# Lucky Microseconds

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# s2n

- s2n is a new implementation of TLS from AWS (Amazon Web Services).
- Nice logo!
- Source code released on github June 30$^{th}$ 2015.
- 6,000 lines of C instead of 70,000 lines in OpenSSL.
- Three external security audits/code reviews were performed before release.

# s2n press at launch

About 297 results (0.25 seconds)

**AWS** security looks to avoid cloud reboots with **s2n**
TechTarget - Jun 30, 2015
Amazon Web Services (**AWS**) unveiled **s2n** on its security blog this week. Signal to Noise (**s2n**) is meant to be a simplified, more easily ...

Amazon's **s2n** encryption library aims to be small, light, and auditable
InfoWorld - Jun 30, 2015

Amazon releases open source cryptographic module
PCWorld - Jun 30, 2015

Amazon introduces new open-source TLS implementation '**s2n**'
ZDNet - Jun 30, 2015

Amazon Releases **S2N** TLS Crypto Implementation to Open Source
Threatpost - Jun 30, 2015


InfoWorld


ZDNet


Threatpost

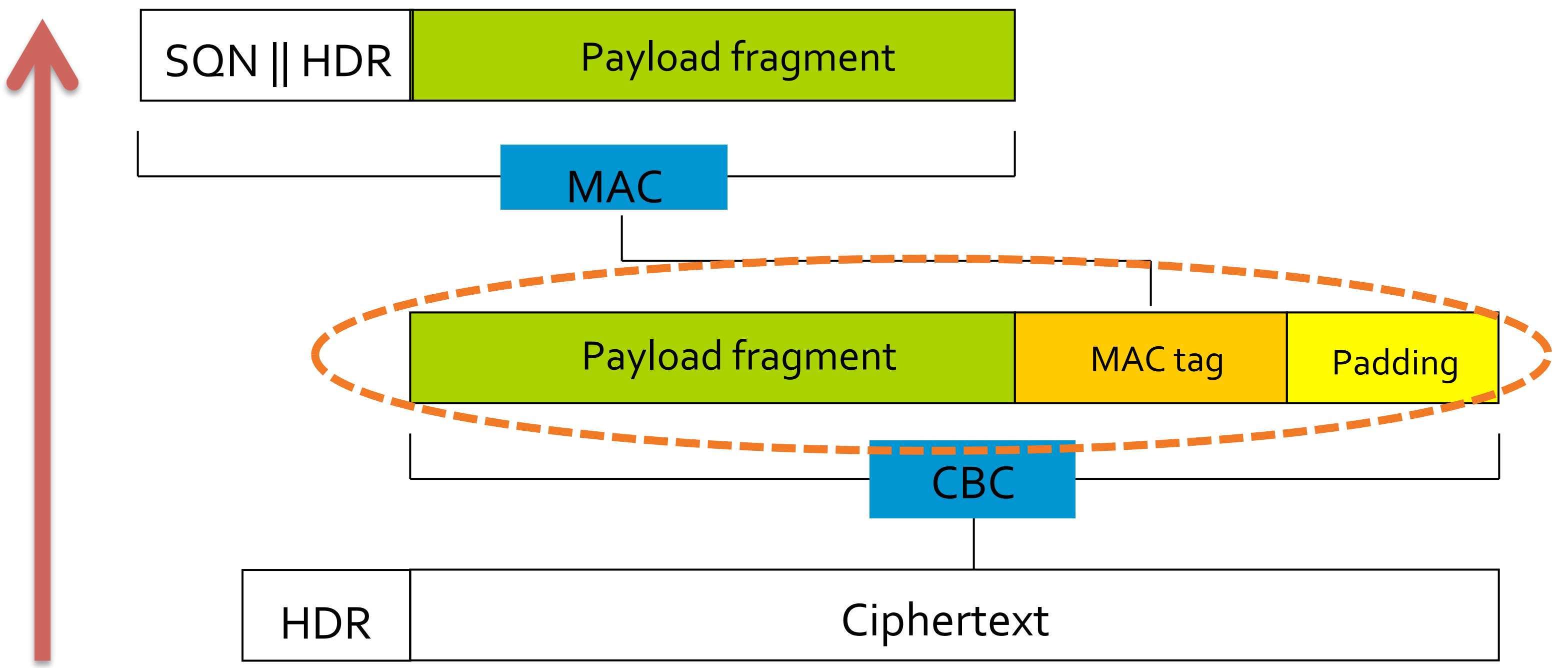

Network World

**Explore in depth** (17 more articles)

# s2n and CBC-mode encryption

- s2n implements SSLv3 and TLS 1.0, 1.1 and 1.2.
- So supports CBC-mode encryption.
- Lucky 13:
  - Timing attack based on low-level internals of cryptographic processing for CBC-mode.
- Countermeasures to Lucky 13 in OpenSSL needed 500 lines of code.
- **Our first reaction**: there's no way s2n can be secure against Lucky 13 in just 6 kLoC!

# TLS Record Protocol: MAC-Encode-Encrypt (MEE)




**Problem**: how to parse unauthenticated plaintext as payload, padding and MAC fields without leaking any information via error messages, timing or anything else?

# Constant Time Decryption for MEE

- Lucky 13 exploits leakage from TLS's MEE decryption processing for CBC-mode.
- Proper constant-time, constant-memory access implementation is needed to fully prevent it.
- Hard when plaintext is a mix of unauthenticated padding, MAC and payload fragment.
- See Adam Langley's blogpost at:

  https://www.imperialviolet.org/2013/02/04/luckythirteen.html

  for full details on how Lucky 13 was fixed in OpenSSL and NSS.
- **TL;DR**: it's a bit of a nightmare to do it properly.

# s2n and Lucky 13

- s2n protected against Lucky 13 using two countermeasures:
