Pseudo Constant Time Implementations of TLS Are Only Pseudo Secure

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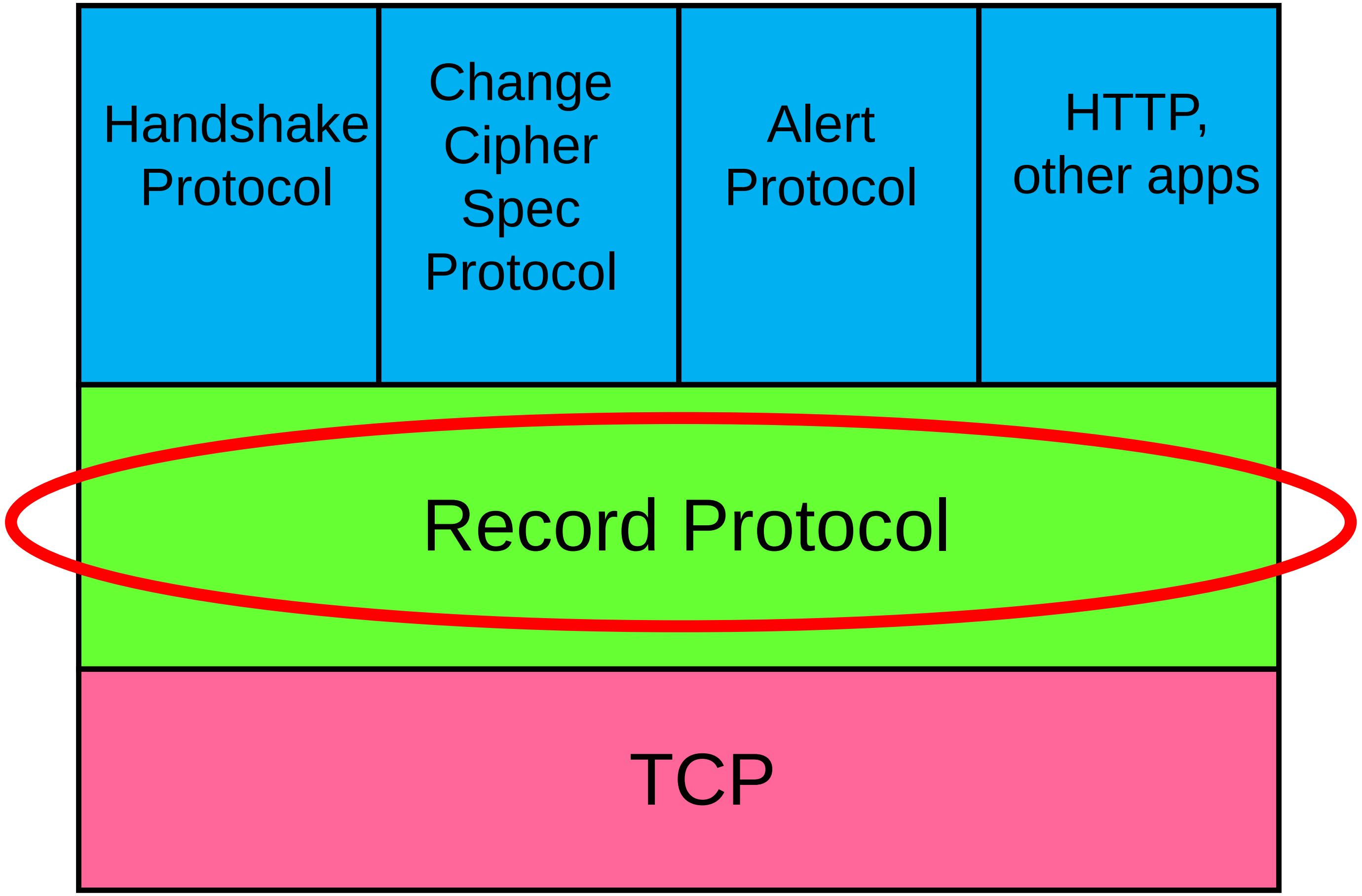
Talk Outline

1. TLS and CBC_HMAC ciphersuite
2. Side channel attack mitigations: Pseudo Vs Fully constant time
3. Padding attack on CBC_HMAC
4. New cache attacks on CBC_HMAC

Transport Layer Security (TLS)

- The most widely used cryptographic protocol
- Provides communication security (https, VPN, etc.)
  - TLS handshake is used for authentication and secure key exchange
  - TLS Record layer protects the communication
  - Allows for cryptographic agility using different cipher suites

Transport Record Layer

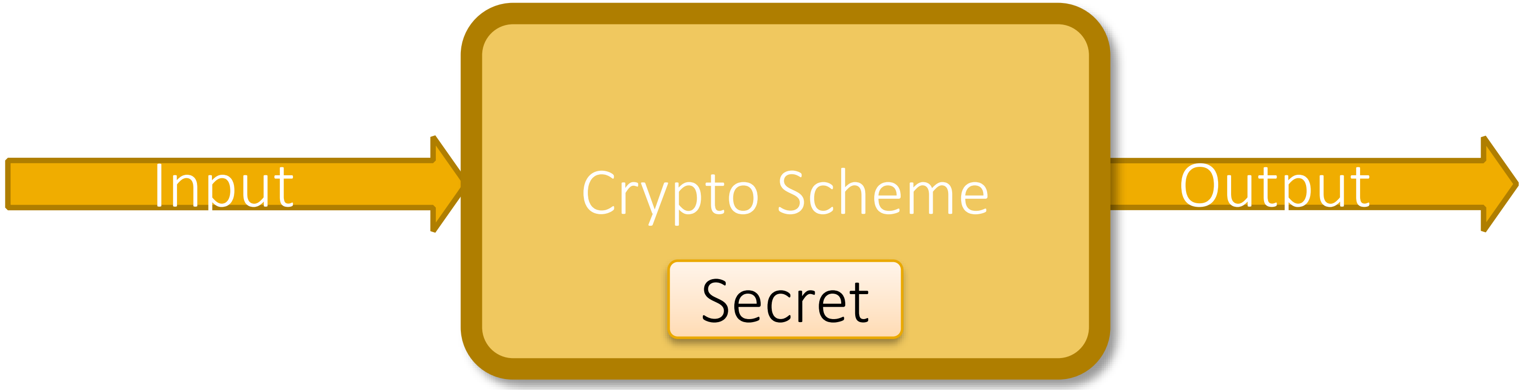


CBC_HMAC Ciphersuite in TLS

- Implements the HMAC-then-CBC scheme
- Once the most popular TLS record cipher suite
- Long history of practical **implementation** attacks

- Still widely used (Oct 2018)
  - ~8% by Mozilla's Telemetry
  - ~11% by ICSI Certificate Notary
  - Better alternatives now available (e.g. AES-GCM)
  - Supported for backwards compatibility

Crypto Scheme Vs Implementation



- HMAC-then-CBC functionality for TLS is secure* [Krawczyk01, PRS11]

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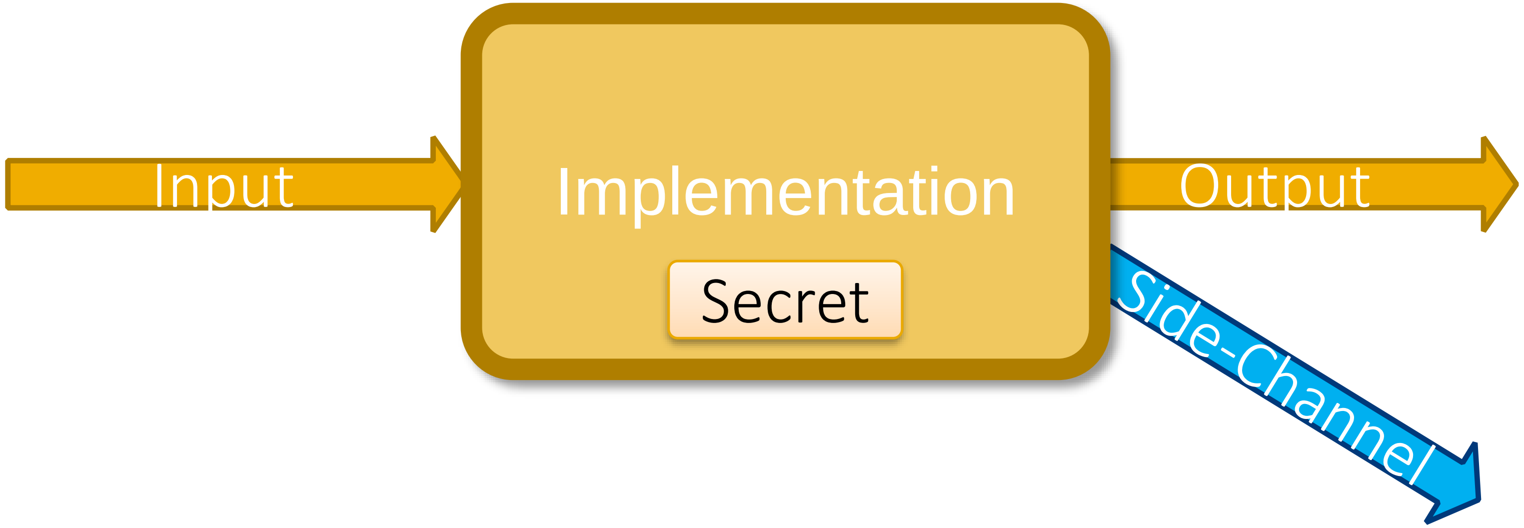

