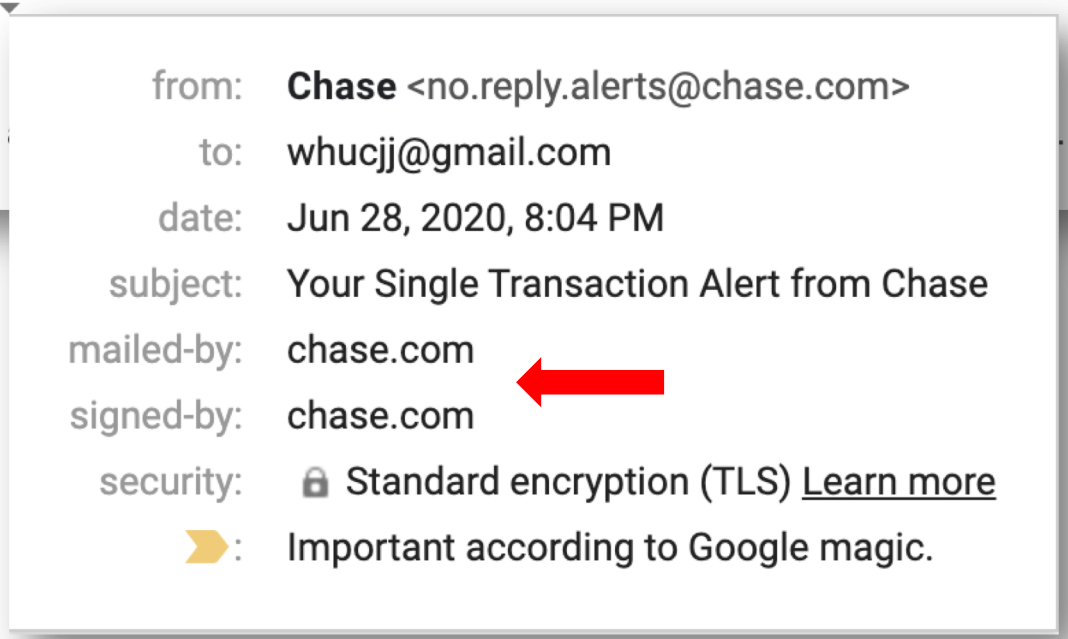
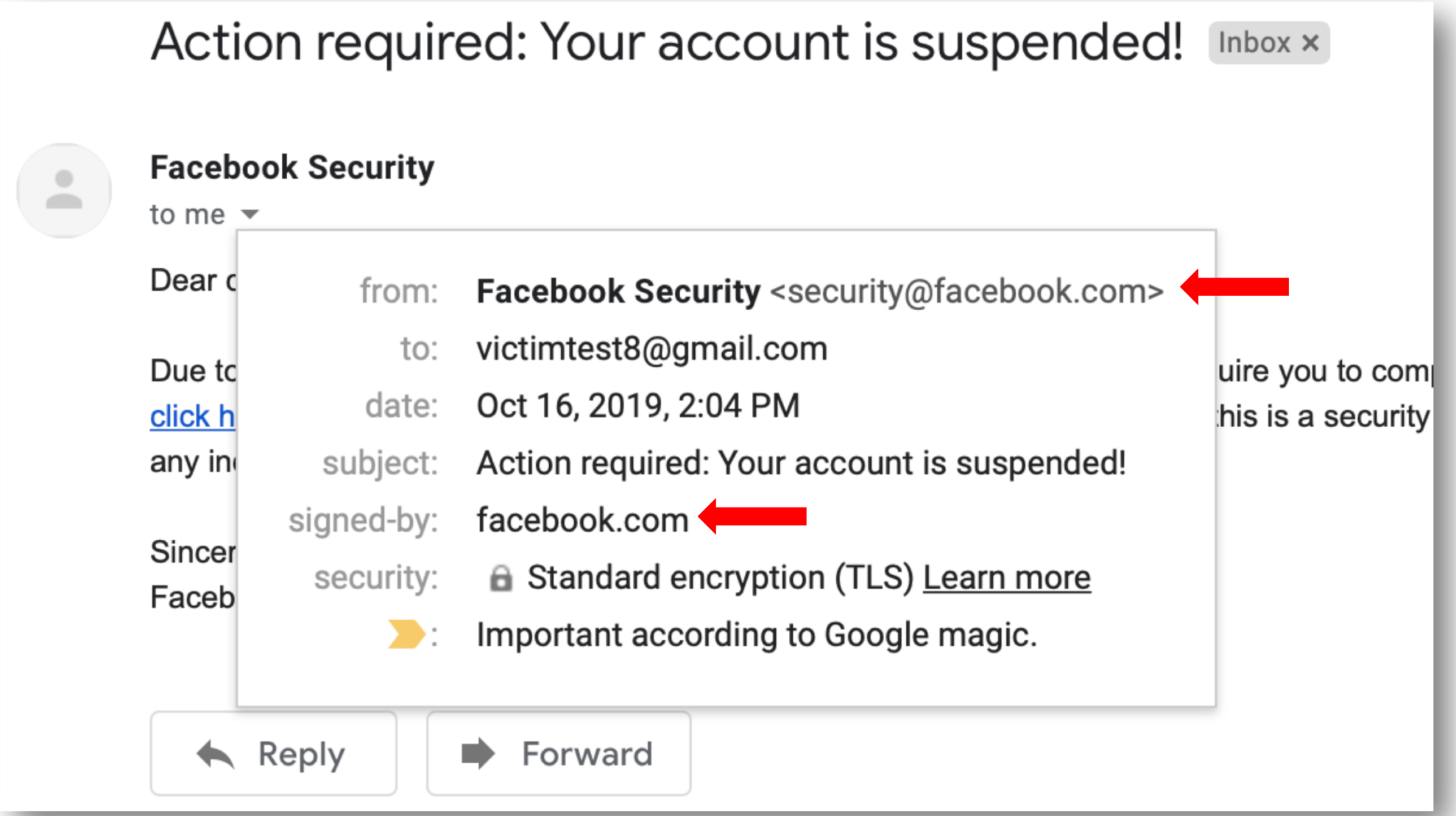
F5 (shape security)