  - Dummy HMAC computations and padding checks to try to equalise running time.
  - Addition of random timing delays on decryption failure, to mask any residual timing differences.

- Each countermeasure had a problem…

# s2n_verify_cbc

```
int payload_and_padding_size = decrypted->size - mac_digest_size;

/* Determine what the padding length is */
uint8_t padding_length = decrypted->data[decrypted->size - 1];

int payload_length = payload_and_padding_size - padding_length - 1;
if (payload_length < 0) {
      payload_length = 0;
}

/* Update the MAC */
GUARD(s2n_hmac_update(hmac
GUARD(s2n_hmac_copy(&copy,

/* Check the MAC */
uint8_t check_digest[S2N_MAX_DIGEST_LEN];
lte_check(mac_digest_size, sizeof(check_digest));
GUARD(s2n_hmac_digest(hmac, check_digest, mac_digest_size));
```

Uses the last byte of the last block to decide how long padding should be.
Sets `payload_length` by subtracting this value from total size.
(Padding check done later.)

# s2n_verify_cbc

```c
int payload_and_padding_size = decrypted->size - mac_digest_size;

/* Determine what the padding length is */
uint8_t padding_length = decrypted->data[decrypted->size - 1];

int payload_length = p                              ng_length - 1;
if (payload_length < 0)
    payload_length =
}

/* Update the MAC */
GUARD(s2n_hmac_update(hmac, decrypted->data, payload_length));
GUARD(s2n_hmac_copy(&copy, hmac));

/* Check the MAC */
uint8_t check_digest[S2N_MAX_DIGEST_
lte_check(mac_digest_size, sizeof(ch
GUARD(s2n_hmac_digest(hmac, check_digest, mac_digest_size));
```

Updates the HMAC value (but does not yet finalise it).

`payload_length` bytes are passed to HMAC here.

# s2n_verify_cbc

```
int payload_and_padding_size = decrypted->size - mac_digest_size;

/* Determine what the padding length is */
uint8_t padding_length = decrypted->data[decrypted->size - 1];

int payload_length = payload_and_padding_size - padding_length - 1;
if (payload_length < 0) {
     payload_length = 0;
}

/* Update the MAC */
GUARD(s2n_hmac_update(hmac, decrypted->data, payload_length));
GUARD(s2n_hmac_copy(&copy, hmac));

/* Check
uint8_t                                          T_LEN];
lte_chec                                         check_digest));
GUARD(s2                                         digest, mac_digest_size));
```

Makes copy of HMAC data structure for later time equalisation.