- Securely implementing CBC_HMAC for TLS is hard
  - Padding oracle attacks due to non constant time implementation
  - All implementations were vulnerable to Lucky 13 [AP 2013]
  - Multiple rounds of attacks and patches

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- Attacker might be able to see error messages, measure running time, detect memory access patterns, and more

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SSL

RSA

AES

Pseudo Vs Fully Constant time

Full Constant time

- Program flow independent from secret values
- Blocks all currently known classes of attacks*
- "Full" is easy to test
- Very high code complexity
  - Hard to write/review
  - OpenSSL AES-NI CBC_HMAC vulnerabilty (2013-2016)

Pseudo Constant time

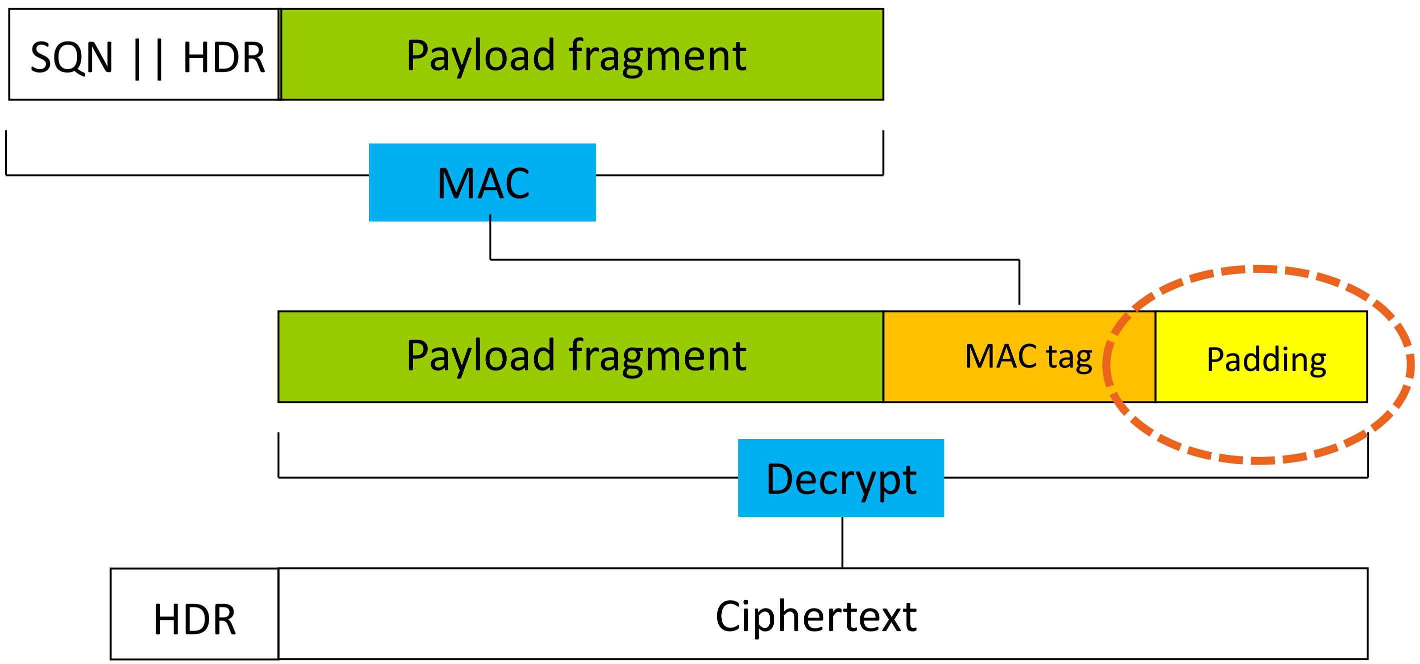
- Mask program flow dependencies on secret values
- Blocks only currently implemented attacks
- Lower code complexity
- "Pseudo" is Hard to test
  - Lucky 13 Strikes back [IIES 2015]
  - Lucky Microseconds [AP 2016]
  - ???

Our Findings

``All secure implementations are alike; each insecure implementation is buggy in its own way.'' -- after Leo Tolstoy, *Anna Karenina*

- All fully constant time implementations of HMAC-then-CBC are secure*
- All pseudo constant time implementations are vulnerable
  - Amazon's S2N, mbed TLS, GnuTLS, wolfSSL
  - All countermeasures were buggy
  - All implementations were vulnerable to different novel variants of cache attacks

CBC_HMAC – Lucky 13 Attack



HMAC-MD5, HMAC-SHA1, HMAC-SHA256

CBC-AES128, CBC-AES256, CBC-3DES, RC4-128

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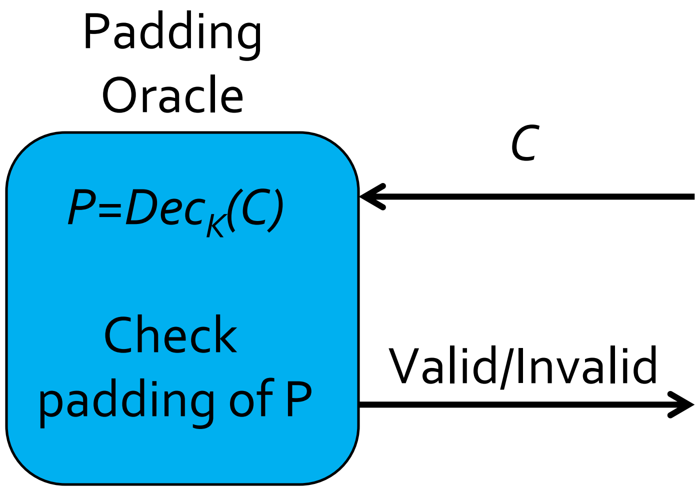
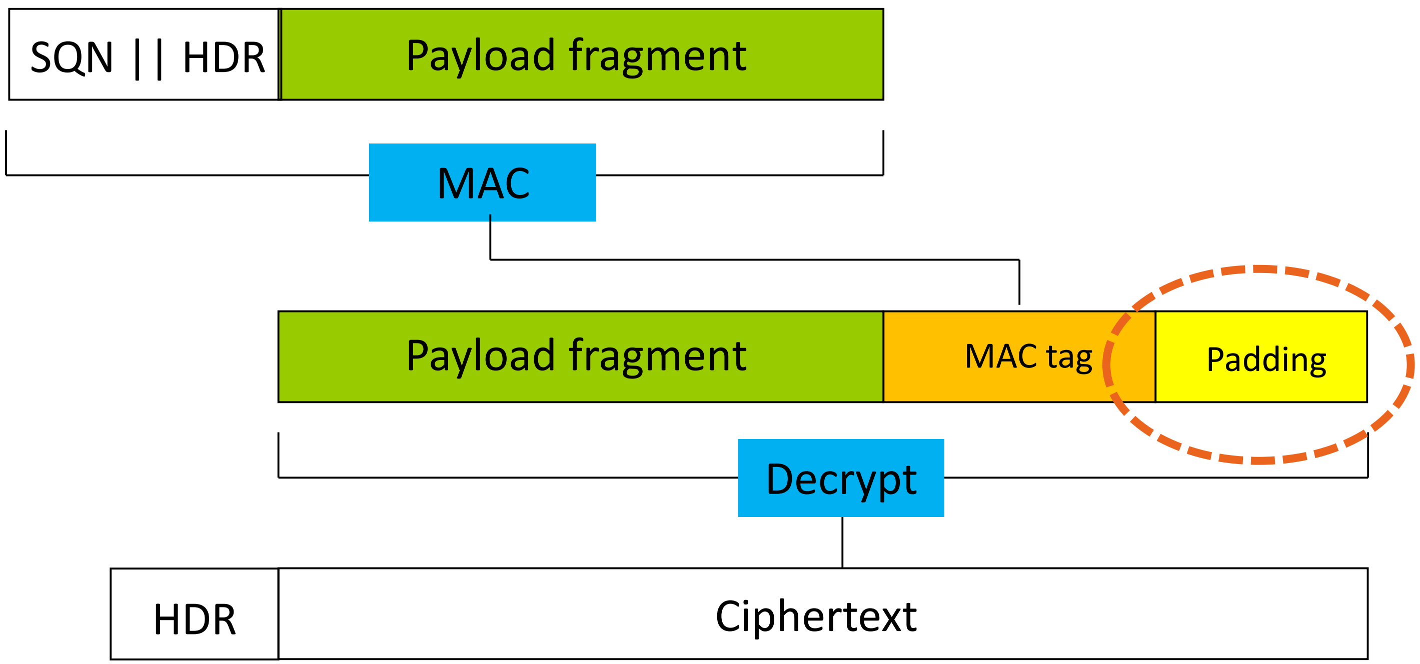
CBC Padding oracles [Vaudenay 2002]