How Do You Verify the Email Sender?





A Case of Our Spoofing Attacks on Gmail (Fixed)



Background:
Sender & Authentication

Background: Who's the Sender?

SMTP envelope

HELO helo.sender.com
MAIL FROM: <s@mfrom.sender.com>
RCPT TO: <bob@email.com>

The user who transmitted the message (usually not displayed)

From: Secure Bank <noreply@bank.com>
To: Bob <bob@email.com>
Subject: Account Alert: Suspicious Purchase

Dear Bob,

We are writing to inform you that…

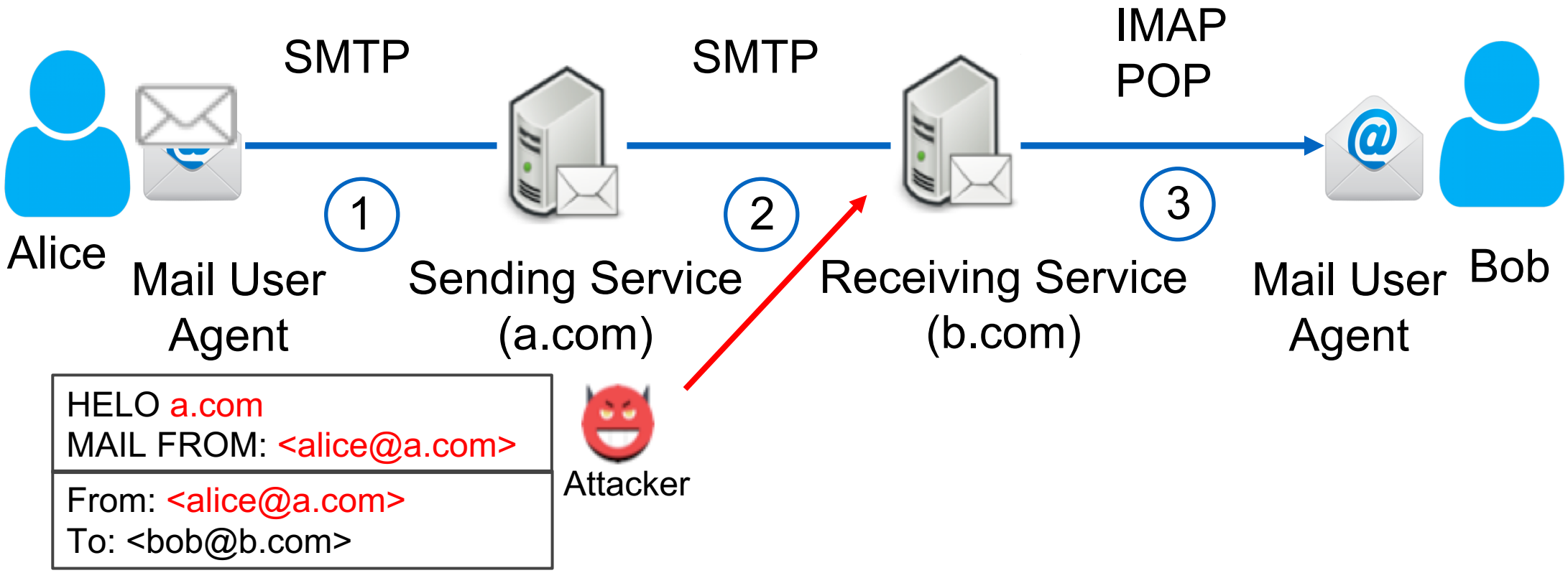
The user who composed the message (Visible to the end-user)