# s2n_verify_cbc

```
int payload_and_padding_size = decrypted->size - mac_digest_size;

/* Determine what the padding length is */
uint8_t padding_length = decrypted->data[decrypted->size - 1];

int payload_length = payload_and_padding_size - padding_length - 1;
if (payload_length < 0)
     payload_length = 0
}

/* Update the MAC */
GUARD(s2n_hmac_update(h                                _length));
GUARD(s2n_hmac_copy(&co

/* Check the MAC */
uint8_t check_digest[S2N_MAX_DIGEST_LEN];
lte_check(mac_digest_size, sizeof(check_digest));
GUARD(s2n_hmac_digest(hmac, check_digest, mac_digest_size));
```

Finalises the HMAC value. Running time depends on value of `payload_length`, which in turn depends on `padding_length`, which *might* leak plaintext information.

# s2n_verify_cbc

```
    int mismatches = s2n_constant_time_equals(decrypted->data +
                                               payload_length,
                                               check_digest,
                                               mac_digest_size) ^ 1;

    /* Compute a MAC on the rest of th          so that we perform the same
       number of hash operations
    GUARD(s2n_hmac_update(&copy
                           mac_d
                           decryp
                           mac_di
```

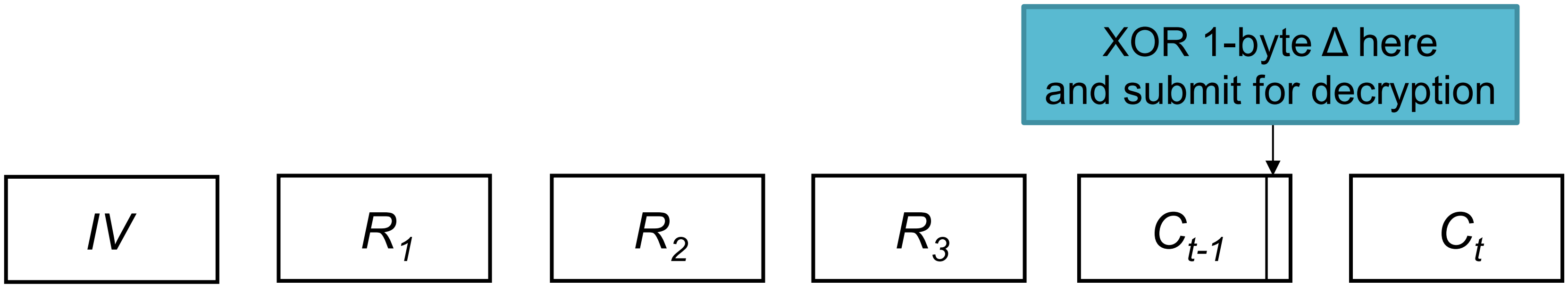
Compares (in constant time!) the computed HMAC value to the one extracted from `decrypted->data`.