- In CBC mode Padding Oracles can be used to build a Decryption Oracle

CBC_HMAC – Timing Padding Oracle



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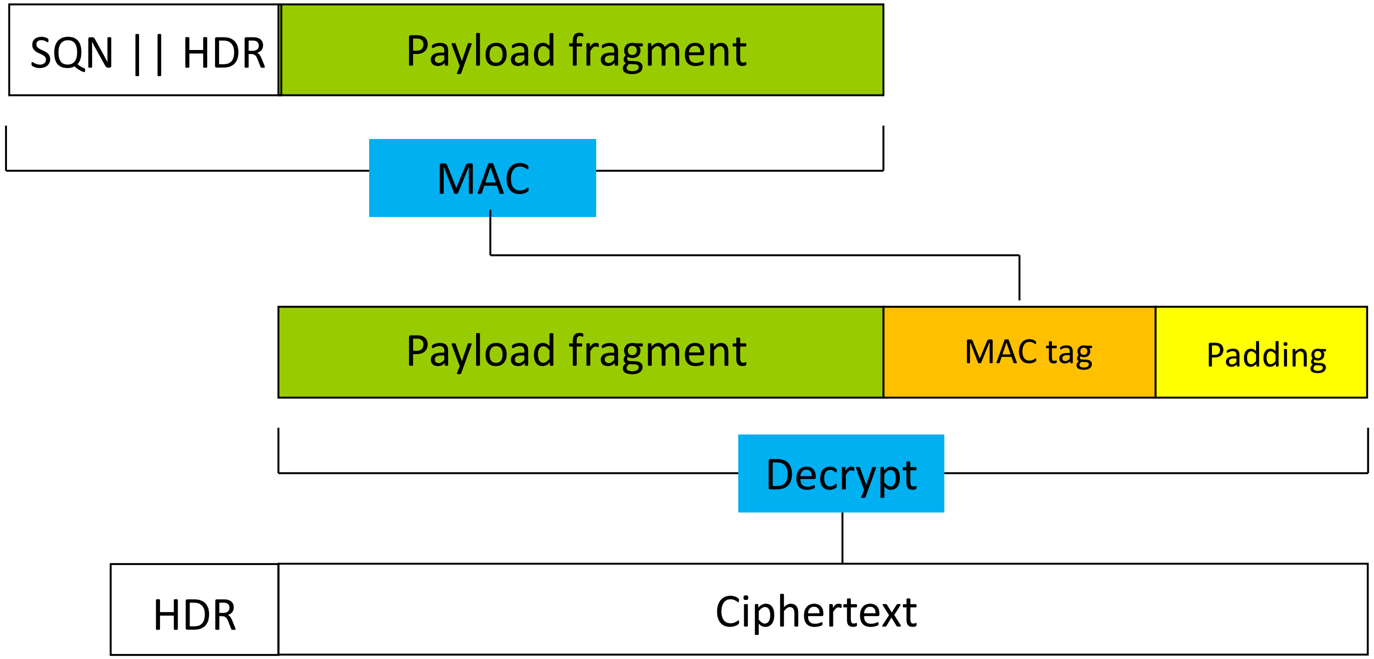
CBC_HMAC – Invalid Padding



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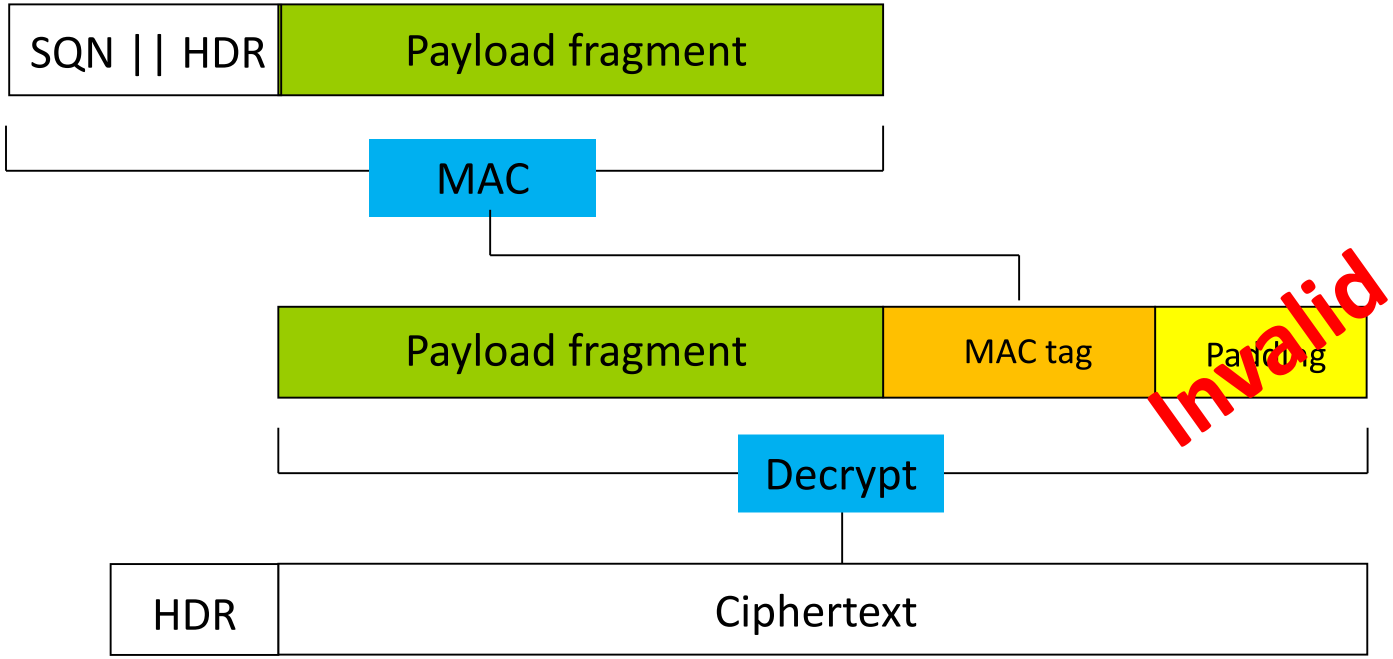

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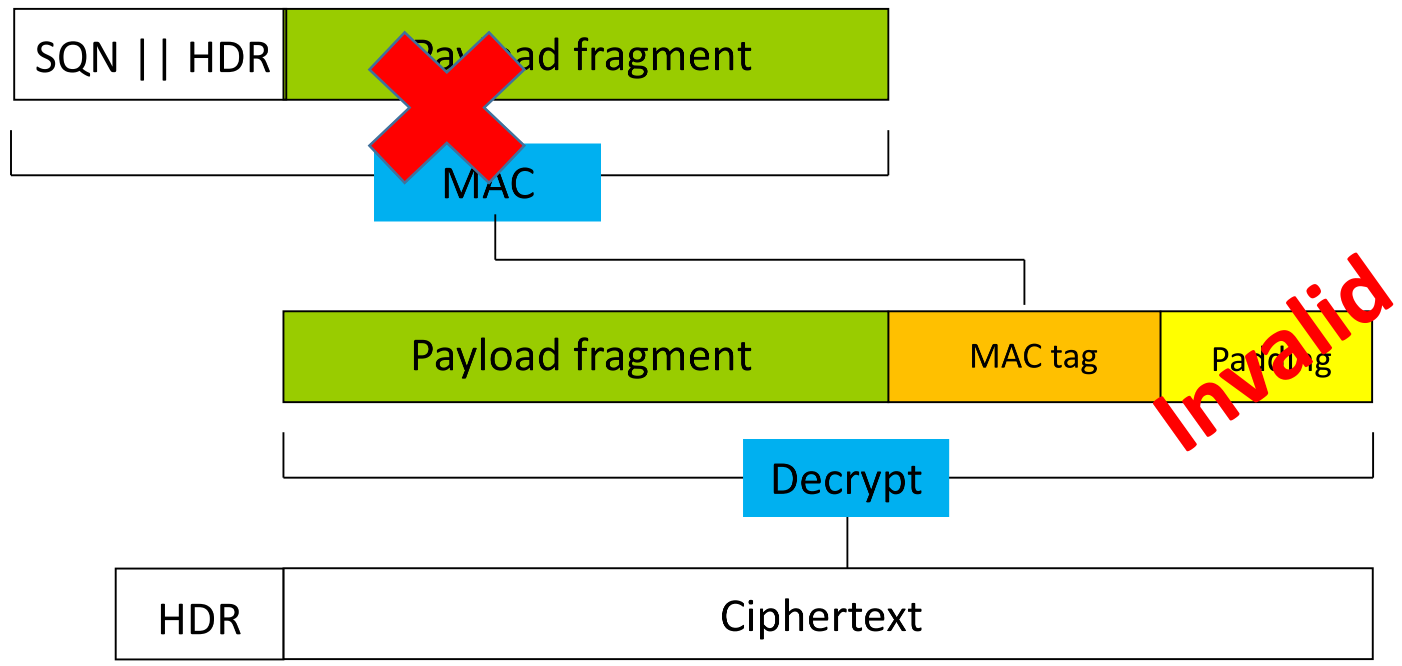

