Nonce-Disrespecting Adversaries: Practical Forgery Attacks on GCM in TLS

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TLS Encryption

1. ~~Asymmetric key exchange~~
   - ~~RSA, DHE, ECDHE~~

2. Symmetric encryption

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   - RC4 (stream cipher)
   - (new: ChaCha20/Poly1305)
   - AES-GCM

CBC / HMAC

- Arbitrary padding in SSLv3
- Implicit IVs in TLS 1.0
- MAC-then-Pad-then-Encrypt

2014 Poodle

2011 BEAST

2002 Padding Oracles

Lucky microseconds

Lucky 13

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RC4

- Generates a key stream
  - Some bytes more likely to occur

2001: Fluhrer, Mantin, Shamir

2013: Isobe et al.

2013: AlFardan et al.

2015: Vanhoef, Piessens

2015: Garman et al.

- https://www.rc4nomore.com/
- RFC 7465: Prohibiting RC4 Cipher Suites

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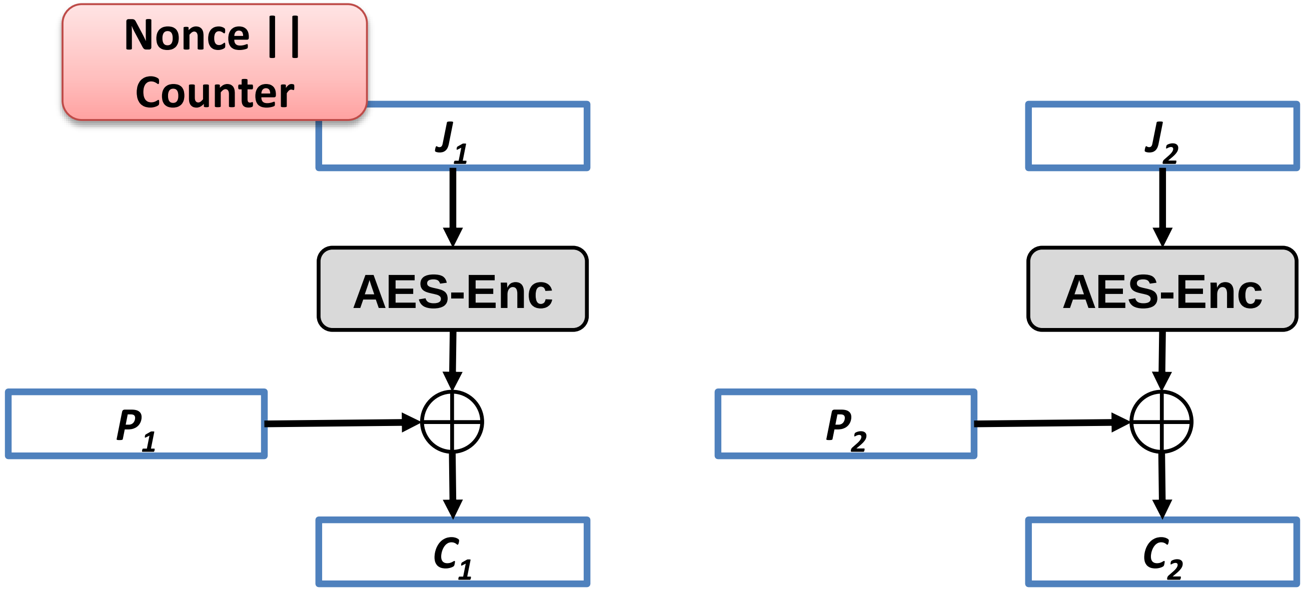
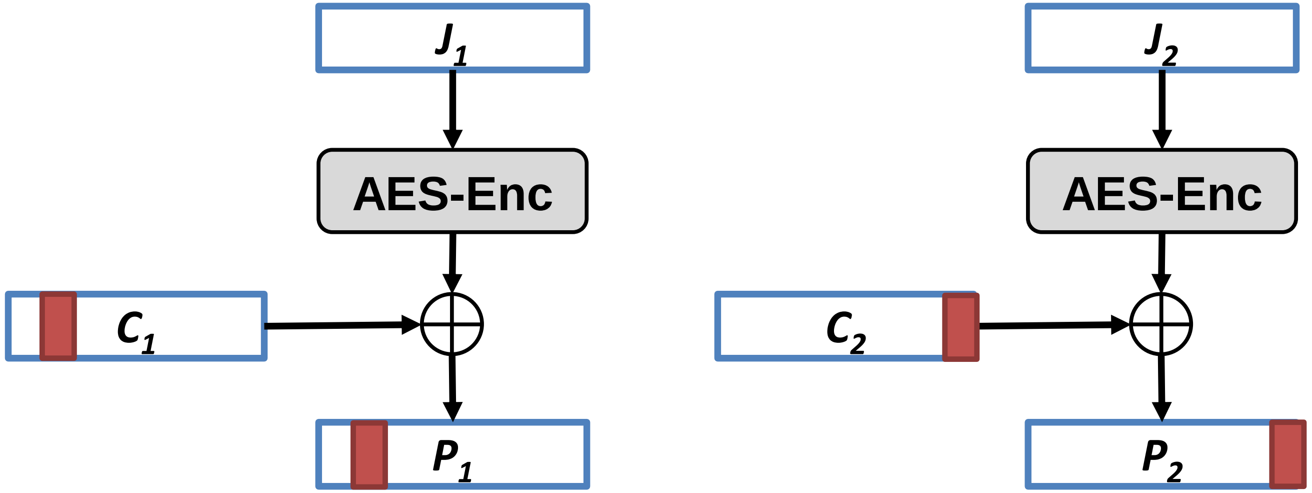
Overview