Message data

Background: SMTP Lacks Authentication

The original SMTP has no built-in authentication mechanism

- Anyone can spoof any identity in HELO/MAIL FROM and From



Three Sender-Authentication Protocols

- Sender Policy Framework (SPF, RFC 7208)
  - verifying the IP address of the sending domain
- DomainKeys Identified Mail (DKIM, RFC 6376)
  - verifying the email is signed by the sending domain
- Domain Message Authentication, Reporting and Conformance (DMARC, RFC 7489)
  - “how to” policy for recipient based on SPF and DKIM
  - “fix” the alignment problem of SPF and DKIM

Sender Policy Framework (SPF)

1 Publish authorized IP lists via DNS

2 Query the domain in HELO and MAIL FROM to obtain the IP lists

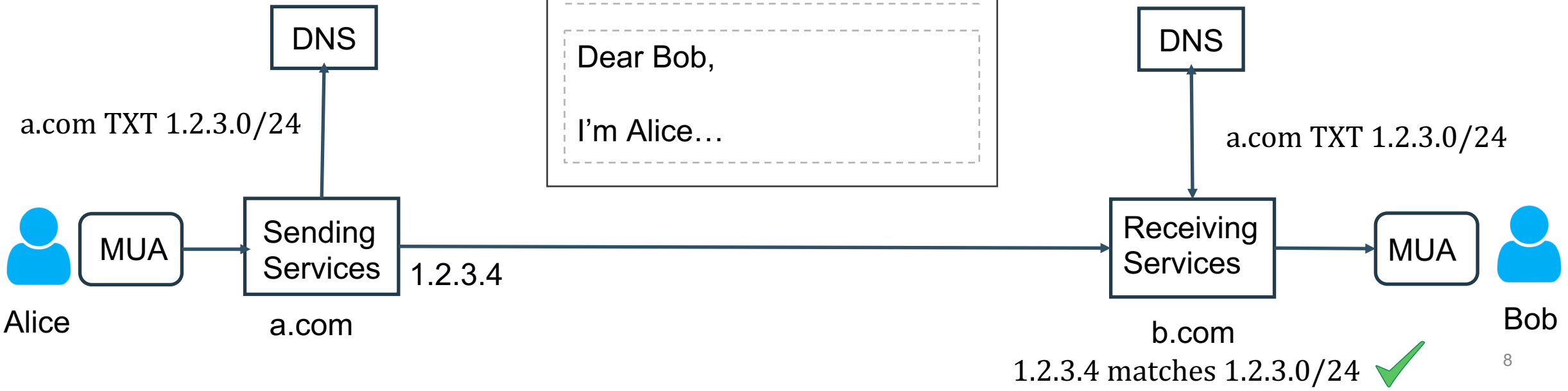
3 Check if the sender's IP matches the IP lists
- If yes, SPF pass

HELO a.com
MAIL FROM: <s@a.com>
RCPT TO: <bob@b.com>

From: Alice <alice@a.com>
To: Bob <bob@b.com>
Subject: Hello from Alice

Dear Bob,

I'm Alice…



DomainKeys Identified Mail (DKIM)

1. Publish public key via DNS

2. Generate DKIM-Signature with private key and attach it to the message.

HELO ehlo.a.com
MAIL FROM: <s@mfrom.a.com>
RCPT TO: <bob@b.com>

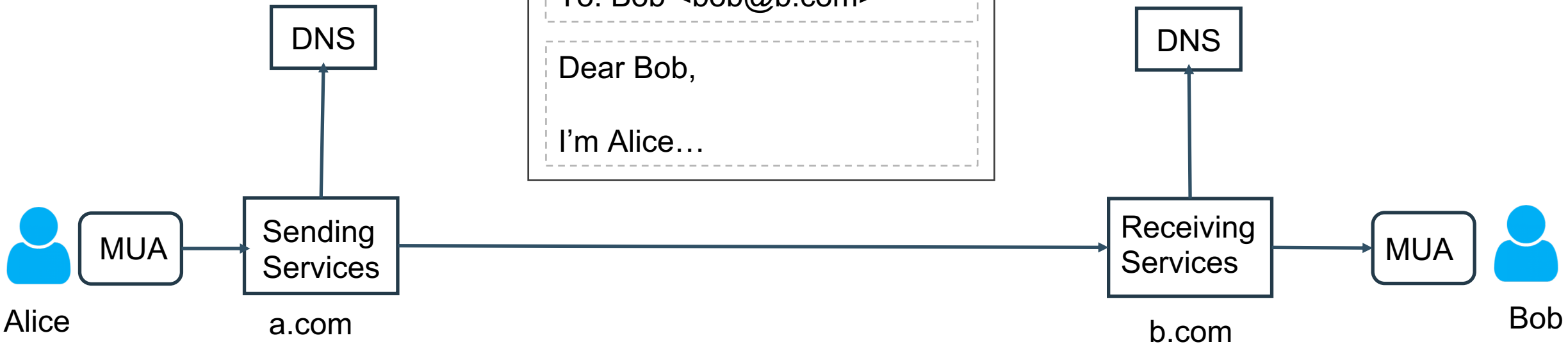
DKIM-Signature: ...;d=a.com; s=any;…
From: Alice <alice@a.com>
To: Bob <bob@b.com>

