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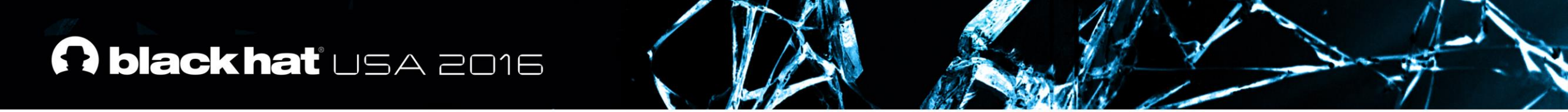
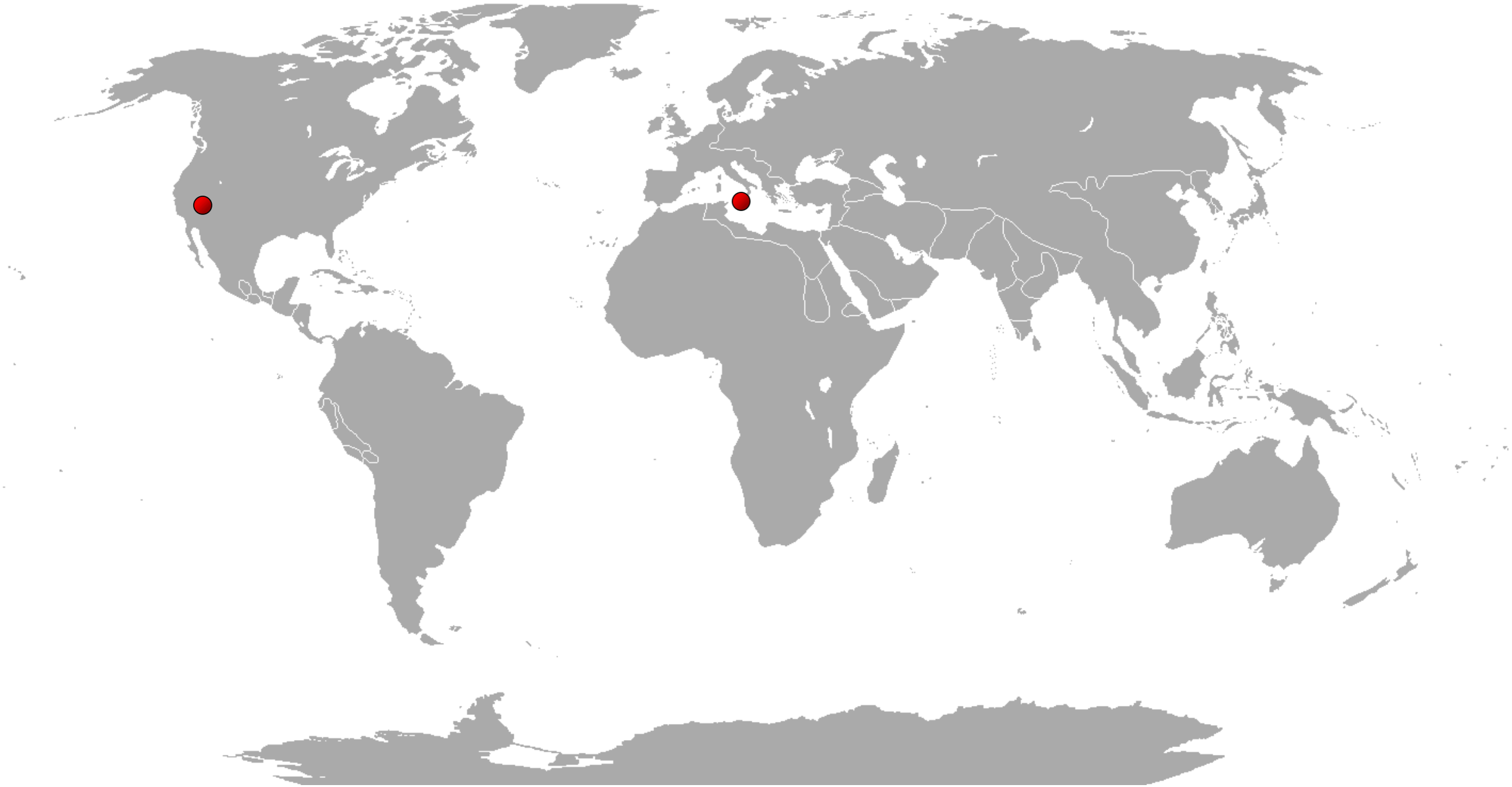


Recover a RSA private key from a TLS session with Perfect Forward Secrecy

(Marco Ortisi – 2016)

About me

- Netizen and IT Security enthusiast since 1996
- Penetration Tester since 1999
  - ✓ *In love with buffer overflow flaws*
  - ✓ *I adore exotic vulnerabilities*
- Senior/Principal Penetration tester? Just a curious guy
- Get in touch with me! marco.ortisi at segfault.it

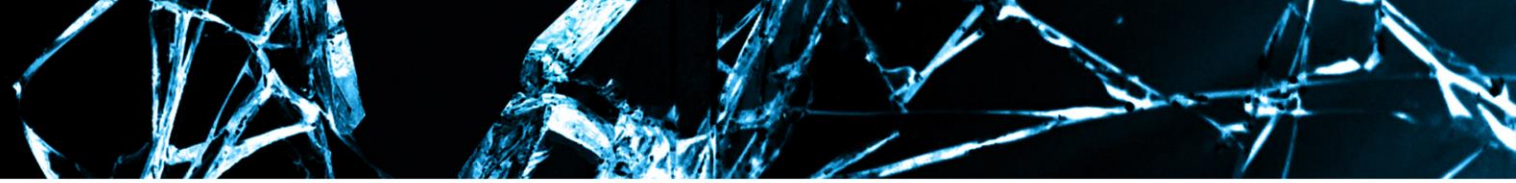


About the topic

- Imagine you can get a server private key by sniffing TLS traffic or interacting through the network with a TLS service. Does it look quite exotic?