1. **AES-GCM**
2. **The Forbidden Attack**
3. **Evaluation**
4. **Attack Scenario**

AES Counter Mode



Bit Flipping in AES Counter Mode

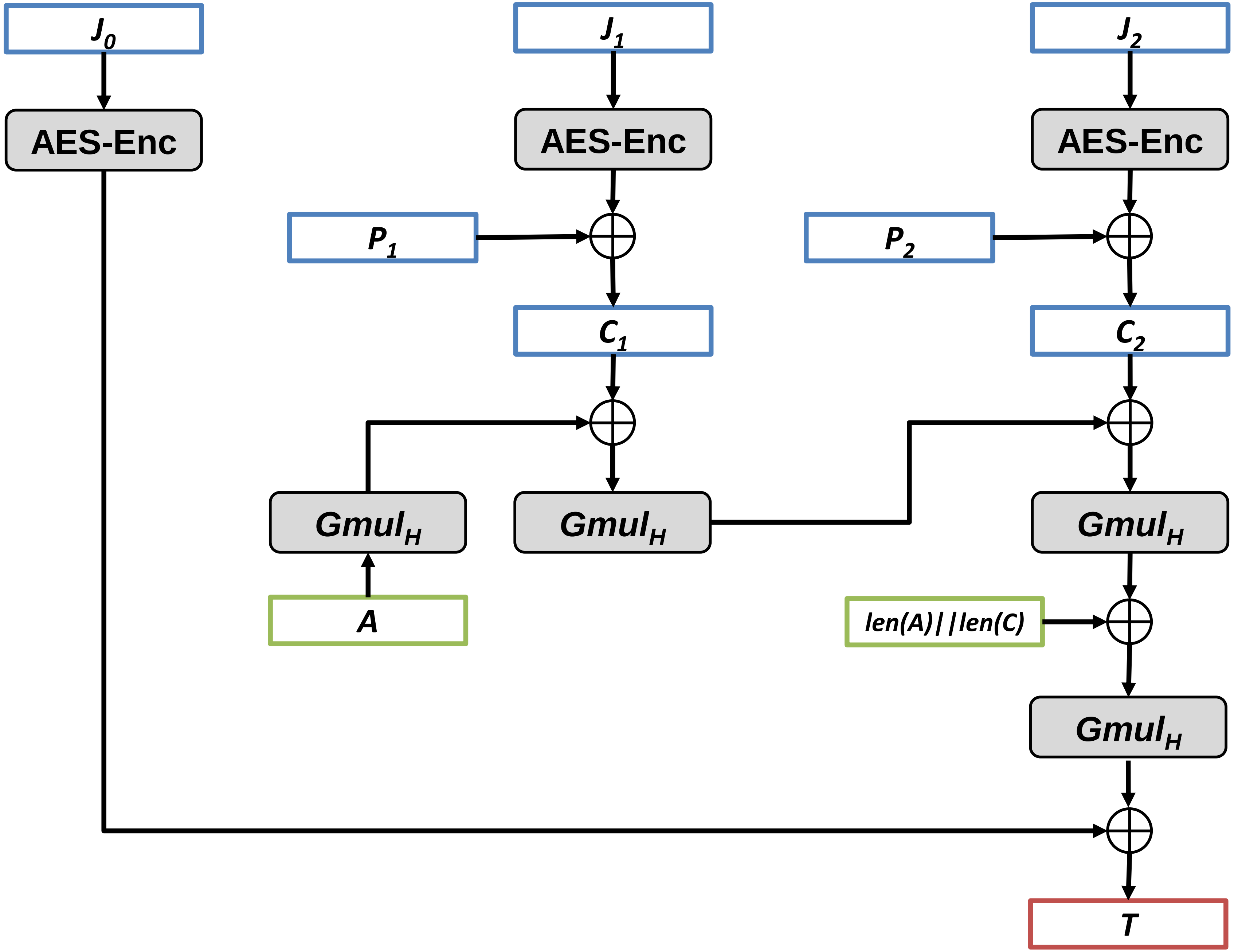


Attacker can modify messages

AES-GCM

- GCM – Galois Counter Mode
- AEAD (Authenticated Encryption with Additional Data)
- Only in TLS 1.2
- Combination of **Counter Mode** and **GHASH** authentication
  - Computed over Galois field

AES-GCM



Hash key ***H***

Encryption of 128

zero bits: ***H=Enc(0)***

Output: C || T

GCM: Opinions of Cryptographers

- "Do not use GCM. Consider using one of the other authenticated encryption modes, such as CWC, OCB, or CCM." (Niels Ferguson)
- "We conclude that common implementations of GCM are potentially vulnerable to authentication key recovery via cache timing attacks." (Emilia Käsper, Peter Schwabe, 2009)
- "AES-GCM so easily leads to timing side-channels that I'd like to put it into Room 101." (Adam Langley, 2013)
- "The fragility of AES-GCM authentication algorithm" (Shay Gueron, Vlad Krasnov, 2013)
- "GCM is extremely fragile" (Kenny Paterson, 2015)

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The Forbidden Attack

- Nonce:
  - – Number used once
  - – TLS: 8 Byte / 64 Bit nonce
- Joux (2006): Nonce reuse allows an attacker to recover the authentication key
- Attacker can modify messages