Dear Bob,

I'm Alice…

3. Query "s._domainkey.d" (any._domainkey.a.com) to obtain public key

4. Validate DKIM signature with the public key



What's Wrong with SPF/DKIM?

HELO ehlo.attack.com
MAIL FROM: <s@mfrom.attack.com>
RCPT TO: <bob@b.com>

DKIM-Signature: ...;d=attack.com;
s=2020;…
From: Alice <alice@a.com>
To: Bob <bob@b.com>
Subject: Hello from Alice

Dear Bob,

I'm Alice…

What SPF verifies

What DKIM verifies

What the end-user sees

Neither SPF nor DKIM validate the From header that is displayed to the end-user.

Domain Message Authentication, Reporting and Conformance (DMARC)

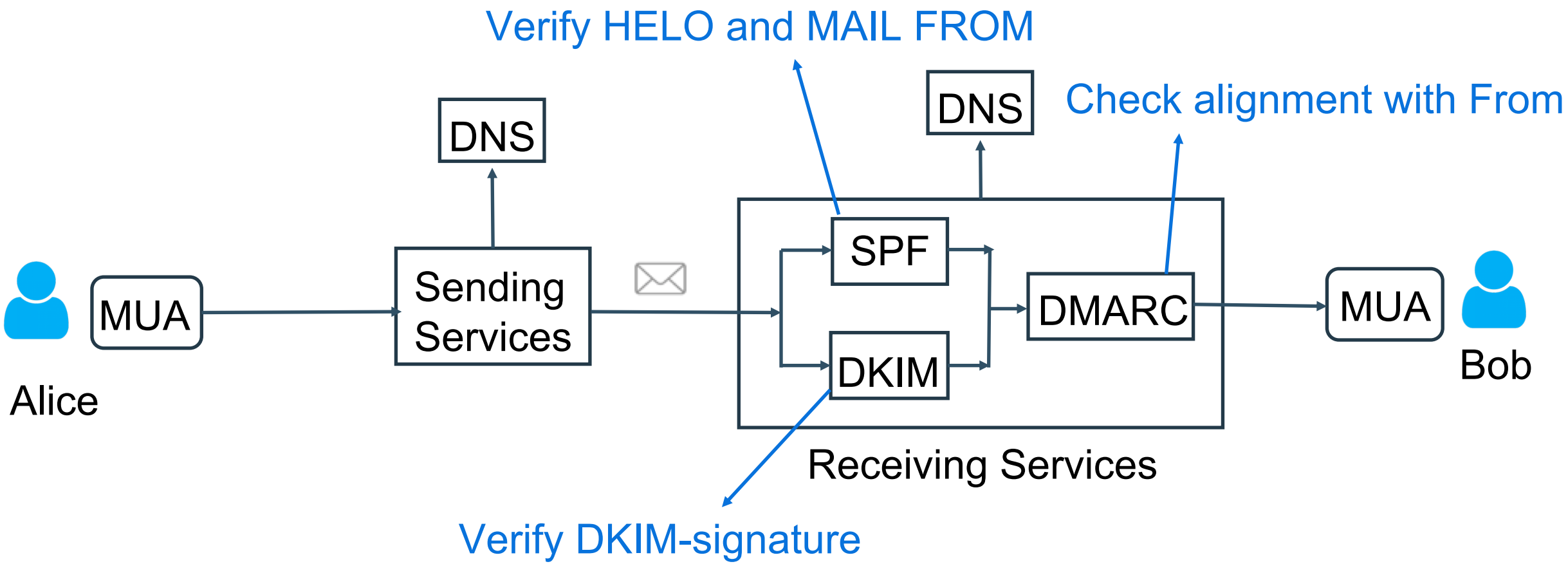
③ Receiving services perform **identifier alignment test** to check if the domain in From header matches SPF or DKIM-verified domain.

