Randomness of random in Cisco ASA

Ryad BENADJILA (CryptoExperts)*
ryad.benadjila@cryptoexperts.com
Arnaud EBALARD (ANSSI)
arnaud.ebalard@ssi.gouv.fr

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*Work performed while at ANSSI.

The beginning of the story ...

Work on development projects

- X-509 parser [x509-parser]
- Elliptic Curve Cryptography library libecc [libecc]

Tests on a >250 millions X.509 certificates set led to ...

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X.509 Certs (TLS campaign)

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82k dup. ECDSA nonces

113k dup. ECDSA keys

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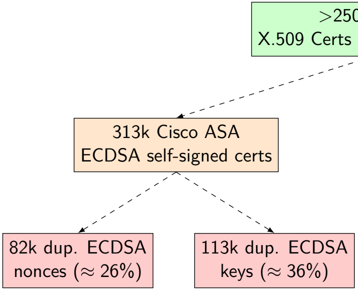

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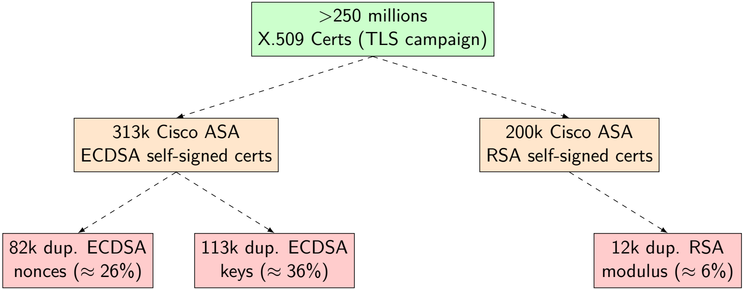

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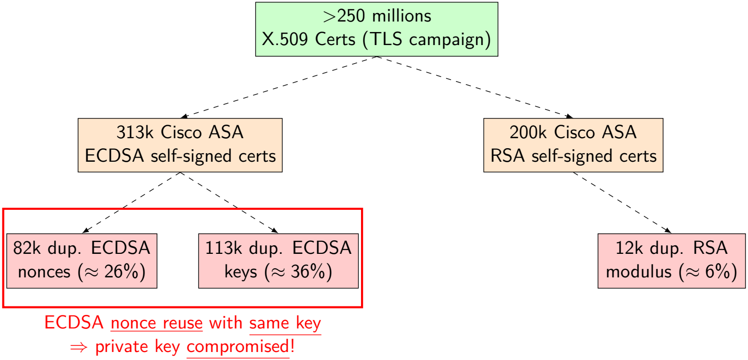

ECDSA signature algorithm

...and resulting nonce and key recovery from duplicated nonce

secret / public

1: $h = H(m)$
2: $e = OS2I(h) \bmod q$
3: $k \leftarrow \mathcal{R},\ k \in]0, q[$
4: $W = (W_x, W_y) = k \times G$
5: $r = W_x\ mod\ q$
6: $s = k^{-1} \times (xr + e) mod\ q$
7: Return (r,s)

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From 6: above, we draw for two signatures (r, s_1) and (r, s_2) sharing the same duplicated nonce k for different messages:

Nonce recovery from nonce duplication

$$
\begin{aligned}
s_1 - s_2 = & k^{-1} \times (xr + e_1) - k^{-1} \times (xr + e_2)\ mod\ q \\
& k^{-1} \times (xr + e_1 - xr - e_2)\ mod\ q \\
& k^{-1} \times (e_1 - e_2)\ mod\ q
\end{aligned}
$$