# s2n_verify_cbc

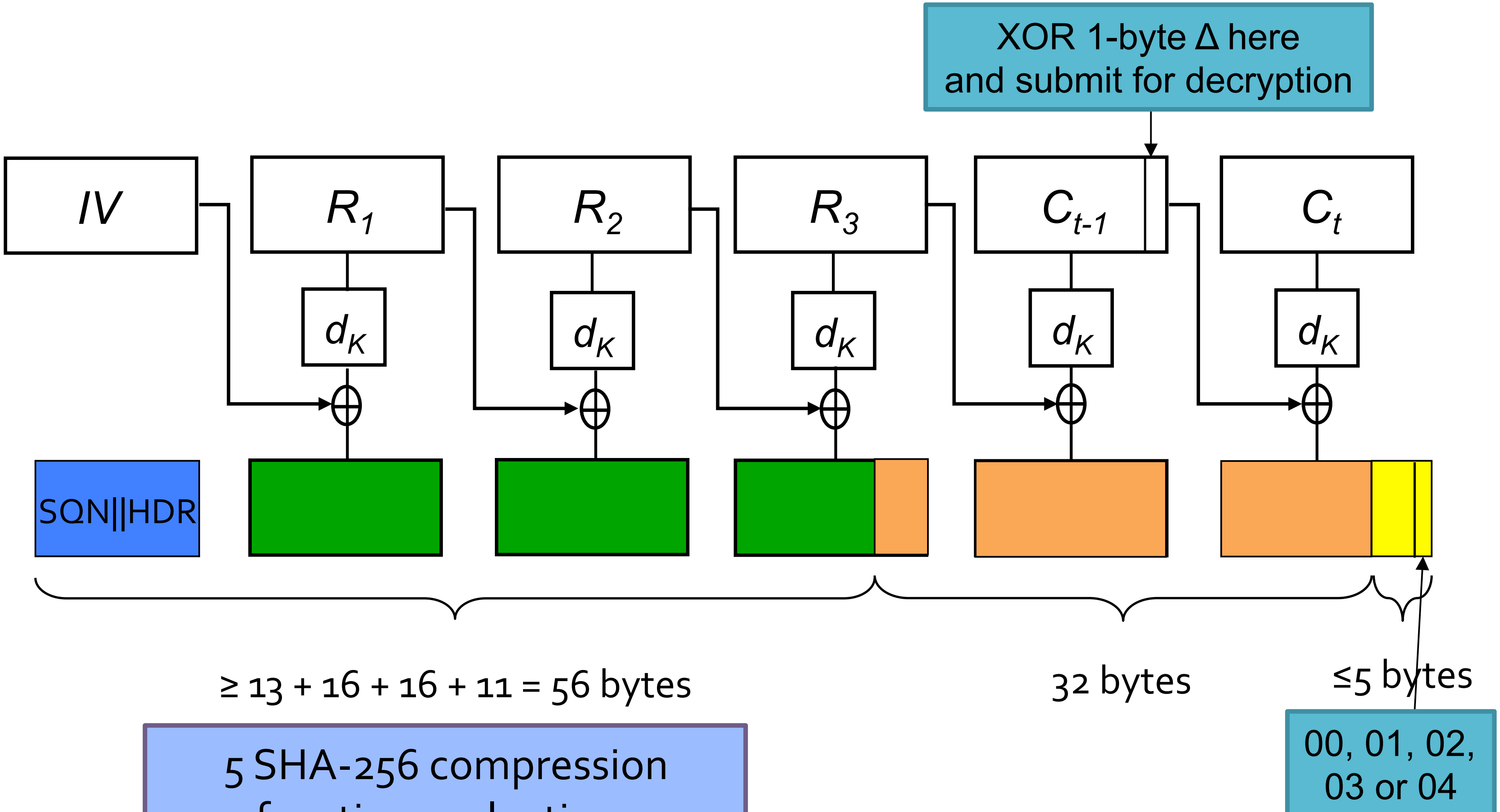
```
int mismatches = s2n_constant_time_equals(decrypted->data +
                                          payload_length,
                                          check_digest,
                                          mac_digest_size) ^ 1;

/* Compute a MAC on the rest of the data so that we perform the same
   number of hash operations */
GUARD(s2n_hmac_update(&copy, decrypted->data + payload_length +
                      mac_digest_size,
                      decrypted->size - payload_length -
                      mac_digest_size - 1));
```

Performs dummy `hmac_update` operations to equalise running time of HMAC.