- Done via a side channel attack

- Side Channel Attack – from *Wikipedia*
  - *"…any attack based on information gained from the physical implementation of a cryptosystem, rather than brute force or theoretical weaknesses in the algorithms (compare cryptanalysis). For example,* ***timing information****,* ***power consumption****,* ***electromagnetic leaks*** *or even* ***sound*** *can provide an* ***extra source of information****, which can be exploited to break the system…"*



Roadmap

- Introduction
- First demo
- More insight into the attack
- Second demo
- Greetings and questions

The attack and roots with the past

- (**1996**) *Arjen Lenstra* demonstrated the usage of the so-called CRT (Chinese Remainder Theorem) optimization put the RSA implementations **at great risk *(aka private key leakage)*** whether a fault occurred during the computation of a **digital RSA signature**. (*https://infoscience.epfl.ch/record/164524/files/nscan20.PDF*)

What is a RSA signature

- **RSA encryption**
  - ✓ public key is used to encrypt a message
  - ✓ private key is used to decrypt that message

- **RSA signing**
  - ✓ private key is used to sign a message (see it as an encryption operation)
  - ✓ public key is used to verify a signature (see it as a decryption operation)

The attack and roots with the past

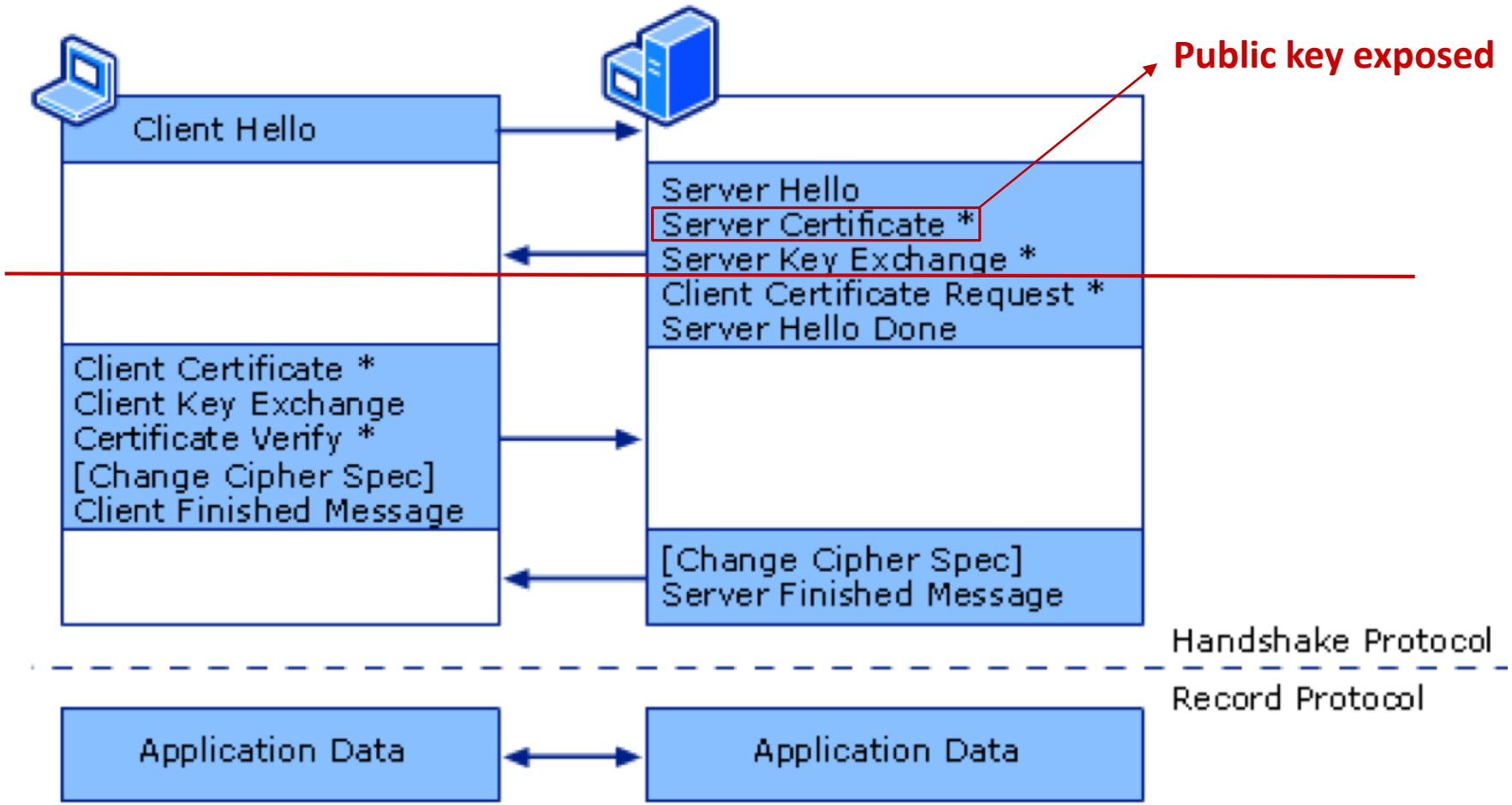
- (**1996**) *Arjen Lenstra* demonstrated that the usage of the so-called CRT (Chinese Remainder Theorem) optimization put the RSA implementations **at great risk *(aka private key leakage)*** if a fault occurred during the computation of a **digital RSA signature**. (*https://infoscience.epfl.ch/record/164524/files/nscan20.PDF*)

- (**200x?**) - Attack conjectured as possible on smartcards if someone has **physical access** to the device and can disrupt the math behind the RSA operations by artificially injecting hardware faults

The attack and roots with the past

- (**2001**) **OpenPGP Attack** (*http://eprint.iacr.org/2002/076.pdf*).
  a) get a local copy of file containing the encrypted private key;
  b) tamper with it in order to introduce faulty bits;
  c) capture a single message subsequently signed with the modified encrypted private key (for example an email);
  d) enjoy your leaked **private key** ☺