- Exactly match (strict) or have the same registered domain* (relaxed, default mode)

④ The email passes DMARC authentication if:
1) either SPF or DKIM show a positive result, and
2) the From header domain passes the alignment test.

* Defined in public suffix list, https://publicsuffix.org/

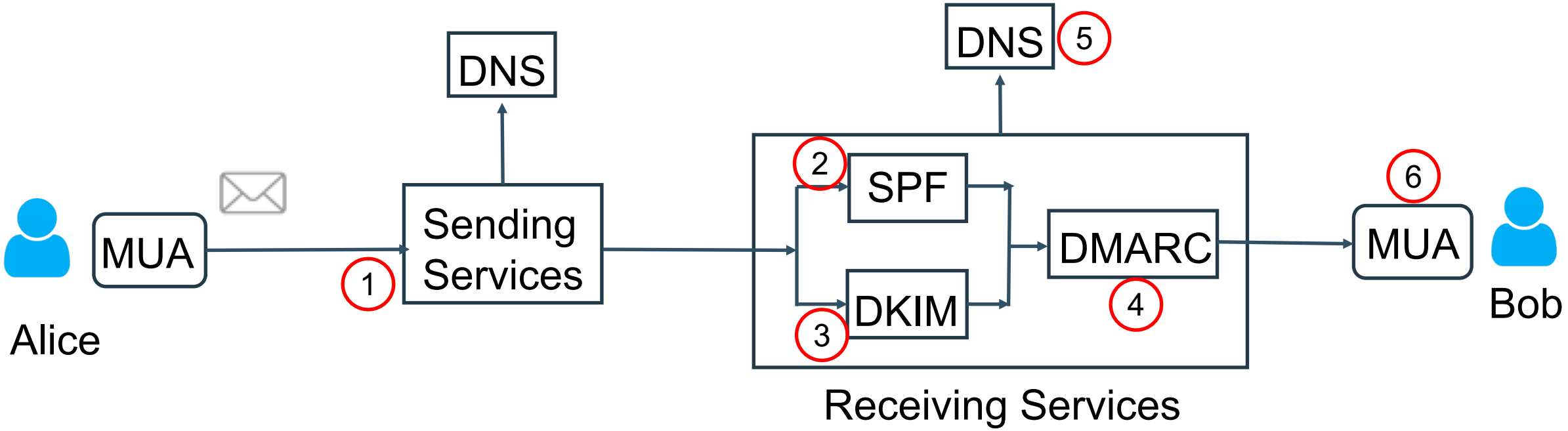
Overview of Email Authentication Flow



What could possibly go wrong?

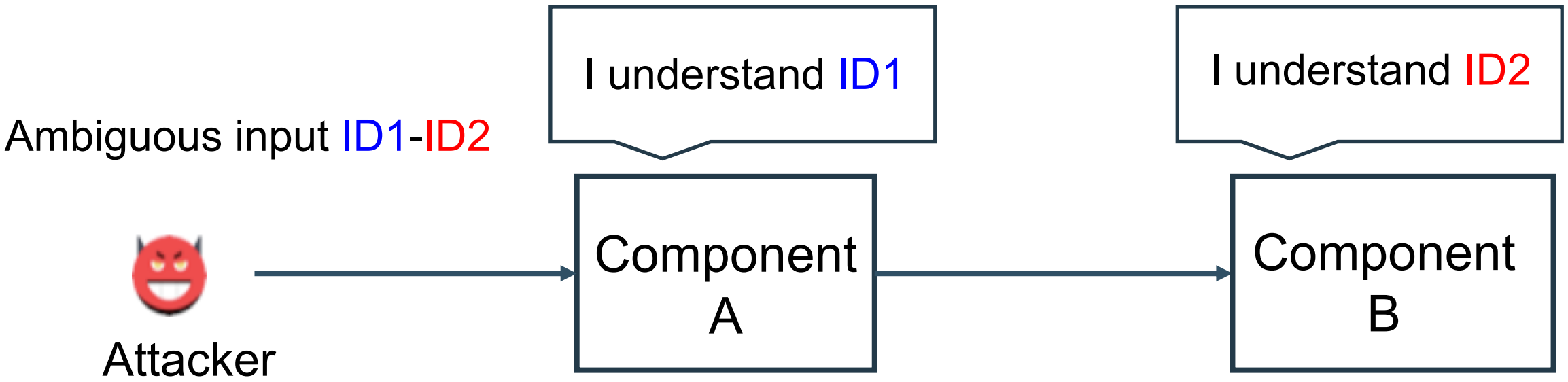
Bypassing the Authentication

Key Idea of Our Attacks



Inconsistencies between different components could lead to security vulnerabilities.