# Let's build a magic ciphertext!

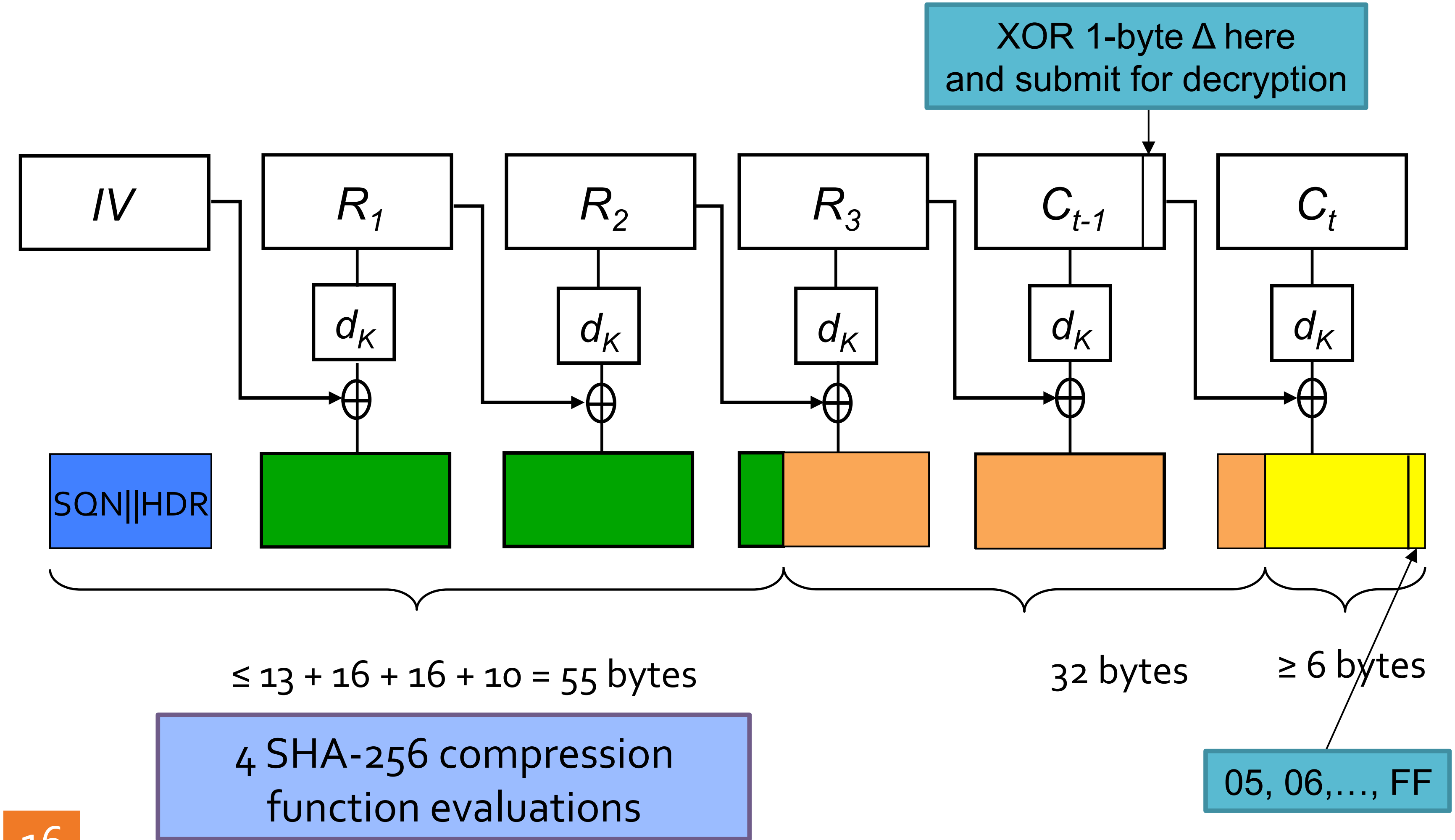


# Case 1: last byte is 00, 01, 02, 03, 04




5 SHA-256 compression function evaluations

# Case 2: last byte is 05, 06,…, FF



# Dummy HMAC computations in s2n

- So there's a timing difference for the entire HMAC computation depending on whether the last byte is in {00, 01, 02, 03, 04} or in {05, 06,…,FF}.
- But this last byte relates to the corresponding target plaintext byte in a controlled way.
- The timing difference is of the same size as in the original Lucky 13 attack.

- **But what about that equalisation code, using dummy call to `hmac_update`?**

# s2n_verify_cbc

```

int mismatches = s2n_constant_time_equals(decrypted->data +
                                          payload_length,
                                          check_digest,
                                          mac_digest_size) ^ 1;

/* Compute a MAC on the rest of the data so that we perform the same
   number of hash operations */
GUARD(s2n_hmac_update(&copy, decrypted->data + payload_length +
                      mac_digest_size,
                      decrypted->size - payload_length -
                      mac_digest_size - 1));
```

For the magic ciphertexts, the input size is always 60 bytes.
So **zero** extra HMAC compression function computations are done, in either case!

# Experimental results: timing `s2n_verify_cbc`

| Byte value | Cycles | Byte value | Cycles | Byte value | Cycles |
|---|---|---|---|---|---|
| 0x00 | 2251.96 | 0x05 | 1746.49 | ... | ... |
| 0x01 | 2354.57 | 0x06 | 1747.65 | 0xfc | 1640.79 |
| 0x02 | 2252.07 | 0x07 | 1705.62 | 0xfd | 1634.61 |
| 0x03 | 2135.11 | 0x08 | 1808.73 | 0xfe | 1648.70 |
| 0x04 | 2130.02 | 0x09 | 1806.50 | 0xff | 1634.64 |

Table 3: Timing of function **`s2n_verify_cbc`** (in cycles) with $H$ = SHA-256 for different values of last byte in the **`decrypted`** buffer, each cycle count averaged over $2^8$ trials.