- (**2015**) by targeting TLS, **Florian Weimer** (Red Hat) unveiled the attack can have **remote impacts**.
  https://people.redhat.com/~fweimer/rsa-crt-leaks.pdf


Public key exposed
Client Hello
Server Hello
Server Certificate *
Server Key Exchange *
Client Certificate Request *
Server Hello Done
Client Certificate *
Client Key Exchange
Certificate Verify *
[Change Cipher Spec]
Client Finished Message
[Change Cipher Spec]
Server Finished Message
Handshake Protocol
Record Protocol
Application Data
Application Data

Recover a RSA private key: Prerequisites

- (**a**) Presence of a RSA signature calculated using the RSA-CRT optimization…
- (**b**) The signature must be applied on values known by the attacker…
- (**c**) Generated signature faulty/miscalculated…

What if the attack is successful?

- Private key is exposed
- The real server can be impersonated
- **Man-in-The-Middle** attack can be performed without alerting the legitimate clients

What if the attack is successful?

DEMO TIME (PART 1)

(enter High Voltage!)

From: **http://support-public.cfm.software.dell.com/33164_sonicos_5.8.4.2_releasenotes.pdf**

Resolved issue	Issue ID
A specialized RSA-CRT attack can cause private key leakage in relatively rare cases. This security vulnerability has not been publically disclosed and it is very difficult to perform this attack. To be cautious, Dell SonicWALL recommends that customers upgrade firmware. Occurs when the SonicOS management interface or a port on the firewall is accessed using SSL, and the following conditions are met: • A highly sophisticated tool is used to harvest this vulnerability; this tool is not available to the general public • The Enable Hardware RSA option is enabled in the internal SonicOS settings (by default this option is disabled, in which case the firewall is not vulnerable)	166825

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(a) RSA Signature with RSA-CRT

- The modular exponentiations required by RSA are computationally expensive
- RSA-CRT introduced a less expensive way to do RSA operations (decryption and signing)
- RSA-CRT is used by default in almost every known crypto library out there (*openssl*, *OpenJDK*, *libgcrypto*, *PolarSSL*, etc…)
- Condition (a) is normally satisfied

(c) Presence of faulty signature

- We identify a faulty RSA signature with the letter "**Y**"
- Events causing the generation of a faulty digital RSA signature can't be predicted but they are out there
- Induced by the same vectors like in a typical bit-squatting attack:
  - ✓ *CPU overheating*
  - ✓ *RAM errors*
  - ✓ *massive exposure of hardware to solar rays*
  - ✓ *etc…*

(b) Signature calculated on known values

- We define "**X**" as the value to be signed
- **Digital signature =** *plain-text value* -> *hashing function* -> *padding* -> *encryption*
- Padding can influence the final "shape" of "**X**" before being signed and make this unpredictable…
- …but with SSL3.0, TLS 1.0, 1.1 and 1.2 the padding scheme (a variant of PKCS1.5) is fully deterministic (not randomized) and then predictable

(b) PKCS 1.5 Padding

- Payload:

```
0D3F8FF87A4D697E73FE86077FD1D10C4ECC59797E759EDD89931B
2208B8044CB4A1B96A
```

- Padded Payload (RSA 2048 bits):

```
0001FFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFF
FFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFF
FFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFF
FFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFF
FFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFF
FFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFF
FFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFF
FFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFF
FFFFFF000D3F8FF87A4D697E73FE86077FD1D10C4ECC59797E759E
DD89931B2208B8044CB4A1B96A
```

(b) Signature calculated on known values

- We define "**X**" as the value to be signed
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- Padding can influence the final "shape" of "**X**" before being signed and make this unpredictable…
- …but with SSL3.0, TLS 1.0, 1.1 and 1.2 the padding scheme (a variant of PKCS1.5) is fully deterministic (not randomized) and then predictable
- Of course we need the presence of a digital signature. This condition is **ALWAYS** satisfied in our attack if we carefully negotiate the right ciphersuites during the TLS handshake.

The right ciphersuite…

- RSA_WITH_AES_256_CBC_SHA
  - ✓ ***RSA*** *= Authentication + Key Exchange*
  - ✓ ***AES*** *= Symmetric algorithm used to encrypt data*
  - ✓ ***CBC*** *= Mode of operation*
  - ✓ ***SHA*** *= Hashing algorithm to avoid data tampering*
- RSA private key leaked = all TLS sessions compromised (current, past and future ones)
- The "*Certificate*" message contains a Signature created with the private key of CA
  - ➢ statically embedded inside the certificate (not generated on the fly)
  - ➢ the condition (**b**) is not satisfied