Key Idea of Our Attacks



Inconsistencies between different components could lead to security vulnerabilities.

Exp. 1: Inconsistencies b/w DKIM and DNS

Ambiguity: What DKIM uses differs from what DNS queries

HELO attack.com
MAIL FROM: <any@attack.com>

DKIM-Signature: ...;d=bank.com;
s=attack.com.\x00.any;...
From: <sec@bank.com>
To: <victim@victim.com>

Dear Customer,

We are writing to inform you that…

1. Attacker signs the message with his private key and sends the message
2. When receiving the message, DKIM should query 's._domainkey.d' to obtain the public key. (attack.com.\x00.any._domainkey.bank.com)
3. But DNS takes \x00 as a terminator, and obtains public key from *attack.com*
4. DKIM **pass**, DMARC **pass**

Exp. 2a: Multiple From Headers

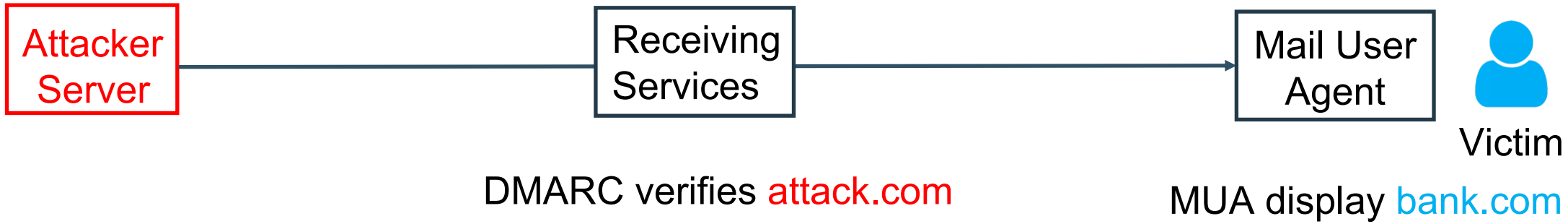
Ambiguity: What receiving server verifies differ from what MUA displays

From: <any@attack.com>
From: <admin@bank.com>
To: <victim@victim.com>

Dear Customer,…

From: <any@attack.com>
From: <admin@bank.com>
To: <victim@victim.com>

Dear Customer,…



- RFC 5322: Messages with multiple From should be rejected
- In practice: 19/29 accept (15 use first, 3 use last, 1 show both)

Exp. 2b: Multiple From Headers with Space

Three types of variants:

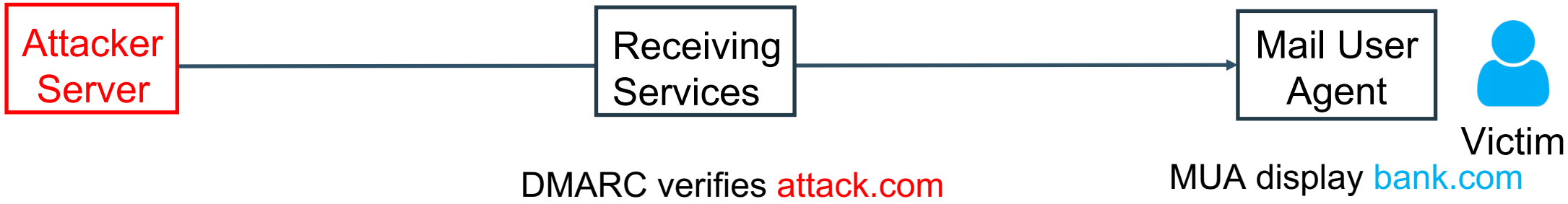
1) _From: a@a.com ; 2) From_: a@a.com; 3) From\r\n_: a@a.com

```
From
  : <any@attack.com>
From:  <admin@bank.com>
To: <victim@victim.com>

Dear Customer,…
```

```
From
   : <any@attack.com>
From:  <admin@bank.com>
To: <victim@victim.com>

Dear Customer,…
```



Exp. 3: From Alternative Headers

- 7/19 MUAs display Sender or Resent-From header value when From header is absent

From
: <any@attack.com>
Sender: <admin@bank.com>
To: <victim@victim.com>

Dear Customer,…

From
: <any@attack.com>
Sender: <admin@bank.com>
To: <victim@victim.com>

Dear Customer,…

Email Parsing Process

Complex From Header Syntax

Display Name Comments Route portion Real address

From: Secure (b@b.com) Bank <@c.com, @d.com: a@a.com (e@e.com) > (f@f.com)

A quick example of valid (!) From header

- **Multiple address lists.** [RFC 5322]
- **Encoding**: defined to support no-ascii character. [RFC 2047]