Consider one block

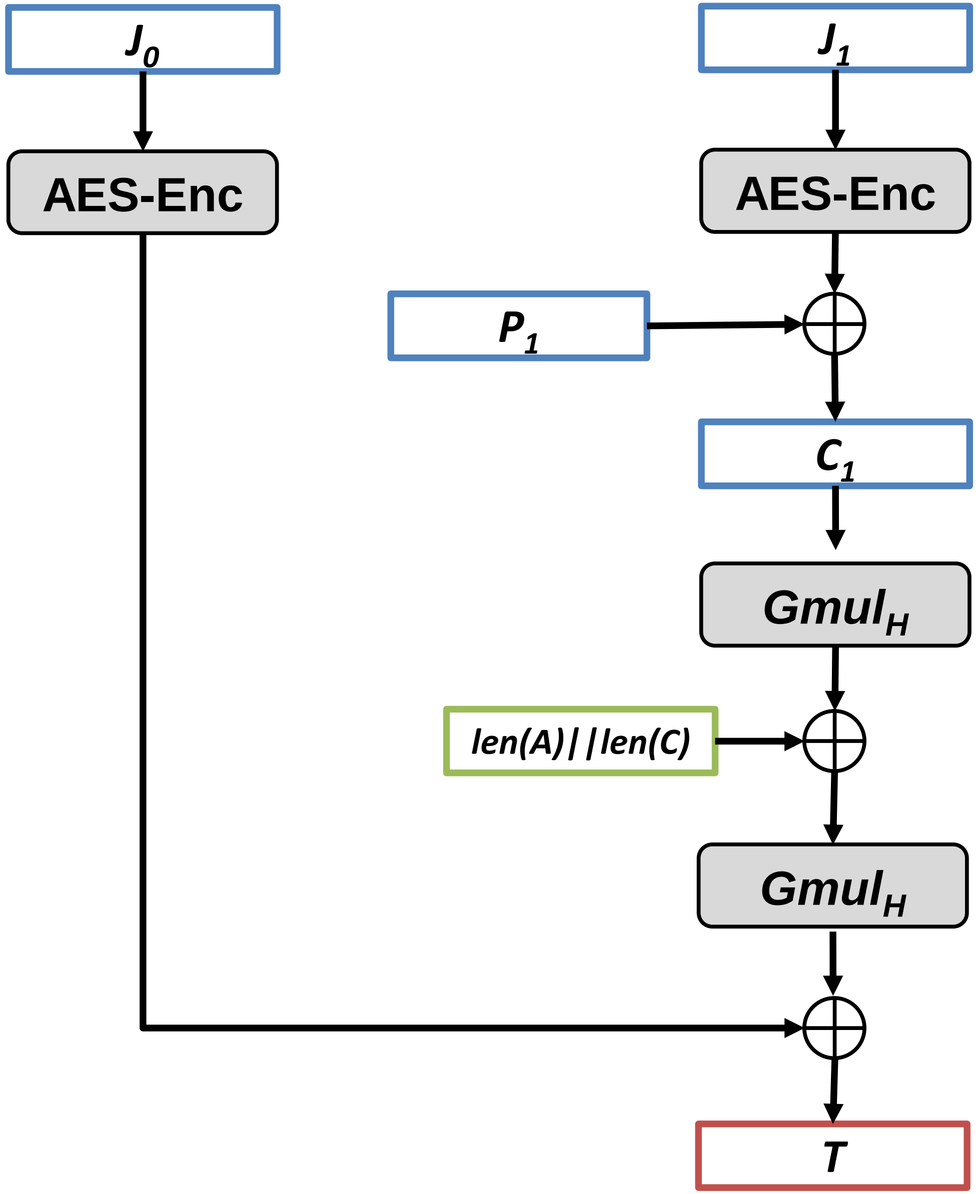
$H = AES\ (0)$

$T = \ (\ C_1 * H + L) * H \ \ + AES\ (J_0)$

$T = C_1 * H^2 + L * H + AES\ (J_0)$

Unknown values:

- H
- $AES\ (J_0)$



Duplicate nonce

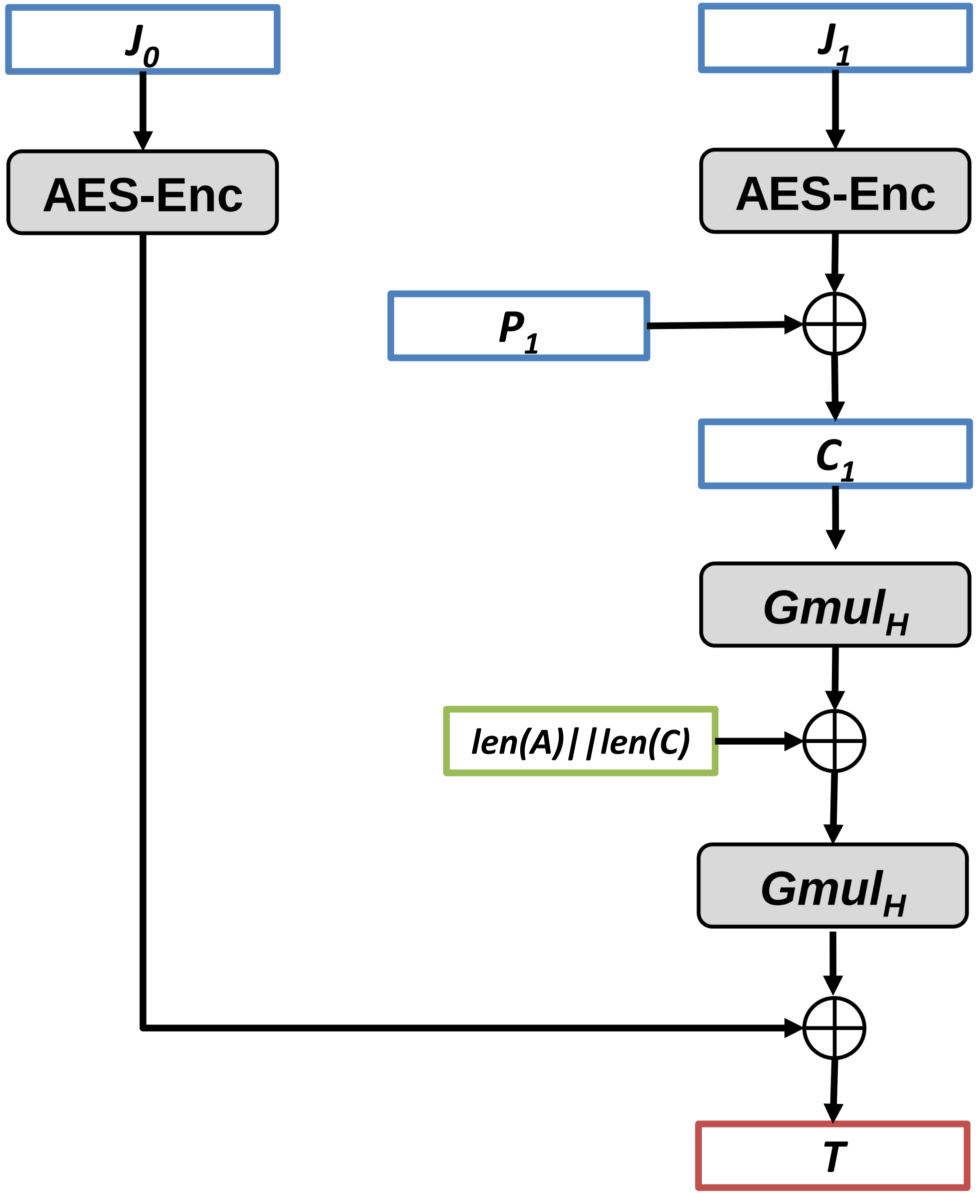
$H = AES\ (0)$

$T_1 = C_{1,1} * H^2 + L_1 * H + AES\ (J_0)$

$T_2 = C_{2,1} * H^2 + L_2 * H + AES\ (J_0)$

$$T_1 - T_2 = (C_{1,1} – C_{2,1}) * H^2 + (L_1 – L_2) * H$$

Finding *H* possible



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TLS 1.2 / RFC 5288

"Each value of the nonce_explicit **must** be distinct for each distinct invocation of the GCM encrypt function for any fixed key. Failure to meet this uniqueness requirement can **significantly degrade** security. The nonce_explicit **may** be the 64-bit sequence number.“

Two problems:

- Random nonces: Collision probability
- Repeating nonces

How about real implementations?

Internet-wide Scan

- **184** hosts with repeating nonces
  - Radware (Cavium chip)
  - Several pages from VISA Europe
- **72445** hosts with random looking nonces
  - A10, IBM Lotus Domino (both published updates)
  - Sangfor (no response)
- More devices that we were unable to identify

Example: Radware

```
0100000003001741
0100000003001741
f118cd0fa6ff5a15
f118cd0fa6ff5a16
f118cd0fa6ff5a74
```