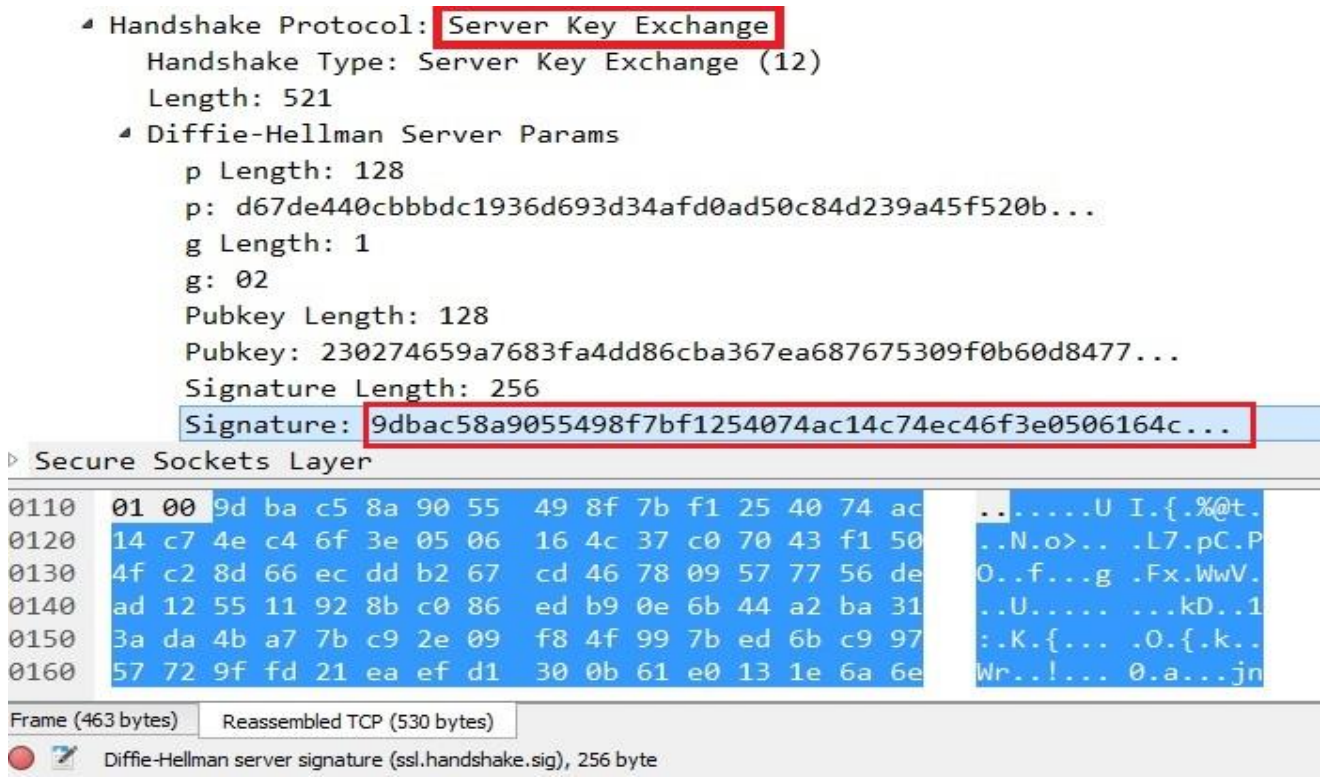
The right ciphersuite...

- [EC]DHE_RSA_WITH_AES_256_CBC_SHA
  - ✓ ***[EC]DHE*** *= Key Exchange*
  - ✓ ***RSA*** *= Only used for Authentication*
  - ✓ *[the rest is the same as previously mentioned]*

- The key exchange is done using private/public keys generated on the fly
  - ➢ *Compromission of a private key breaks only that specific encrypted session, not all the previously established*
  - ➢ *This is called "Perfect Forward Secrecy"*

PFS fits REALLY perfectly to us

- RSA signature appended onto a TLS *Server Key Exchange* Message



How High Voltage! works…

TLS Client Hello (PFS ciphersuites only negotiation)

```
▲ Handshake Protocol: Client Hello
    Handshake Type: Client Hello (1)
    Length: 198
    Version: TLS 1.2 (0x0303)
  ▲ Random
      GMT Unix Time: May 30, 1981 07:53:42.000000000 ora legale Europa occidentale
      Random Bytes: 6179c141c844786767bd4867051955676853c5ea74dcc122...
    Session ID Length: 0
    Cipher Suites Length: 30
  ▷ Cipher Suites (15 suites)
    Compression Methods Length: 1
```