  From: bob <b@b.com> is equal to

  From: =?utf-8?B?Ym9i?=<b@b.com> in Base64 encoding
- **Quoted-pair**: use '\' to escape special characters like '('. [RFC 5322]

Exp. 4a: Exploiting Differences in Feature Support

From: <any@attack.com>, <admin@legitimate.com>

Mail server — Email client

From: <@attack.com, @any.com: admin@legitimate.com>

Mail server — Email client

From: bs64(<admin@legitimate.com>), <any@attack.com>

Email client — Mail server

Exp. 4b: Exploiting Parsing Inconsistencies

From: <admin@legitimate.com>\, <any@attack.com>

Email client — Mail server

From: admin@legitimate.com, <any@attack.com>

Email client — Mail server

From: <any@attack.com>admin@legitimate.com

Mail server — Email client

How Prevalent are UI-mismatch Vulnerabilities?

Table 2: Vulnerability of the tested email providers and MUAs to UI-mismatch attacks.

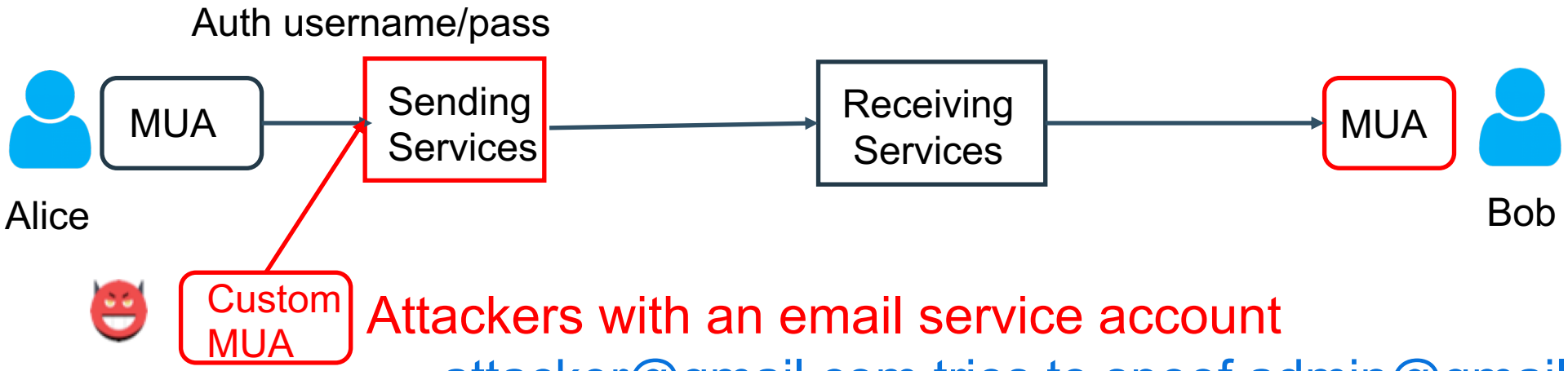
Servers \ MUAs	Web interface	Windows		MacOS		Linux	Android		iOS	
		Mail	Outlook	Mail	eM Client	Thunderbird	Gmail	Outlook	Mail	Gmail
Gmail.com	✓	✓			✓			✓		✓
iCloud.com	✓	✓				✓				
Outlook.com	✓					✓				
Yahoo.com	✓									✓
Naver.com	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Fastmail.com	✓	✓			✓			✓		✓
Zoho.com		✓	✓		✓			✓		✓
Tutanota.com	✓	—	—	—	—	—	—	—	—	—
Protonmail.com	✓	—	—	—	—	—	—	—	—	—
Mail.ru		✓	✓	✓	✓	✓	✓	✓	✓	✓

"✓": email server and MUA combination where we can expose an inconsistent interpretation.
"—": email providers that don't support third-party MUAs for our testing account.

- 43 out of 82 different combinations that could be exploited
- What we found only constitutes a subset of the problem