$$\Longrightarrow k = (e_1 - e_2) \times (s_1 - s_2)^{-1} mod\ q$$

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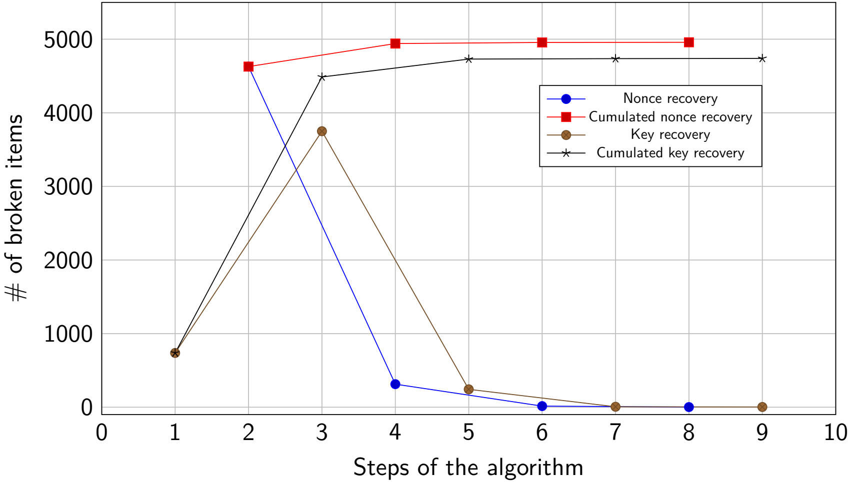
$$\Longrightarrow k = (e_1 - e_2) \times (s_1 - s_2)^{-1} mod\ q$$

key recovery from nonce

$$x = (k \times s_1 - e_1) \times {r_1}^{-1} \ mod\ q$$
$$(k \times s_2 - e_2) \times {r_2}^{-1} \ mod\ q$$

Iterative key recovery

Over 313k X.509 ASA ECDSA self-signed certificates with 216k unique keys



Some background on RNG fails ...

History

[CVE-2008-0166] 05/2008: predictible Debian OpenSSL RNG

⇒ Broken SSH/SSL RSA/DSA keys

[PS3EPICFAIL] 12/2010: Epic Fail ECDSA on the Sony PS3

⇒ Nonce reuse, compromission of the firmware signature key

[PSANDQS] 08/2012: Mining your Ps and Qs (modulus GCD)

⇒ Compromised RSA keys on many embedded devices

[NSBTCFAIL] 01/2013: Recovering BTC private keys

⇒ Nonce reuse, crypto-wallet ECDSA key compromission

[CVE-2019-1715, RWC-2019] Cisco ASA low entropy keys

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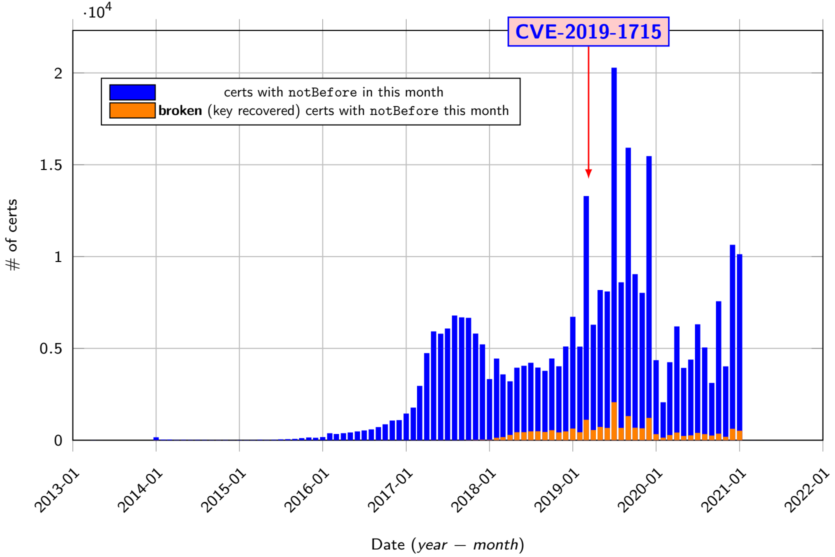
[CVE-2019-1715, RWC-2019] Cisco ASA low entropy keys 🤔

What about understanding and fixing last one for real? 😋 😇

[CVE-2023-20107] Cisco ASA low entropy keys

Distribution per month, broken / total

Over 313k certs ECDSA ASA



Cisco Adaptative Security Appliance (ASA)

- Firewall
- VPN (IPsec / TLS)
- IDS/IPS
- ...