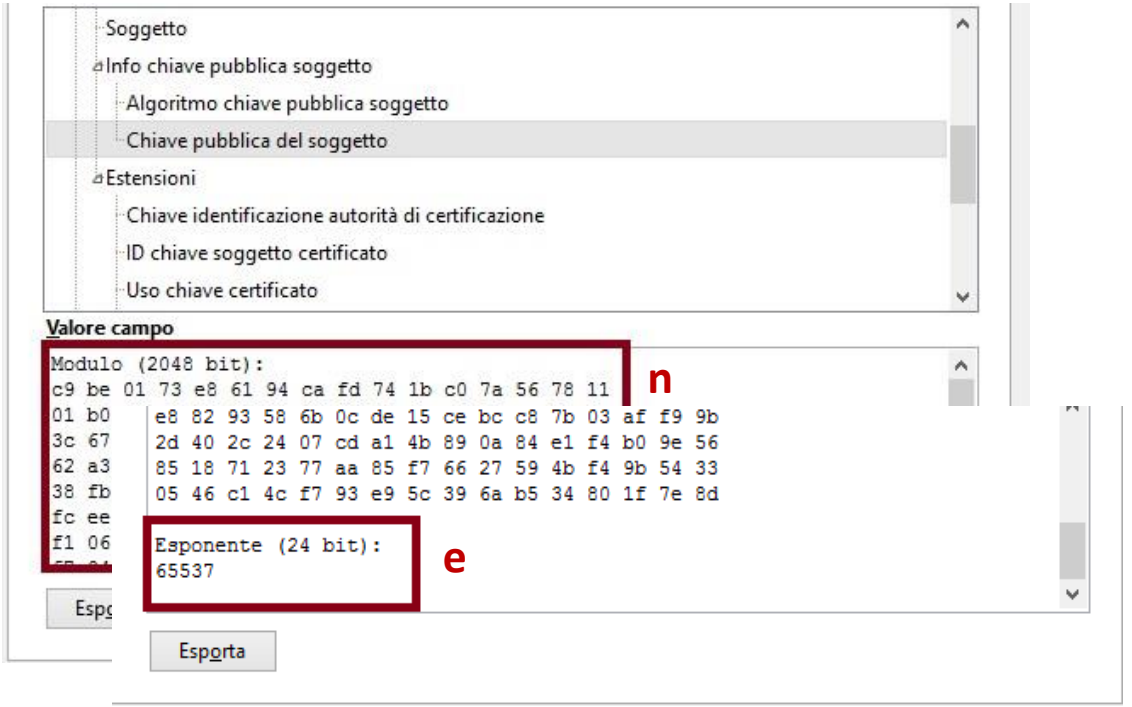
How High Voltage! works…

TLS Server Hello

```
▲ Handshake Protocol: Server Hello
    Handshake Type: Server Hello (2)
    Length: 70
    Version: TLS 1.0 (0x0301)
  ▲ Random
      GMT Unix Time: Feb 10, 2016 19:16:19.000000000 ora solare Europa occidentale
      Random Bytes: 0ddbab1877d6d8d51474dfa833b2c2ed3b05516194e65b18...
    Session ID Length: 32
    Session ID: df27d09ed3c26a6b61d93ae0a47bd6444abc9a1548b61fc0...
    Cipher Suite: TLS_DHE_RSA_WITH_AES_256_CBC_SHA (0x0039)
    Compression Method: null (0)
```

How High Voltage! works...

TLS Server Certificate



How High Voltage! works…

TLS Server Key Exchange

```
▲ Handshake Protocol: Server Key Exchange
    Handshake Type: Server Key Exchange (12)
    Length: 521
  ▲ Diffie-Hellman Server Params
      p Length: 128
      p: d67de440cbbbdc1936d693d34afd0ad50c84d239a45f520b...
      g Length: 1
      g: 02
      Pubkey Length: 128
      Pubkey: 230274659a7683fa4dd86cba367ea687675309f0b60d8477...
      Signature Length: 256
      Signature: 9dbac58a9055498f7bf1254074ac14c74ec46f3e0506164c...
```

How High Voltage! works…

TLS Server Key Exchange

Client Random Struct (*Client Hello Message*)
Server Random Struct (*Server Hello Message*)
Server Param Struct (*Key Exchange Message*)

```
▲ Handshake Protocol: Server Key Exchange
    Handshake Type: Server Key Exchange (12)
    Length: 521
  ▲ Diffie-Hellman Server Params
      p Length: 128
      p: d67de440cbbbdc1936d693d34afd0ad50c84d239a45f520b...
      g Length: 1
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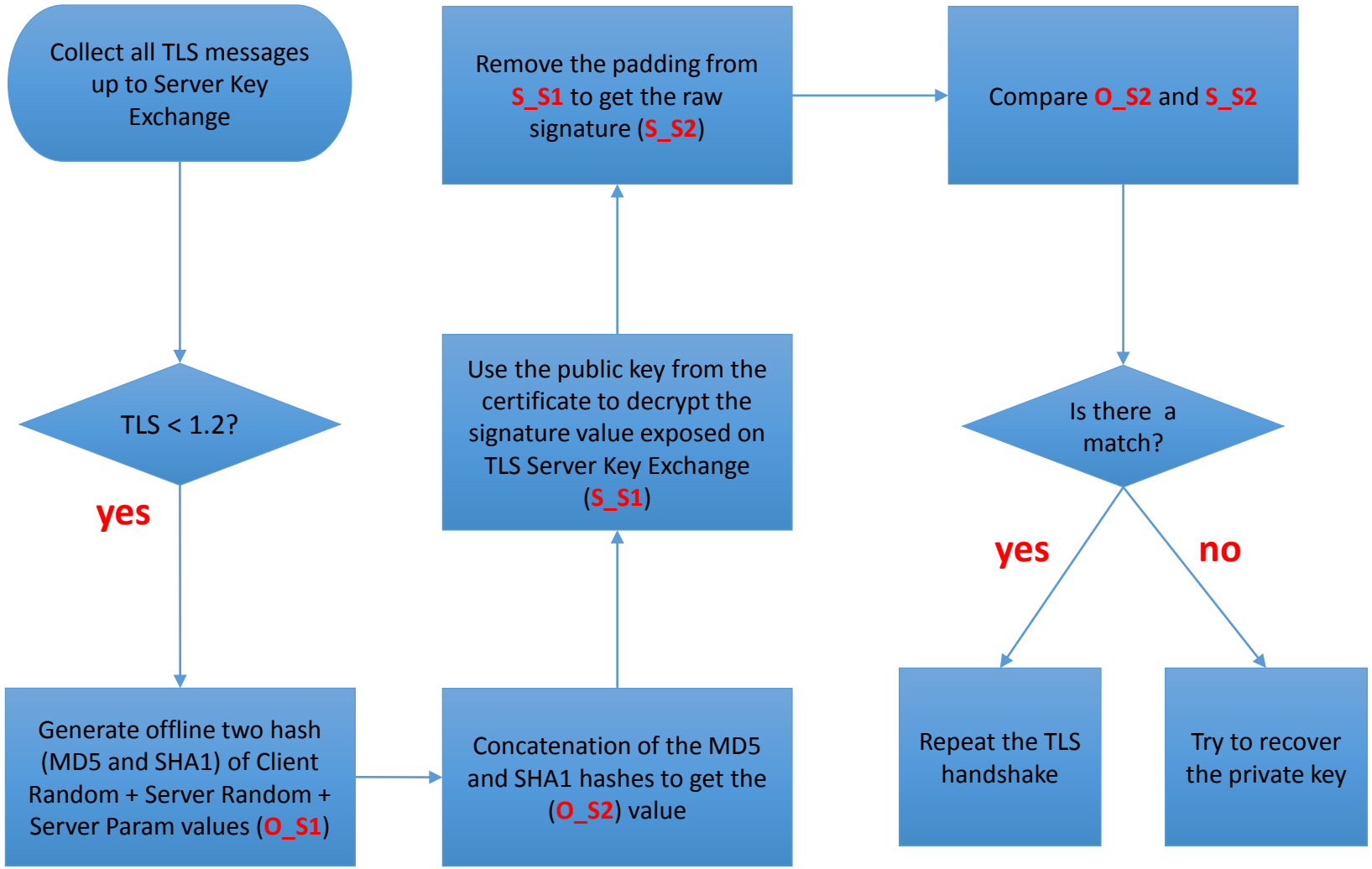
      Signature Length: 256
      Signature: 9dbac58a9055498f7bf1254074ac14c74ec46f3e0506164c...
```

Attacking TLS abusing PFS

- Because of “(c) Presence of faulty signature”, the attack can be carried out only when a RSA signature is faulty. How to determine that?