# Rebooting Lucky 13

- The timing differences would allow for a novel variant of the original Lucky 13 attack to be mounted against the `s2n_verify_cbc` code.
- The attack would recover the last byte of any target block of plaintext.
- Can be upgraded to full plaintext recovery for session cookies using malicious Javascript running in the browser.
- Can be adapted to HMAC-SHA-1 and HMAC-MD-5.
- Can be executed remotely over a network by timing TLS error messages.
    - Attack is in the "challenging but not impossible" category.

# But wait …. random timing delays in s2n!

- Addition of random timing delay in event of cryptographic processing error.
- Intended to mask any residual timing differences from `s2n_verify_cbc`.
- Time delay is a random value between 0 and 10 seconds.
- Is that enough to mask a difference of ~500 clock cycles?
- **Textbook statistical analysis**:

$$N \geq \sigma^2 + cT^2$$

- **Outcome**: trillions of samples would be needed to detect any timing differences if the delay was *uniformly* random.

# Generating random timing delays in s2n

s2n_recv.c

```
int s2n_read_full_record(struct s2n_connection *conn, \
                         uint8_t *record_type, int *isSSLv2)
    /* Decrypt and parse the record */
    if (s2n_record_parse(conn) < 0) {
        GUARD(s2n_connection_wipe(conn));
        if (conn->blinding == S2N_BUILT_IN_BLINDING) {
            int delay;
            GUARD(delay = s2n_connection_get_delay(conn));
            GUARD(sleep(delay / 1000000));
            GUARD(usleep(delay % 1000000));
        }
        return -1;
    }
```

# Generating random timing delays in s2n

```
s2n_recv.c
int s2n_                                  n, \
                       t *record_type, int *isSSLv2)
    /* Decry          d parse the record */
    if (s2n_re  ord_parse(conn) < 0) {
        GUARD(s2n_connection_wipe(conn));
          f (conn->blinding == S2N_BUILT_IN_BLINDING) {
            int delay;
            GUARD(delay = s2n_connection_get_del
            GUARD(sleep(delay / 1000000));
            GUARD(usleep(delay % 1000000));

          turn -1;
    }
```

Yet more stuff – yuck!

And even more stuff!

Generates random delay, uses calls to RNG + rejection sampling.

Sleep for whole number of seconds

Sleep for whole number of microseconds

**It's messy, but it's not necessarily uniform!**

# Two observations + reality

- We can filter out any noise arising from sleep() call by just ignoring any delays larger than 1 second.
  - Effect is to increase number of samples needed by factor of 10.

- Delay from usleep() is a whole number of microseconds, but the timing signal we are looking for is just a few hundred clock cycles.
  - So take all timing measurements modulo 1 microsecond (3300 clock cycles), and only the signal will remain!

# Two observations + reality

- In reality, things are a bit harder than this:
  - usleep() does not give a delay that is an exact number of microseconds, but has its own complex distribution.
  - Several additional noise sources to contend with.
  - Platform-dependent behaviour.