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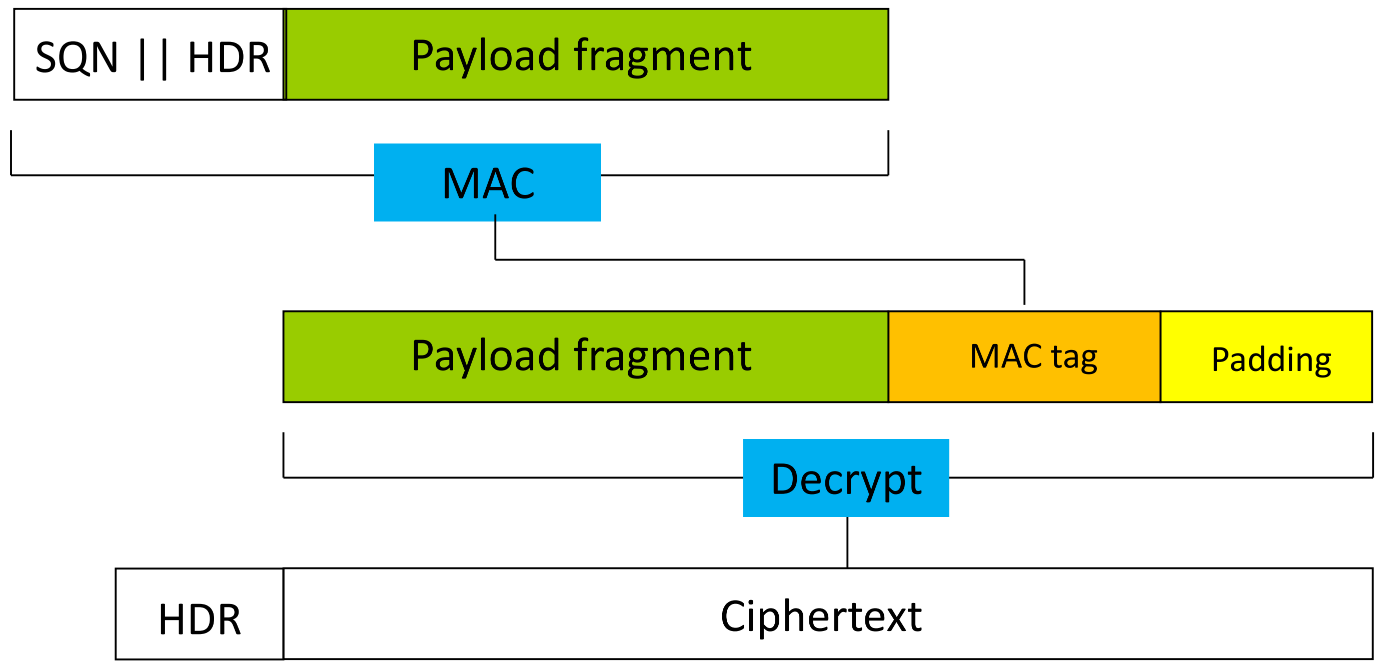
CBC_HMAC – Long Valid Padding



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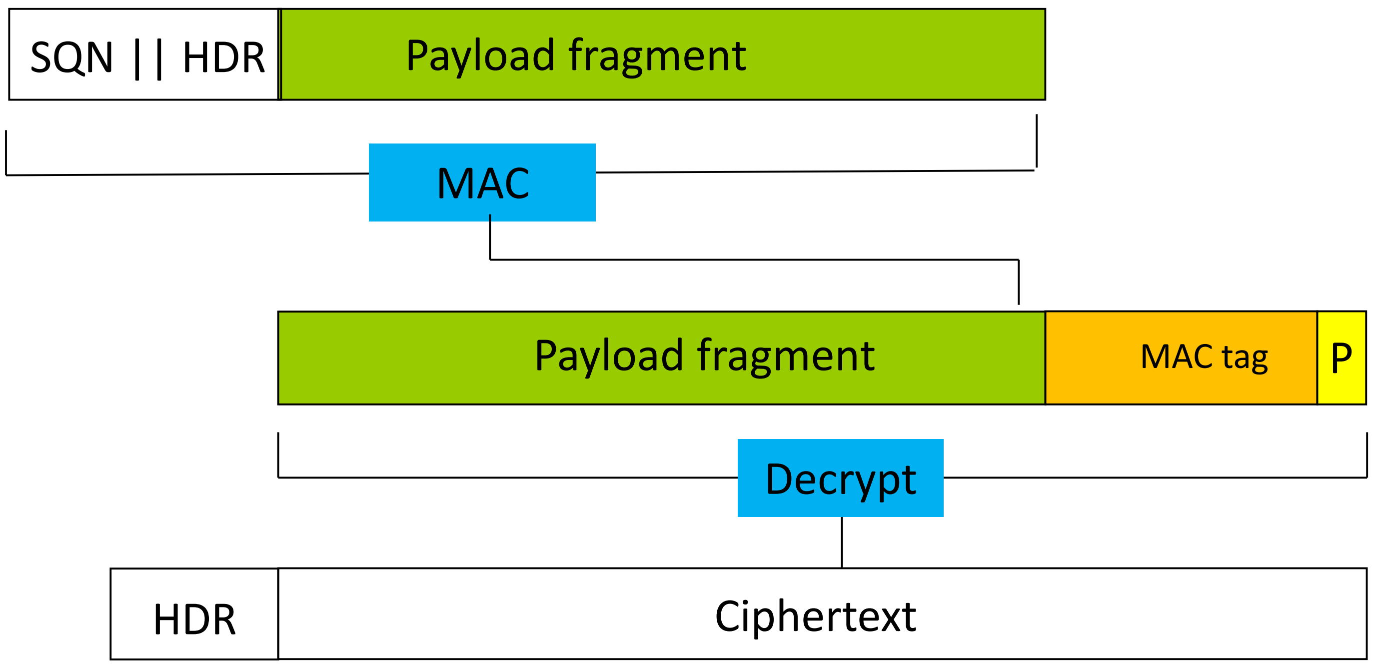
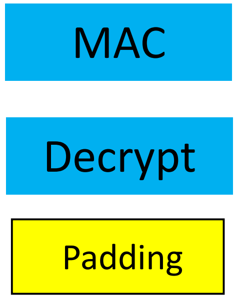
CBC_HMAC – Short Valid Padding





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Padding Oracle to Plaintext Recovery

- Needs multiple oracle queries
  - TLS handshakes' keys are dropped after any error
  - Can only recover data that is fixed between TLS handshakes
- BEAST like attack on session cookies
  - Use JavaScript in browser to repeatedly reopen connections
  - At the start of each connection, the same session cookie is sent in the first packet
  - From the JavaScript we can control the offset of the session cookie in the packet

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MiTM + Cache timing side channel

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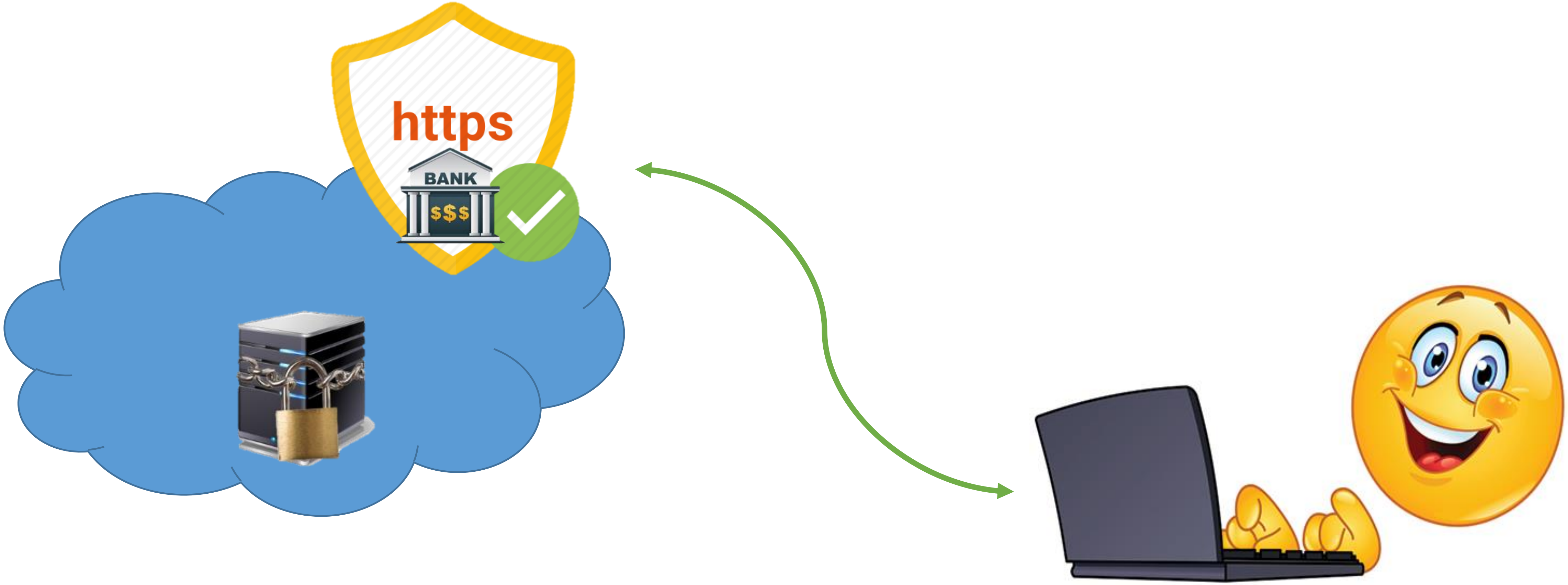