OpenSSL 1.0.1j

```
e_aes.c (EVP_CIPHER_CTX_ctrl/aes_gcm_ctrl):

        if (c->encrypt &&
            RAND_bytes(gctx->iv + arg, gctx->ivlen - arg) <= 0)
            return 0;


t1_enc.c:

    if (EVP_CIPHER_mode(c) == EVP_CIPH_GCM_MODE)
        {
        EVP_CipherInit_ex(dd,c,NULL,key,NULL,(which & SSL3_CC_WRITE)
        EVP_CIPHER_CTX_ctrl(dd, EVP_CTRL_GCM_SET_IV_FIXED, k
        }
```

No random generation
return value check

Open Source Libraries

- Botan, BouncyCastle, MatrixSSL, SunJCE, OpenSSL

- No real problems
- Counter overflows in Botan and MatrixSSL

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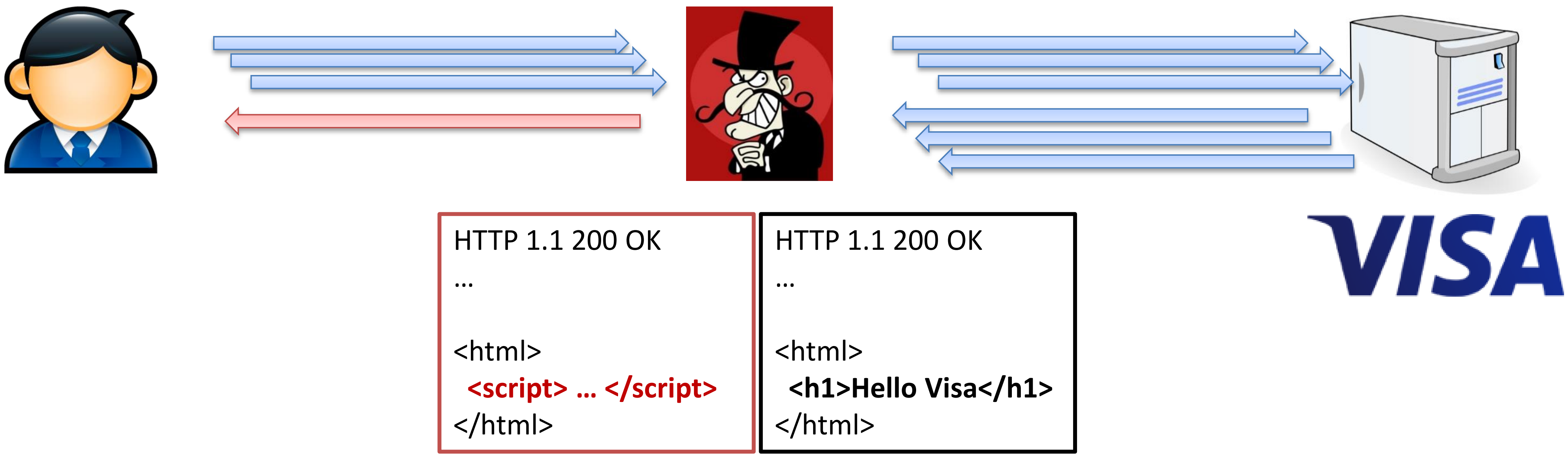
Attacking Vulnerable Websites