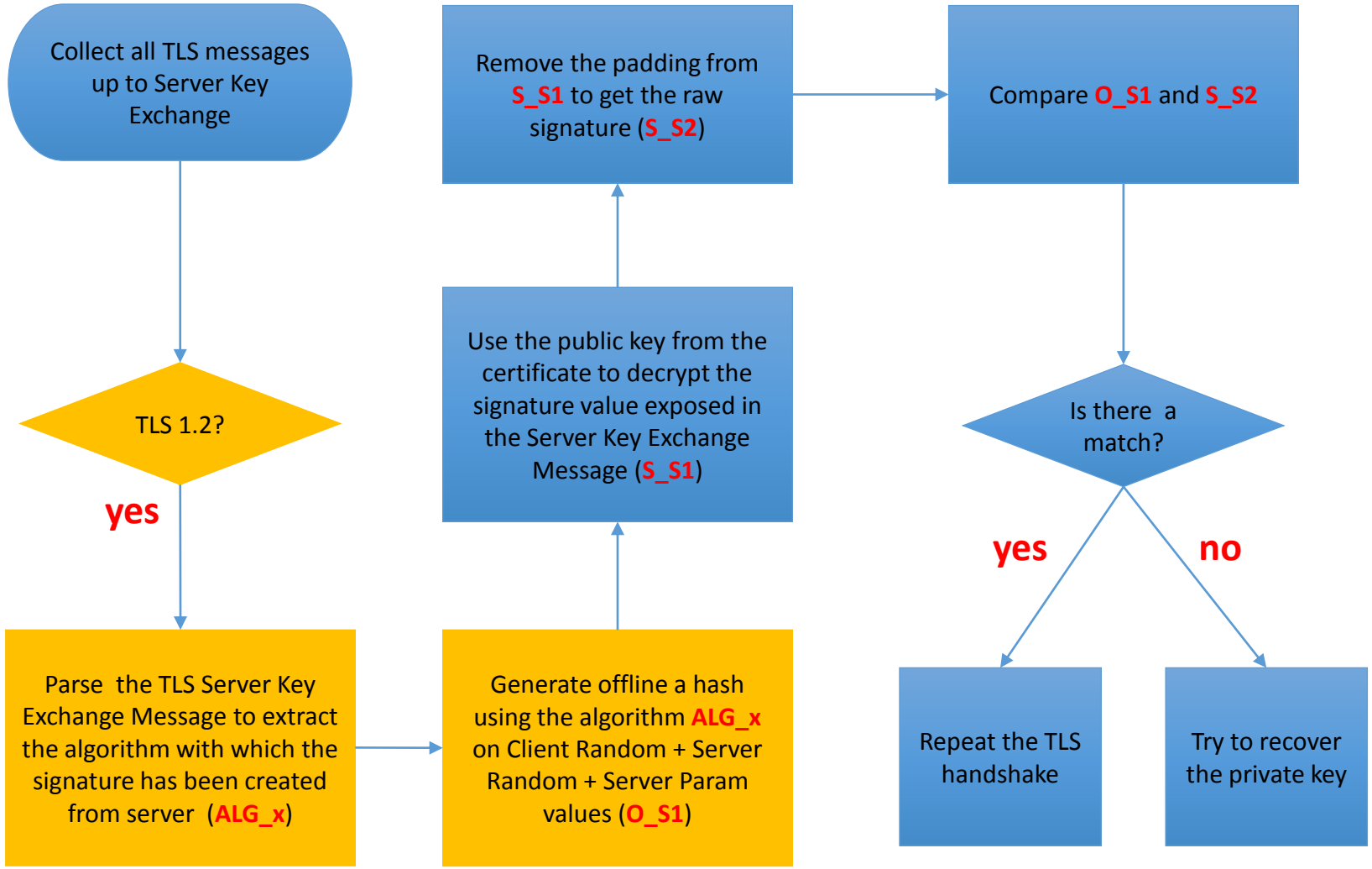
- Looking for faulty signatures!!

How to check if a digital signature is invalid? (TLS < 1.2)



Lenstra Attack 1996

How to check if a digital signature is invalid? (TLS 1.2)



Lenstra Attack 1996

What else?

- How RSA works
- RSA-CRT optimization
- 2nd DEMO

How RSA works

encryption = c = m^e mod n
decryption = m = c^d mod n

- **c** = ciphertext
- **m** = message to encrypt
- **n, e** = public key
- **e** = exponent (usually a value such as *3* or *65537*)
- **n** = big semiprime number (p * q -> said "prime factors")
- **d =** `inverse_mod(e,(p-1) * (q-1))` private key mathematically tied with n

- *getting "p" and "q" a private key can be recovered because "e" is already a public information*

RSA Rule 1

$n = p * q$

$d = inverse\_mod(e,(p-1) * (q-1))$

Gaining a prime factor of n (whatever of the two) we can determine very easily the other one and recover the private key

- **n** = 77 (the public key into the certificate)
- **p** = 7 (leaked prime factor)
- **q** = ?