# Random timing delays in s2n

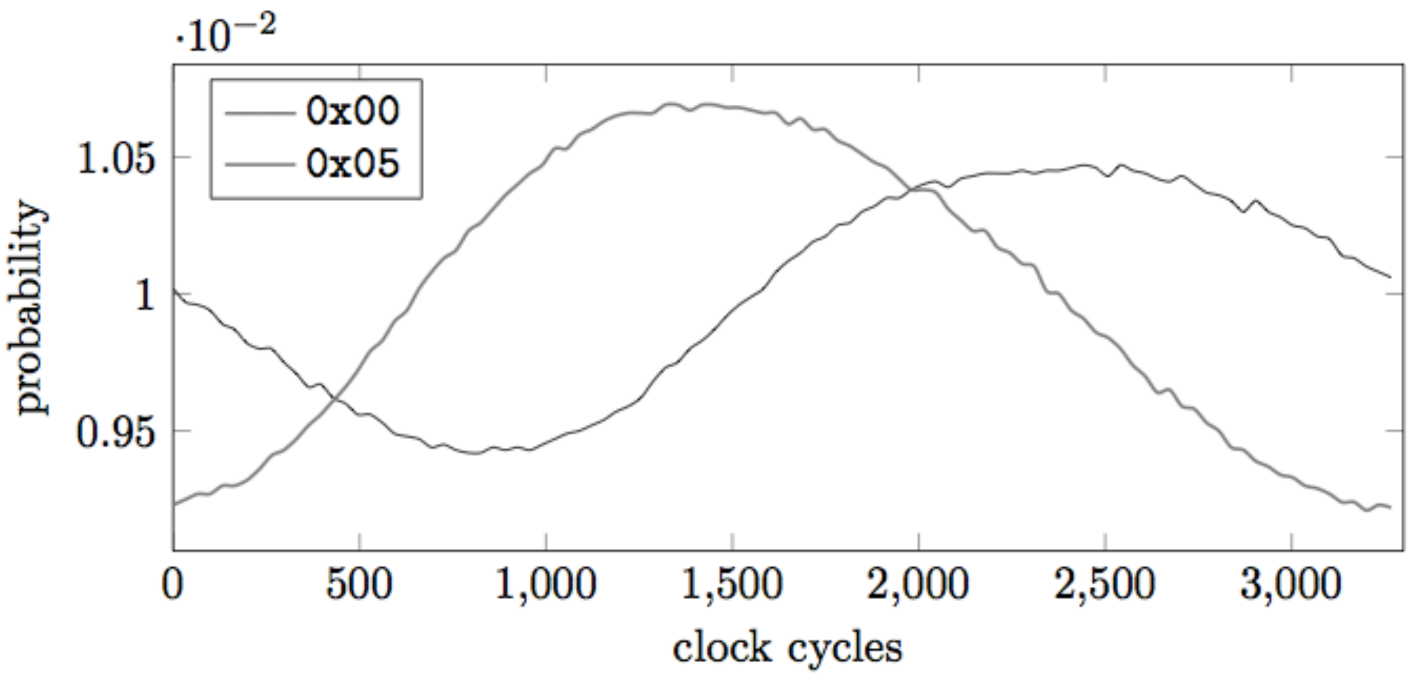



Figure 8: Distribution of clock ticks modulo 3,300 for timing signals on Intel(R) Xeon(R) CPU E5-2667 v2 @ 3.30GHz with the maximum delay restricted to $d = 100,000$.

# Putting it all together

- KL divergence: $3.6 \times 10^{-3}$.
- Hence about 280 ciphertexts are needed to distinguish 0x00 from 0x05, for max delay 100,000 µs.
- So 28k ciphertexts in reality.
  - 10,000,000/100,000 = 100, so we only use 1 in 100 samples.

- Extends to plaintext recovery attack using a standard maximum likelihood based approach.
- But more samples are needed because now we are trying to identify one correct value amongst 255 wrong values.

# Disclosure and interaction with AWS

- s2n was released on June 30th 2015.
- We informed the AWS team about the HMAC processing error in `s2n_verify_cbc` on July 5th 2015.
- AWS patched the s2n code almost immediately.
- They also informed us about their random timing delay countermeasure.
- So we broke that too….
- Meanwhile, AWS switched to using nanosleep().
- Code as released was vulnerable but AWS say that no production systems could have been attacked.
- Disclosure process was very smooth.

# Takeaways

- Lucky 13 is hard to fully protect against.
- OpenSSL does it, but the code is not very…. transparent.
- Don’t mess with MEE unless you really know what you’re doing!
- Pre-release code audits will not catch all subtle crypto flaws.
- AWS invited public analysis of their code and reacted well to our work.

# More information

**Paper**:

http://eprint.iacr.org/2015/1129

**Press**:

http://arstechnica.com/science/2015/11/researchers-poke-hole-in-custom-crypto-protecting-amazon-web-services/

**Martin's blog:**

https://martinralbrecht.wordpress.com/2015/11/24/lucky-microseconds-a-timing-attack-on-amazons-s2n-implementation-of-tls/

**AWS blog**:

https://blogs.aws.amazon.com/security/post/TxLZP6HNAYWBQ6/s2n-and-Lucky-13