Exp. 5: Spoofing via an Email Service Account

Ambiguity: What sending server validates differ from what MUA displays



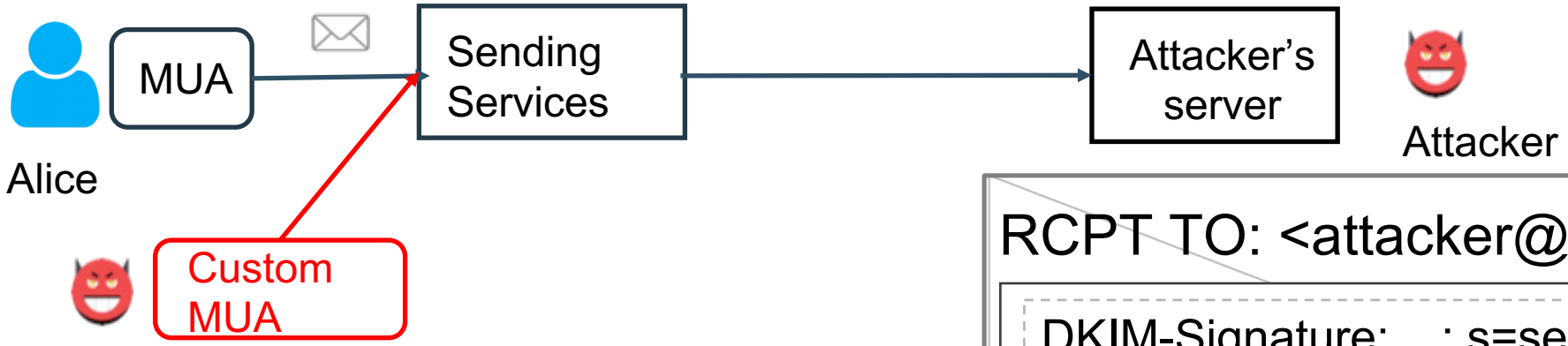
Attackers with an email service account

- attacker@gmail.com tries to spoof admin@gmail.com

- Sending services should ensure that the From header matches authenticated username
  - But From header validation is error-prone because of complex syntax
- We found 7 out of 8 email providers are vulnerable

Exp. 6: Combing Replay and Multiple-From Ambiguity (1/2)

① Attacker emails himself through the email provider server.



RCPT TO: <attacker@gmail.com>

DKIM-Signature: ...; s=selector;
d=gmail.com;...
From: <attacker@gmail.com>
To: <victim@victim.com>

Dear Customer,

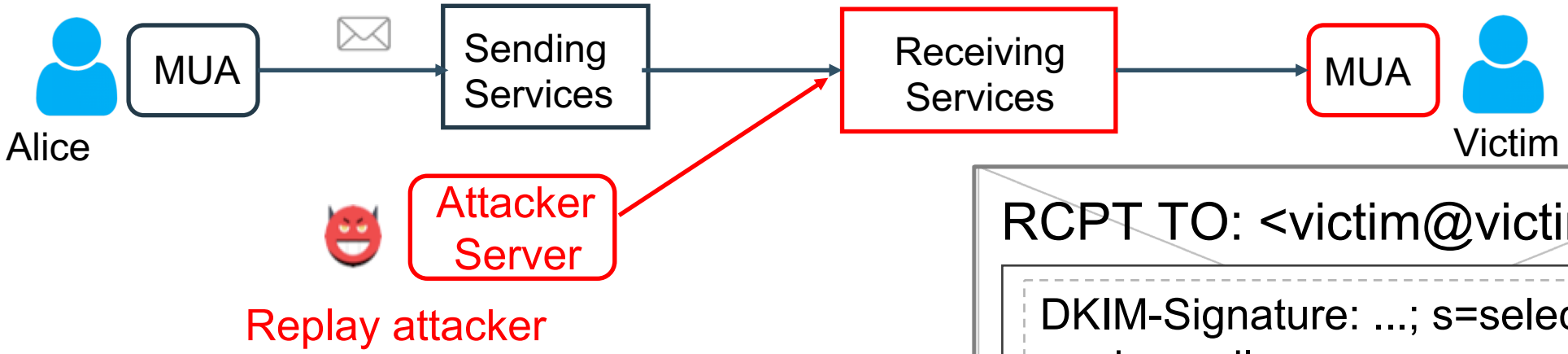
We are writing to inform you that…

Attackers with an email service account

- Create deceptive content in body, To, and Subject, but not From header

Exp. 6: Combing Replay and Multiple-From Ambiguity (2/2)

② Attacker replays the messages with an extra From header.



RCPT TO: <victim@victim.com>

DKIM-Signature: ...; s=selector;
d=gmail.com;...
From: <admin@gmail.com>
From: <attacker@gmail.com>
To: <victim@victim.com>

Dear Customer,
We are writing to inform you that…

Ambiguity: What DKIM verifies differs from what MUA displays

- DKIM components verify the last header
- MUAs show the first header

Thinking on Defense

- Better parsing and protocol spec
  - “Be ~~liberal~~ **strict** in what you accept”
  - make protocol implementation-friendly
    - simple, well-typed/structured messages, reduce/avoid multiple party processing
- Better UI
  - UI needs more explicit security indicators
- For end-users
  - Don’t blindly trust the email sender displayed in email client
  - Use end-to-end authentication such as PGP
    - PGP may also have parsing ambiguities, but hopefully better than those in SPF/DKIM/DMARC.

New tool - espoofer

We will make this tool publicly available at

https://github.com/chenjj/espoofer

Thank you!

See more demo videos on Youtube.