RSA Rule 1

$n = p \times q$

$d = inverse\_mod(e,(p-1) \times (q-1))$

Gaining a prime factor of n (whatever of the two) we can determine very easily the other one and recover the private key

- **n** = 77 (the public key into the certificate)
- **p** = 7 (leaked prime factor)
- **q** = **11** → 77 / 7

- 77 / 11 = 7 **(p)**
- 7 x 11 = 77 **(n)**

RSA-CRT

- RSA-CRT (CRT stands for Chinese Remainder Theorem)

- With this optimization the RSA calculation is broken down into two smaller parts

Signing with RSA-CRT

- Precompute the following values:
  - **qInv** = (1/q) mod p
  - **dP** = d (mod p - 1)
  - **dQ** = d (mod q - 1)

- …and next calculate:
  - **s1** = m^dP mod p
  - **s2** = m^dQ mod q
  - **h** = (s1 - s2) * qInv mod p
  - **m** = s2 + q * h

If during s1 or s2 calculation there is a fault, a faulty RSA signature is generated and one prime factor can be leaked with this formula:

```
gcd(y^e − x, n)
```

Signing with RSA-CRT

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```
gcd(y^e − x, n)
```

Lenstra Attack 1996

Rule 2

We can leak a prime factor of n from a faulty signature when RSA-CRT is used for signing:

```
gcd(y^e – x, n)
```

y = faulty/miscalculated signature (this can be taken directly from the TLS **Server Key Exchange** message)
e = public exponent (found inside the **Certificate**)
x = the original value hashed and padded before to be signed (**PKCS 1.5 padding scheme is deterministic**)
n = public key (p * q) (found inside the **Certificate**)

TLS RSA-CRT Attack in “pills”

1. Establish multiple TLS handshakes until a faulty signature is detected in the *Server Key Exchange* Message
2. Apply the Lenstra Attack (1996) to retrieve a prime factor (**p** or **q**) of **n** (**Rule 2**)
3. When one of the prime factors is known, derive the other one (**Rule 1**):

```
derived_prime_factor  = n / leaked_prime_factor
```

4. Now both of **p** and **q** are known. The private key can be recovered:

```
d = inverse_mod(e,(prime_factor_P - 1) * (prime_factor_Q - 1 ))
```

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```

GAME OVER

TLS RSA-CRT Attack in “pills”

1. **Establish multiple TLS handshakes** until a faulty signature is detected in the *Server Key Exchange* Message
2. Apply the Lenstra Attack (1996) to retrieve a prime factor (**p** or **q**) of **n** (**Rule 2**)
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```

GAME OVER

TLS RSA-CRT Attack in “pills”

1. **Sniff the traffic** until a faulty signature is detected in the *Server Key Exchange* Message
2. Apply the Lenstra Attack (1996) to retrieve a prime factor (**p** or **q**) of **n** (**Rule 2**)
3. When one of the prime factors is known, derive the other one (**Rule 1**):

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d = inverse_mod(e,(prime_factor_P - 1) * (prime_factor_Q - 1 ))
```

GAME OVER

DEMO TIME (PART 2)

(enter Piciolla...)

The bottom line

- IF:
  - you have a piece of software linked to a vulnerable crypto library using RSA-CRT &&
  - that crypto library does not verify the correctness of each RSA signature generated &&
  - environmental factors occur (CPU overheating, RAM error, etc...) causing the miscalculation of a RSA signature

- THEN you might be in trouble…

Vulnerable crypto libraries

- **PolarSSL** < 2.1.1, 1.3.13 and 1.2.16: *MBEDTLS_RSA_NO_CRT* can be defined to disable RSA-CRT but this option is off by default)
- **libgcrypt** < 1.6.3 (equivalent to *CVE-2015-5738*)
- **Nettle** < 3.1: used by GnuTLS
- **Java SE** < 5.0u81, 6u91, 7u76, 8u40, and **JRockit** < R28.3.5 (*CVE-2015-0478*)
- **EMC RSA BSAFE Micro Edition Suite** (MES) 4.0.x and 4.1.x before 4.1.5, **RSA BSAFE Crypto-C Micro Edition** (CCME) 4.0.x and 4.1.x before 4.1.3, **RSA BSAFE Crypto-J** before 6.2.1, **RSA BSAFE SSL-J** before 6.2.1, and **RSA BSAFE SSL-C** before 2.8.9 (*CVE-2016-0887*)

Vulnerable crypto libraries (2)

- **OpenSSL** <= 0.9.7 and *potentially* between 1.0.2 and 1.0.2d because of *CVE-2015-3193* only on x86_64 architectures + custom versions
- **Go** crypto library < 1.6.2
- **Cryptlib** up to latest 3.4.3 (*CRYPT_OPTION_MISC_SIDECHANNELPROTECTION* would prevent the attack but it is set to false by default)
- **wolfSSL** (formerly **CyaSSL**) < 3.6.8 (*CVE-2015-7744*)
- **Libtomcrypt** < **2.00**
- **Eldos SecureBlackbox** < 13.0.280 and 14.0.281
- **MatrixSSL** < 3.8.3
- **Openswan** up to latest version 2.6.47 vulnerable when not compiled with NSS

Device types mainly affected

- **Embedded devices**
  - ✓ Various network appliances (firewalls, routers, etc…)
  - ✓ Consumer / SOHO devices
  - ✓ SSL Accelerators
  - ✓ VPN Concentrators
  - ✓ TLS Reverse Proxies
  - ✓ …

Affected devices

- **FORTINET** (Series 300 / FortiGate < 5.0.13 / 5.2.6 / 5.4.0 observed as vulnerable)
- **Dell** (SonicWALL< SonicOS 6.1.1.12 found affected)
- **F5** (Traffix SDC affected)
- **ZTE ZXSEC Firewall** (affected models US2640B, US2630B, US2620B)
- **LANCOM** wireless devices (version 8.84) <- apparently silently patched since 2014
- **D-Link-DCS-933L** Surveillance camera
- **HILLSTONE NETWORKS** (SG-6000 Firewall)
- **CITRIX**
- **ZYXEL**
- **NORTEL**
- **QNO**
- **Viprinet**
- **BEJY**
- **Alteon**

The Fix

- A few of crypto libraries allow users to disable RSA-CRT (*not convenient due to performance issues*)

- Most vendors have recently issued a patch to address this problem

  ✓Double-checks the correctness of RSA signatures without RSA-CRT optimization:

```
if (y^e = x mod n)
  then signature_is_valid
```

But remember…

- *"…a piece of software linked to a vulnerable crypto library using RSA-CRT…"*

- Wait! Is this problem only related to TLS, right?
- No! PFS and RSA are used **A LOT** in IPSEC VPN (IKE), SSH, etc…

IKEv1 (Internet Key Exchange)

- It is believed that only by sniffing the network traffic is not possible to recover a private key (just as happens for TLS) and an active approach is requested.