GET visa.dk/index.html

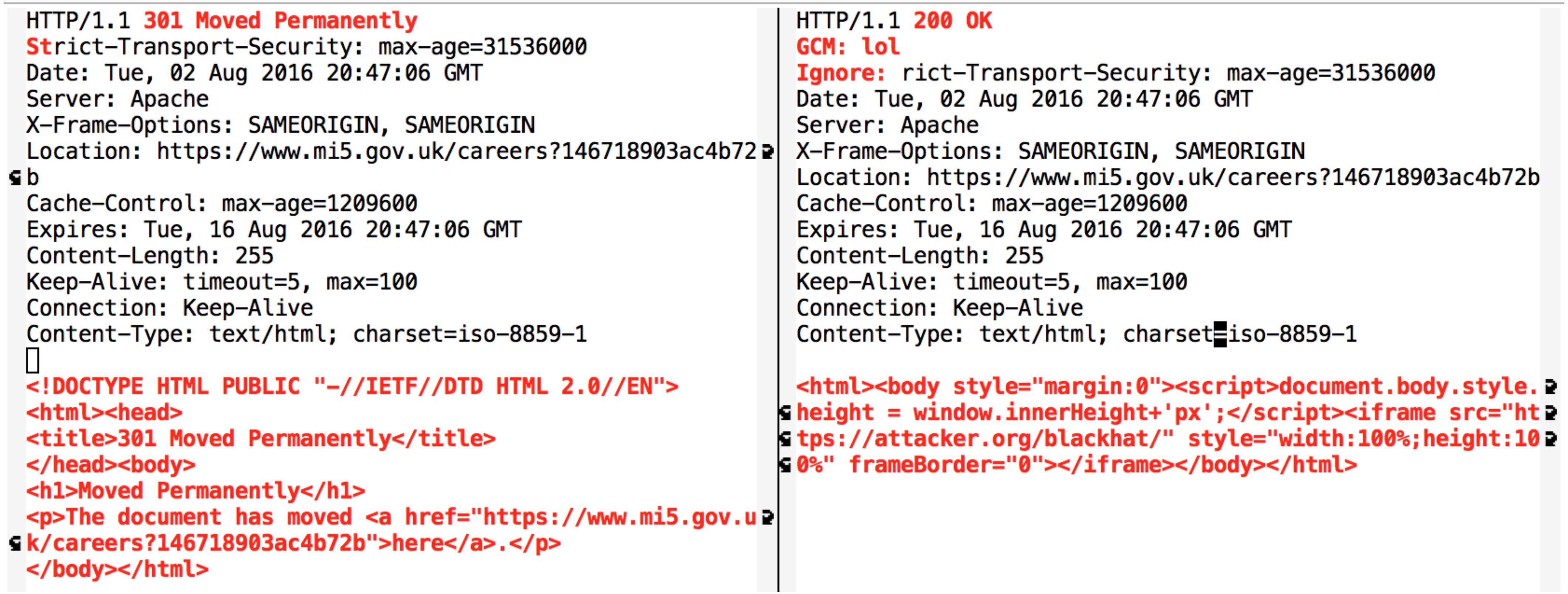


```
HTTP 1.1 200 OK
…

<html>
  <script> … </script>
</html>
```

```
HTTP 1.1 200 OK
…

<html>
  <h1>Hello Visa</h1>
</html>
```

Demo

Attacking mi5.gov.uk



```
HTTP/1.1 301 Moved Permanently
Strict-Transport-Security: max-age=31536000
Date: Tue, 02 Aug 2016 20:47:06 GMT
Server: Apache
X-Frame-Options: SAMEORIGIN, SAMEORIGIN
Location: https://www.mi5.gov.uk/careers?146718903ac4b72
b
Cache-Control: max-age=1209600
Expires: Tue, 16 Aug 2016 20:47:06 GMT
Content-Length: 255
Keep-Alive: timeout=5, max=100
Connection: Keep-Alive
Content-Type: text/html; charset=iso-8859-1
□
<!DOCTYPE HTML PUBLIC "-//IETF//DTD HTML 2.0//EN">
<html><head>
<title>301 Moved Permanently</title>
</head><body>
<h1>Moved Permanently</h1>
<p>The document has moved <a href="https://www.mi5.gov.u
k/careers?146718903ac4b72b">here</a>.</p>
</body></html>
```

```
HTTP/1.1 200 OK
GCM: lol
Ignore: rict-Transport-Security: max-age=31536000
Date: Tue, 02 Aug 2016 20:47:06 GMT
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Connection: Keep-Alive
Content-Type: text/html; charset=iso-8859-1

<html><body style="margin:0"><script>document.body.style.
height = window.innerHeight+'px';</script><iframe src="ht
tps://attacker.org/blackhat/" style="width:100%;height:10
0%" frameBorder="0"></iframe></body></html>
```

Conclusions

- TLS 1.2: no guidance how to use nonces correctly
  - Some people get it wrong
- **Implicit** nonces needed:
  - Chacha20/Poly1305 and TLS 1.3 based on record number
- Better test tools for TLS implementation flaws