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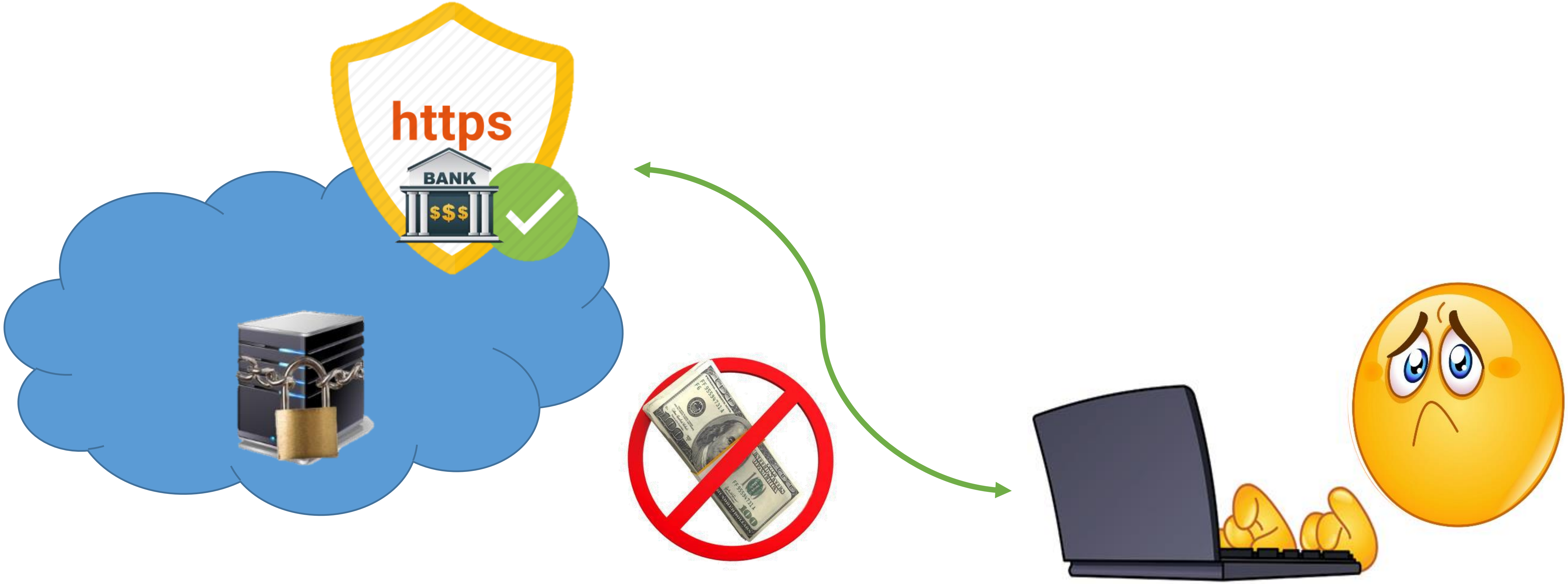

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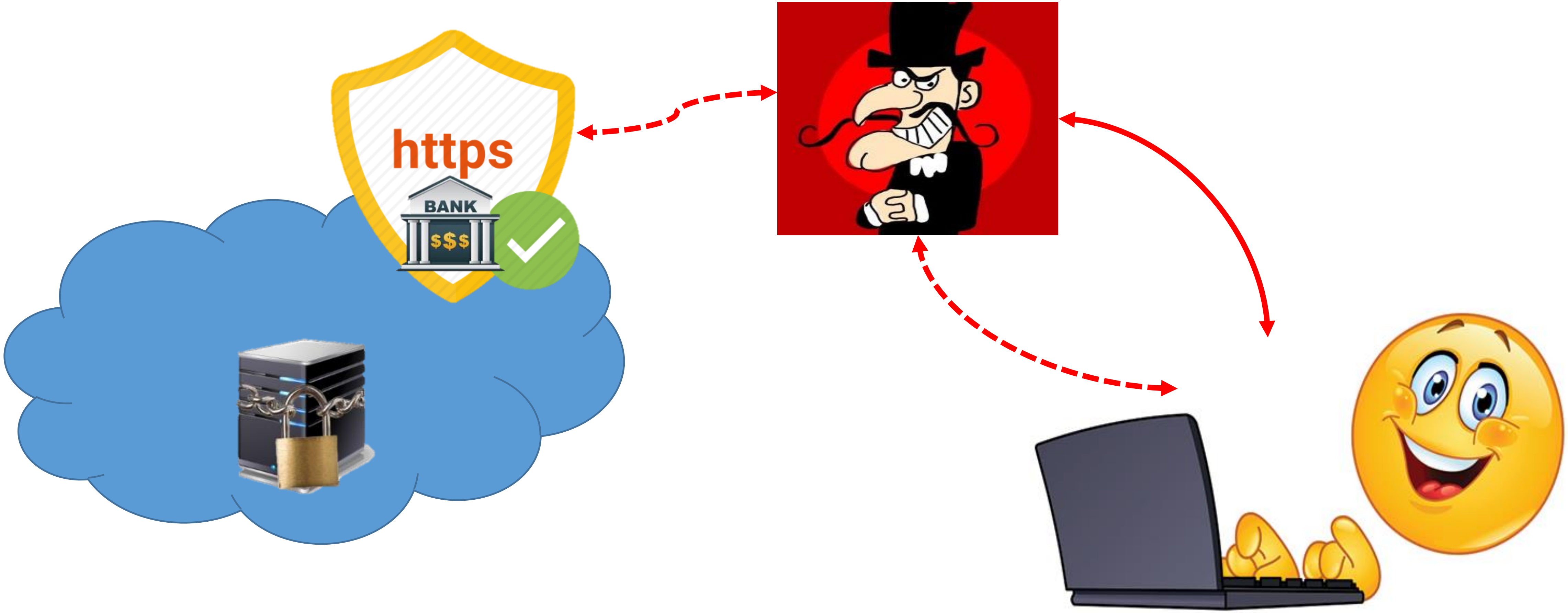

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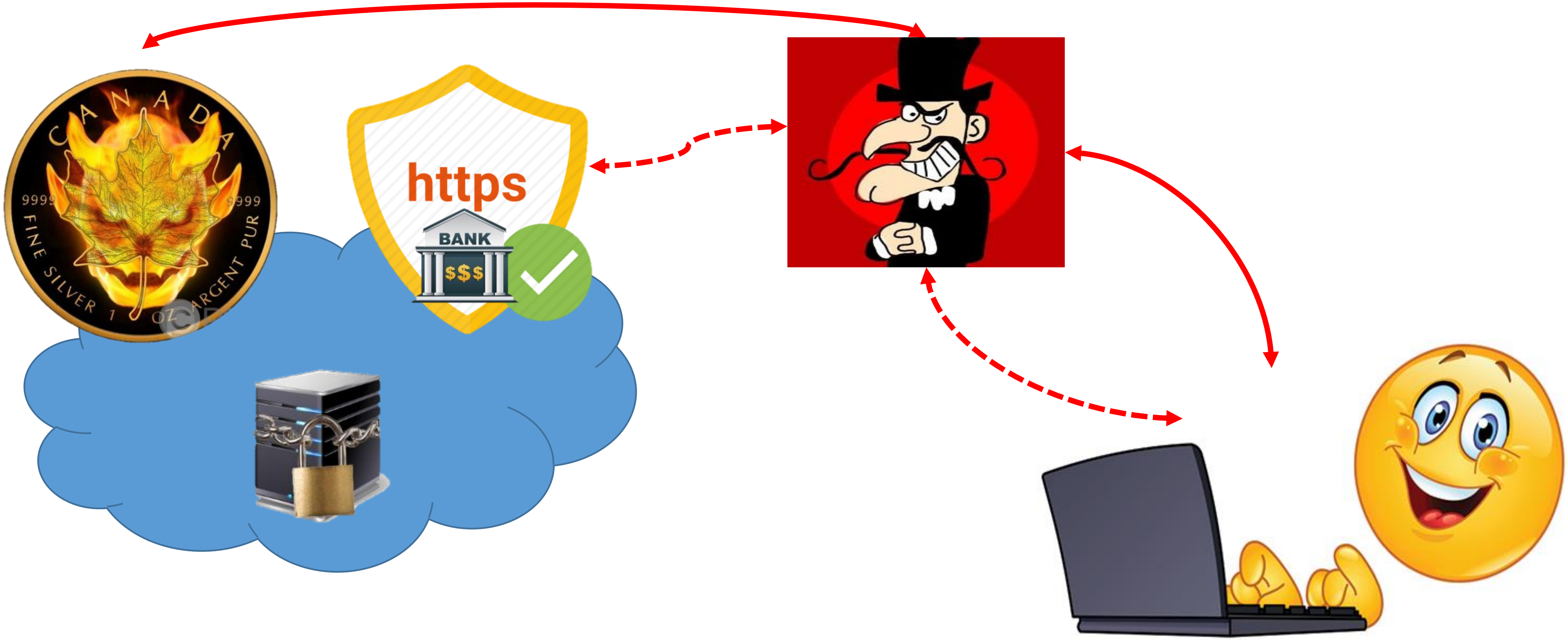