- Two modes for **Phase 1** (*Authentication* of peers and *Negotiation* of SA)
  - ✓ *Main*
  - ✓ *Aggressive*

IKEv1 Phase 1 Main Mode (Signature Auth)

```
Initiator                                   Responder
-----------                                 -----------
(1) HDR, SA                          -->
                                     <--    (2) HDR, SA
(3) HDR, KE, Ni                      -->
                                     <--    (4) HDR, KE, Nr
(5) HDR*, IDii, [ CERT, ] SIG_I      -->
                                     <--    (6) HDR*, IDir, [ CERT, ] SIG_R
```

** Indicates payload encryption*

IKEv1 Phase 1 Aggressive Mode (Signature Auth)

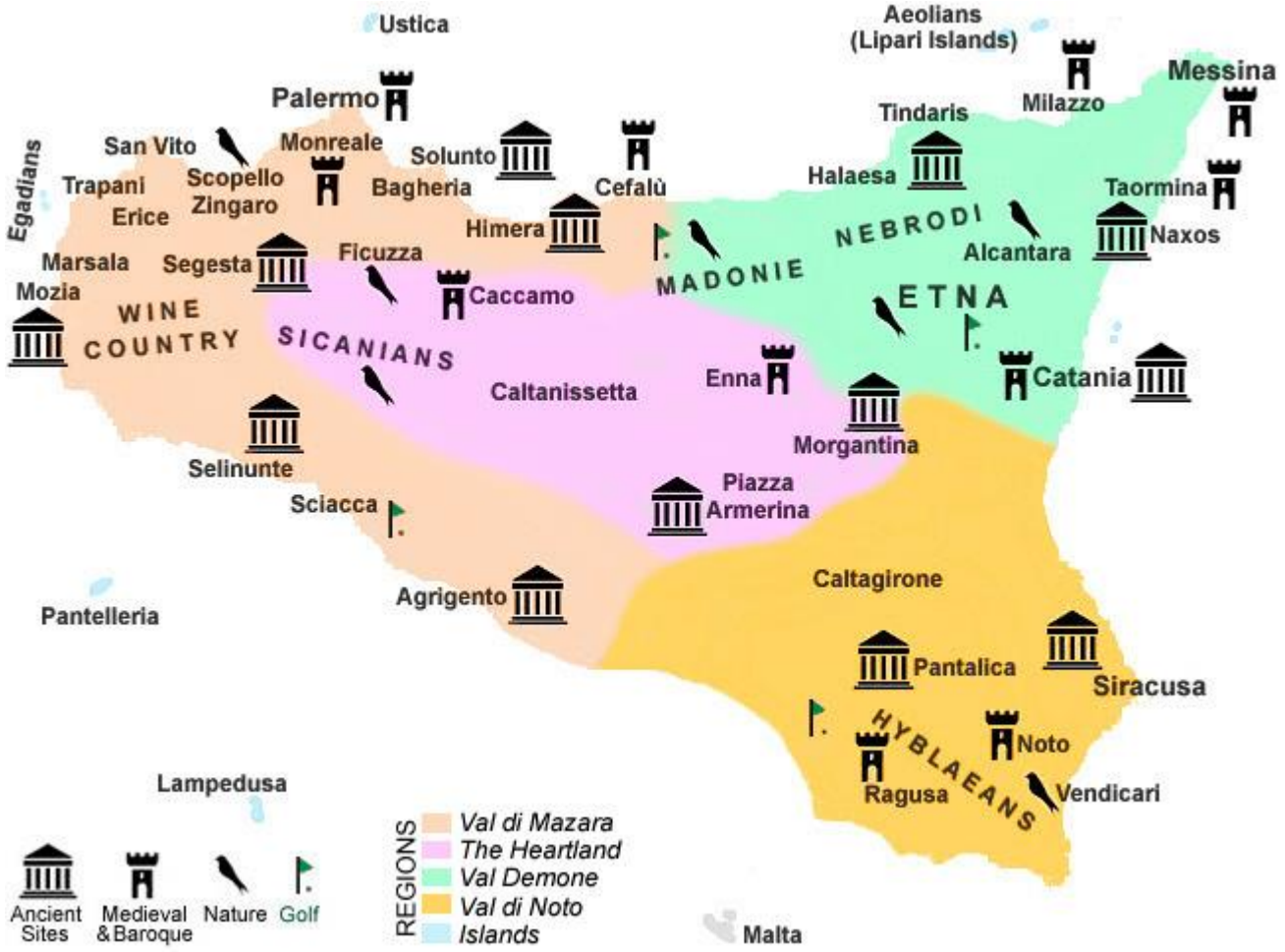
```
Initiator                                   Responder
-----------                                 -----------
(1) HDR, SA, KE, Ni, IDii          -->
                                   <--   (2)HDR, SA, KE, Nr, IDir,
                                                 [ CERT, ] SIG_R
(3) HDR, [ CERT, ] SIG_I           -->
```

SPECIAL THANKS

Frank Bosman for his nice drawings
http://turniphead.deviantart.com

Florian Weimer (Red Hat)
https://access.redhat.com/blogs/766093/posts/1976703
https://pagure.io/symboldb/tree/tls-experiment

PLEASE VISIT SICILY…



Recover a RSA private key from a TLS session with Perferct Forward Secrecy

QUESTIONS?

High Voltage & Piciolla – http://www.segfault.it/tools/
Marco Ortisi (2016) Blog – http://www.segfault.it/

thanks!