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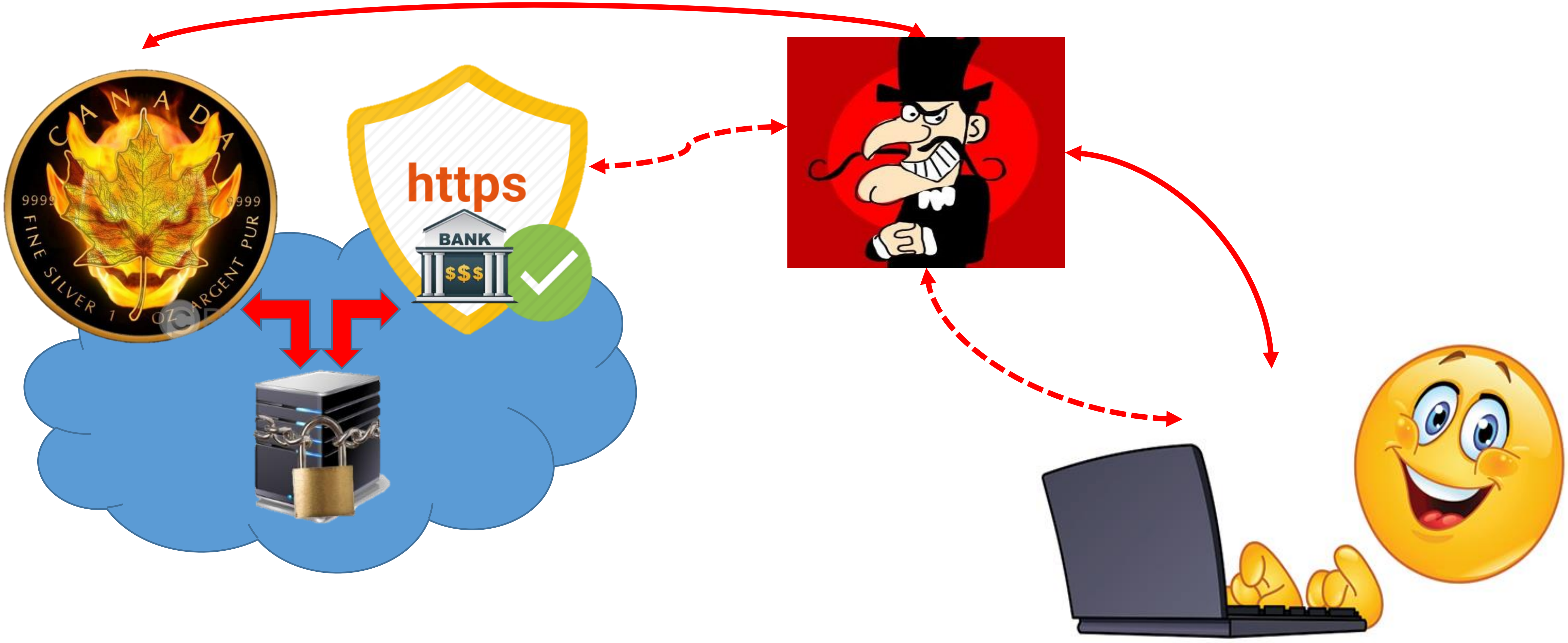
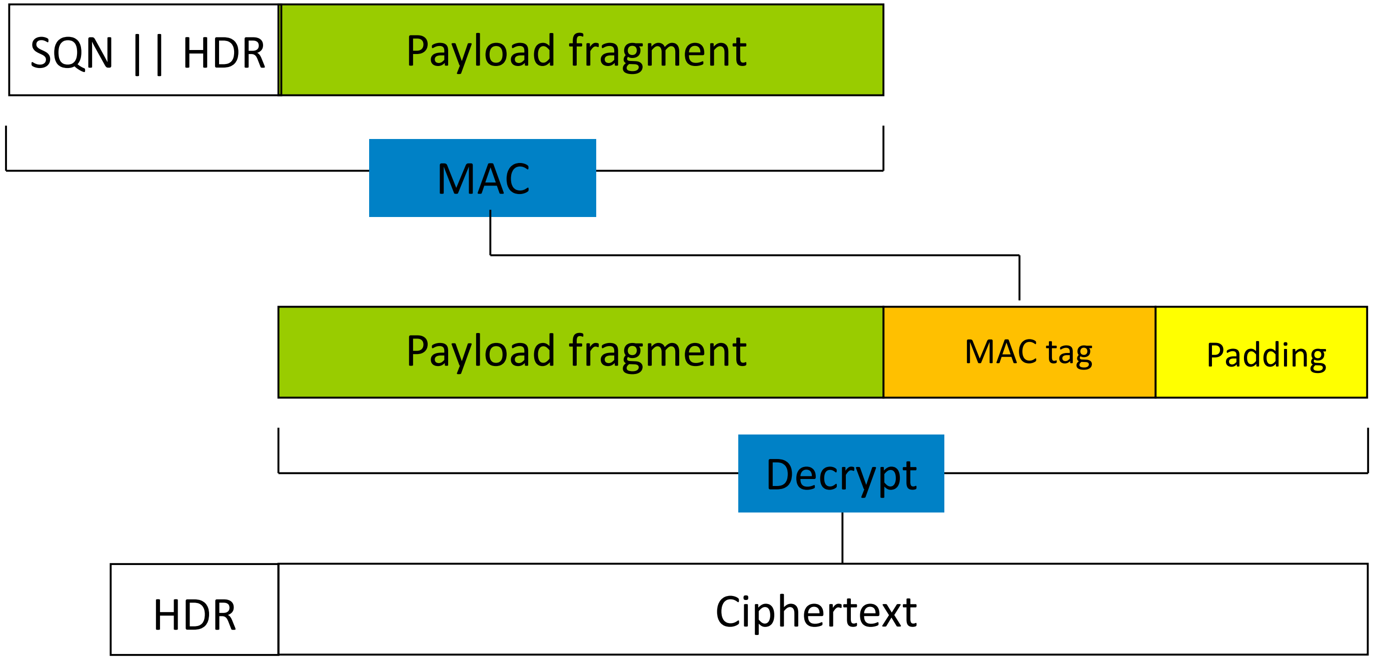


From Timing to Cache based Oracle

- Prior to our attack there was no known attacks against the fully patched pseudo constant time implementations
  - The timing is pseudo constant
  - The overall memory access pattern is constant

- Our main observation
  - The temporal memory access pattern is not constant
  - Using new variants of the PRIME+PROBE cache attack we were able to recreate the padding oracle

CBC_HMAC – Memory Access Long Pad



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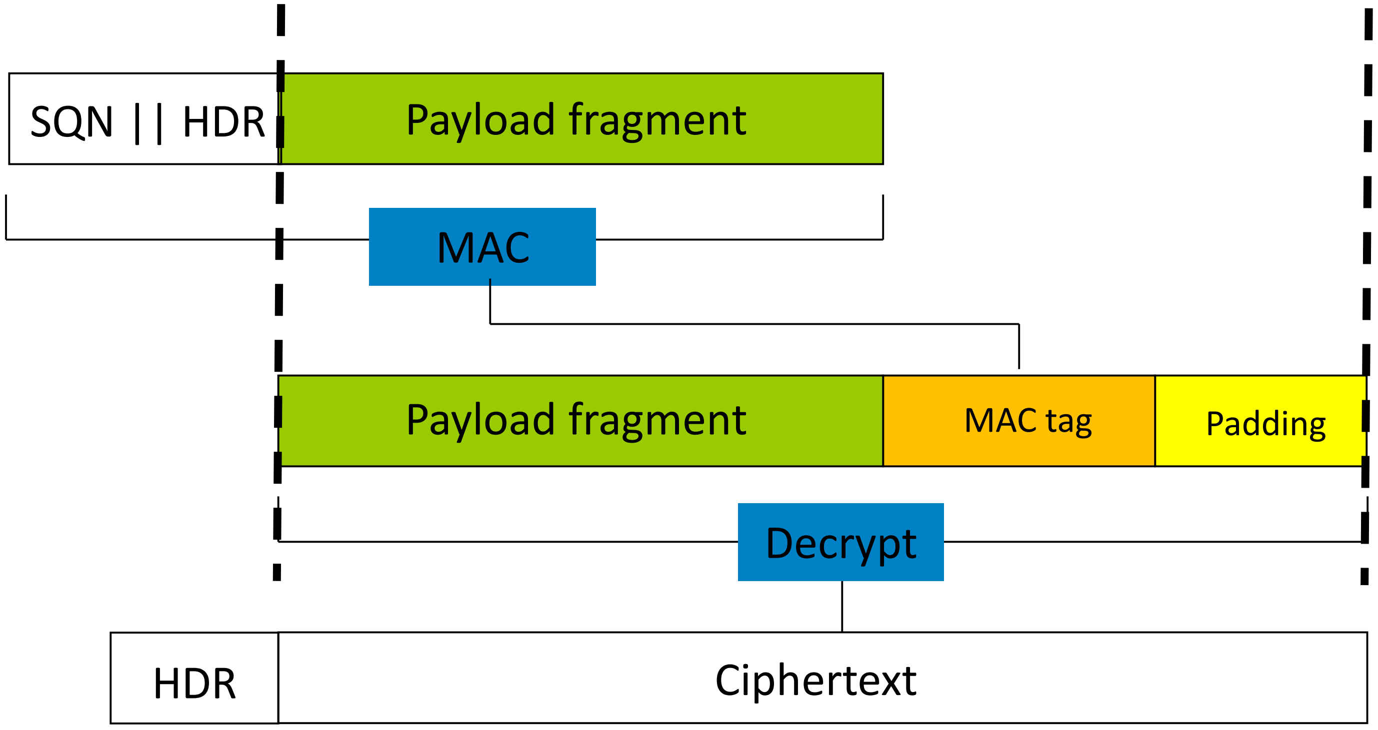
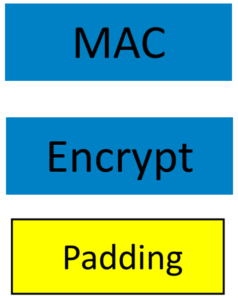


Memory Accessed while decrypting



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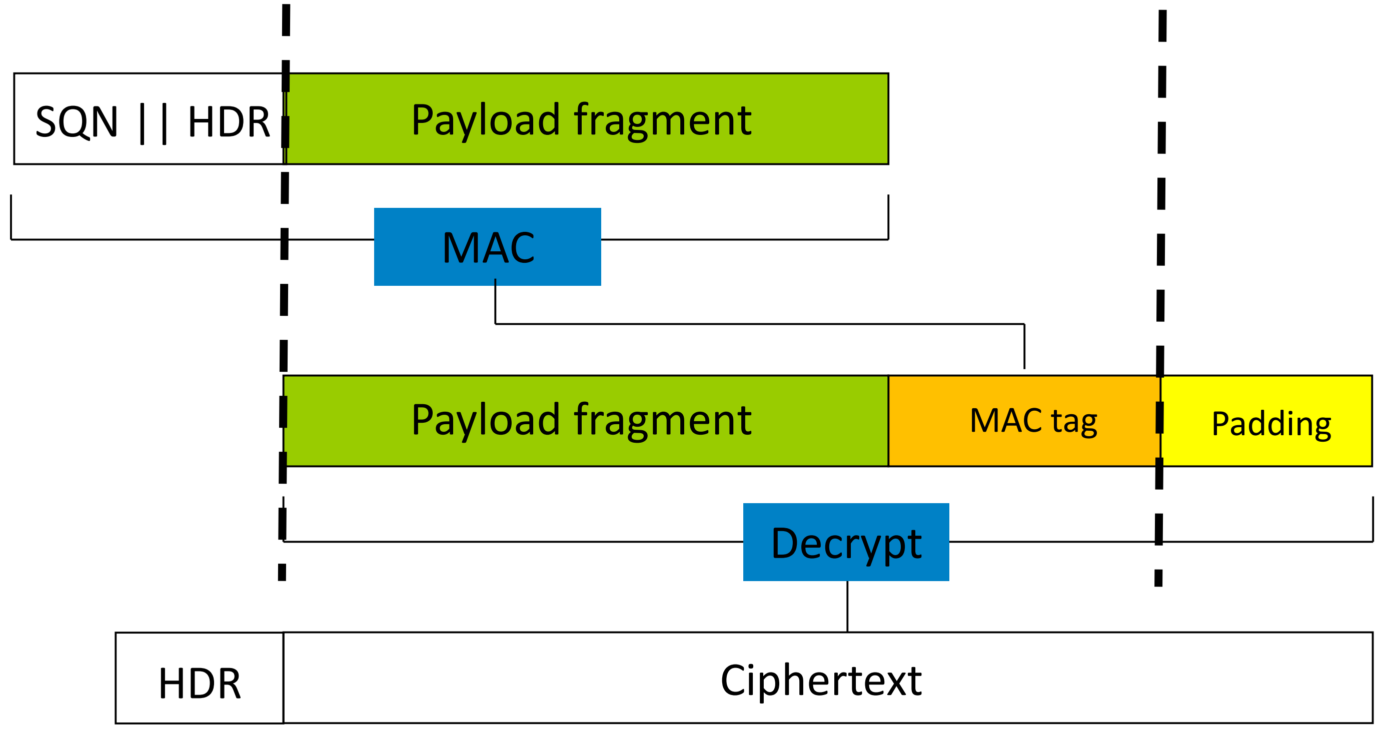

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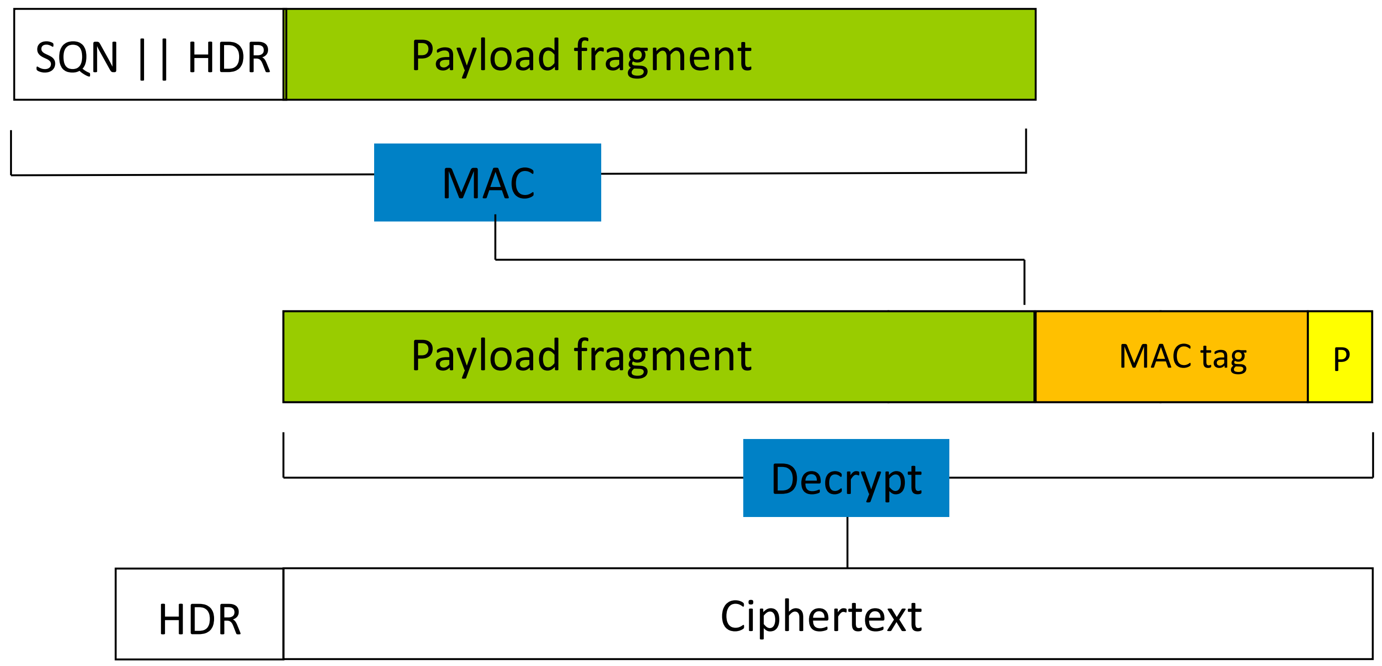

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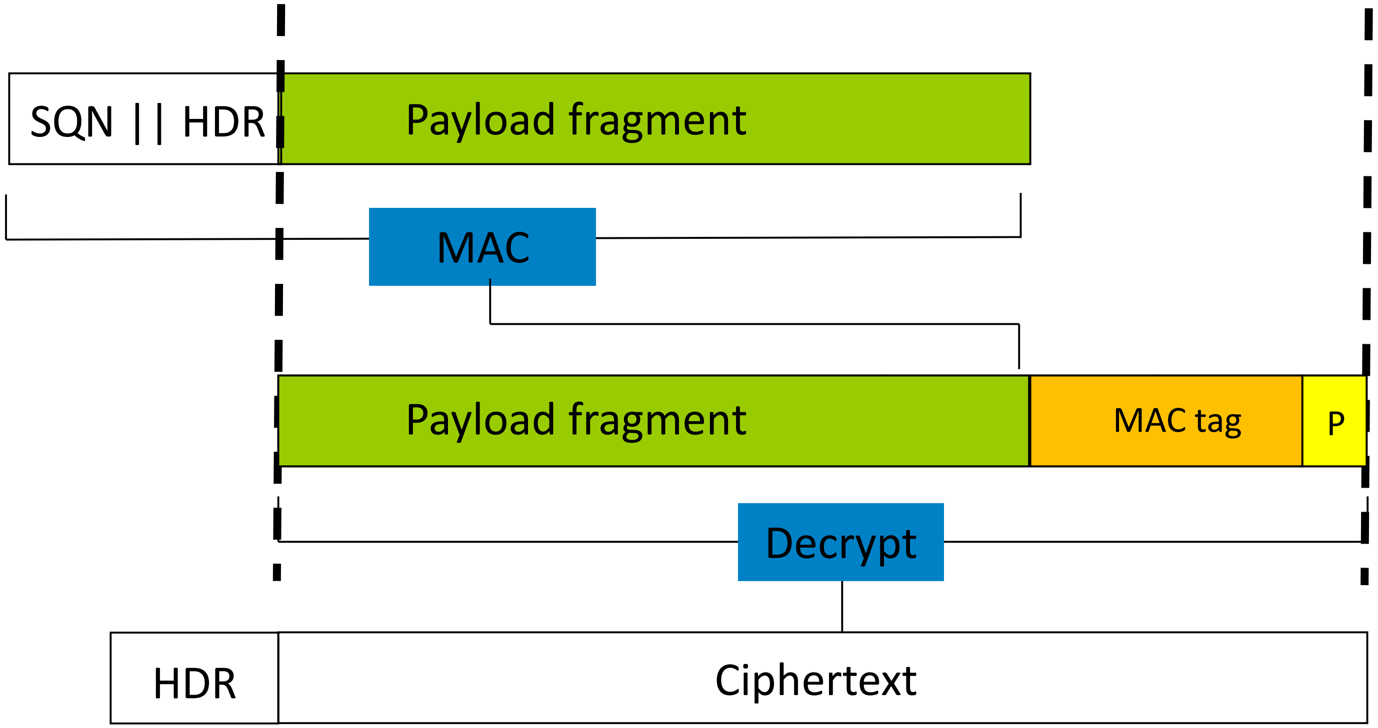

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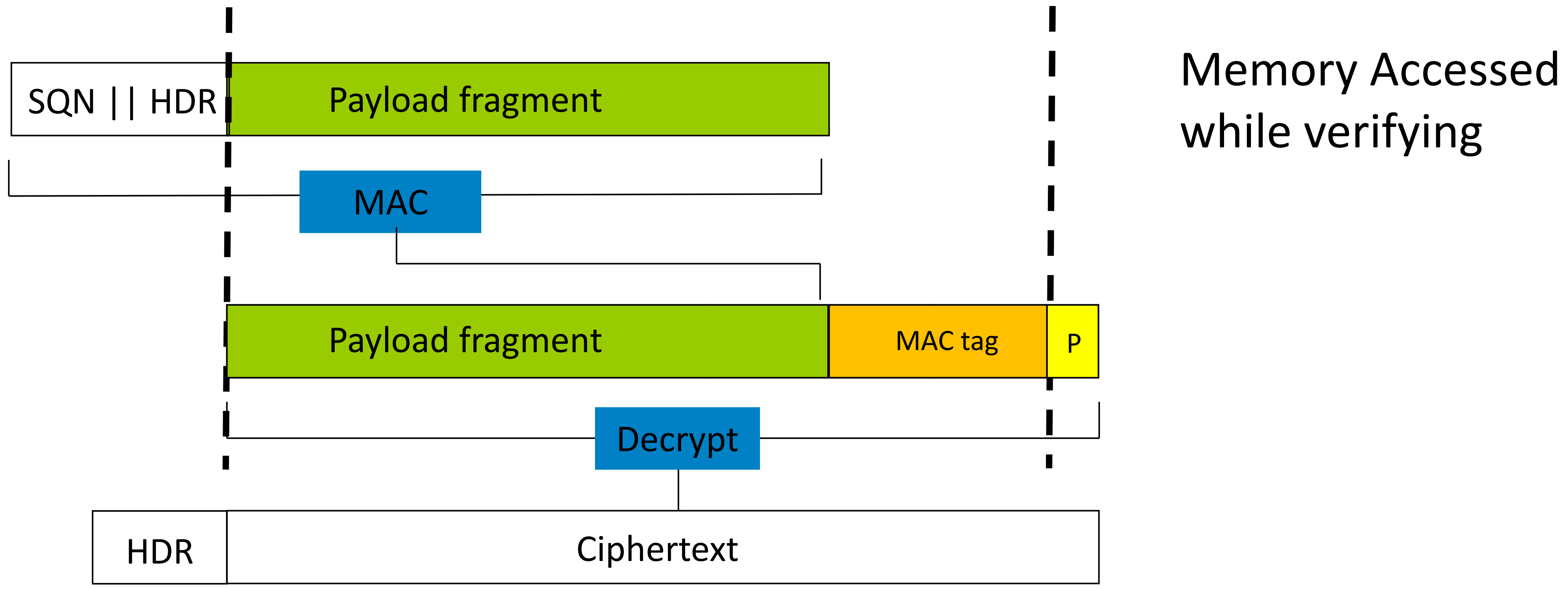

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Our results

- Exploiting the different temporal memory access patterns we can recreate a Lucky 13 attack variant
- PoC for 3 plaintext recovery attack variants
  - Synchronized probe PRIME+PROBE on Amazon's s2n
  - Synchronized prime PRIME+PROBE on wolfSSL, mbed TLS and GnuTLS
  - "PostFetch" cache attack on mbed TLS
  - Greedy Algorithm to optimize plaintext recovery

CBC_HMAC with SHA-384 Bugs

- Most widely used CBC_HMAC cipher suite
- All pseudo constant time countermeasures were vulnerable
  - Dummy operation calculation wrongly based on SHA-1/256 specific hardcoded values
  - Some implementations didn't even protect SHA-1/256
- Hard to test correctness of the pseudo constant time countermeasure
  - All constant time countermeasures were secure

Disclosure

- wolfSSL switched to full constant time (release 3.15.4)
- mbed TLS released security advisory with CVEs 2018-0497 and 2018-0497 that were marked as "high severity"
  - Users urged to update to new version with interim fix
  - Full constant time solution is planned
- Amazon s2n plans to disable CBC_HMAC by default and switch to the BoringSSL full constant time implementation
- GnuTLS made several changes to address the bugs
  - We believe that the code is still vulnerable to variants of the attack

“PostFetch” Cache Attack

- We want to know what part of a short array was read
- Differentiate between long and short access patterns inside a single cache line
- Continuous reading near the end of the cache line will cause the next cache line to be prefetched
- Target our cache attack on the cache line storing the bytes after the array

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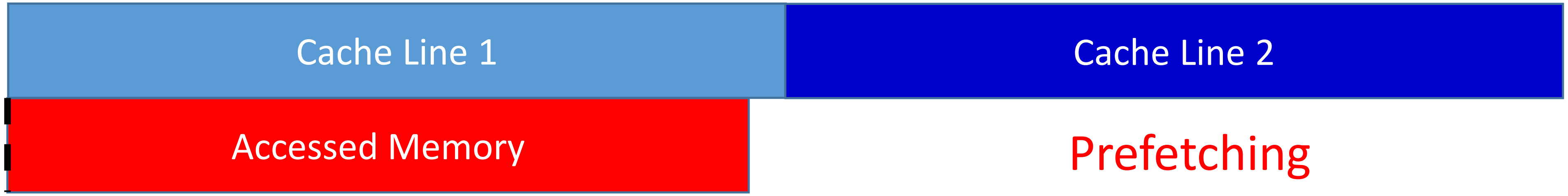

Synchronized probe PRIME+PROBE

- We want to measure the time difference
  - E.g. between sending a message at t_{send} and a memory access by the target at either $t_{send} + t_1$ or $t_{send} + t_2$
  - We choose t_{probe} such that $t_1 < t_{probe} < t_2$
  - We prime the memory before sending the message, and probe at $t_{send} + t_{probe}$
- We also use synchronized prime PRIME+PROBE

Conclusion

- All pseudo constant time implementations we reviewed
  - were buggy and still vulnerable to the original Lucky 13 attack.
  - were vulnerable to one or more of our 3 novel cache attacks
- Writing fully constant time code is hard but it is worth the effort

- Any questions?