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Cisco ASA 5506
40 € Livraison : à partir de 6,50 €

Hardware devices: easily available for a decent price!

Cisco Adaptative Security Appliance (ASA)

- Firewall
- VPN (IPsec / TLS)
- IDS/IPS
- ...

- Virtual appliances ASAv
- Firmware shared with HW
- Difference: no Cavium

Hardware devices: easily available for a decent price!

Virtual appliances ASAv images available

5506-X stats

Black box approach (through scripting)

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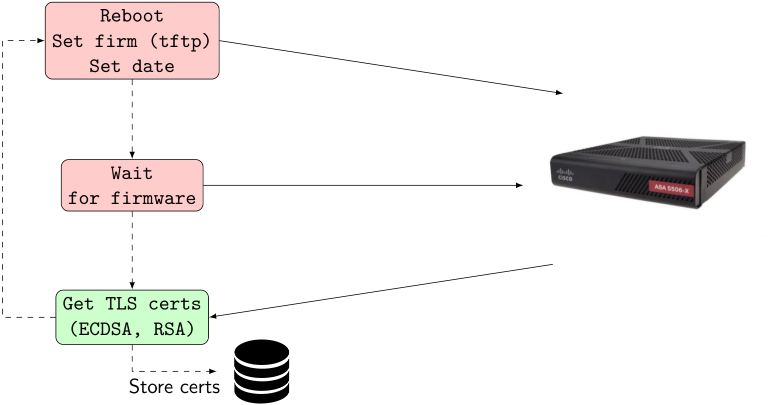


5506-X stats

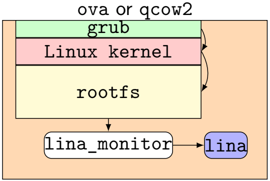
Black box approach (through scripting)

Firmware	RSA modulus	ECDSA `r` nonce	ECDSA `x` key	#generated
9.6.2-23				45
9.6.3-20				15
9.6.4-34	● (red)		● (blue)	15
9.6.4-36	● (red)		● (blue)	15
9.6.4-40	● (red)		● (blue)	15
9.6.4-41	● (red)		● (blue)	15
9.6.4-42	● (red)		● (blue)	15
9.6.4-45	● (red)		● (blue)	45
9.7.1-4				160
9.8.1				60
9.8.2	● (olive)	◗ (orange)	■ (cyan)	60
9.8.3		● (yellow)		60
9.8.4-10		● (yellow)		10
9.8.4-41		● (yellow)		30
9.9.1	● (olive)	● (yellow)	■ (cyan)	30
9.9.2-85		● (yellow)		30
9.10.1-44		◗ (crimson)		30
9.12.4				30
9.12.4-35				30
9.13.1-12				30
9.14.3-18				30
9.15.1-15				30
9.16.2-14				30
9.16.2				45

● collisions shared between firmware versions
◗ = isolated collisions
■ = collisions emerging with same certificate time

| Same color = collision values shared across versions
| Empty box = no observable collisions, inconclusive
| Versions highlighted are vulnerable and NOT concerned by CVE-2019-1715

The need for instrumentation on ASAv



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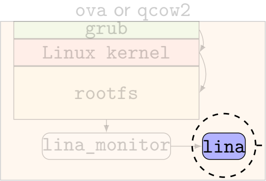
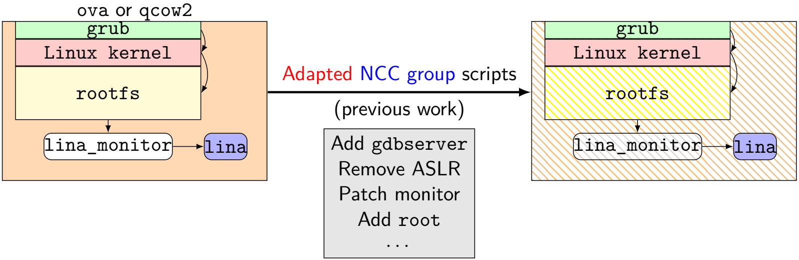


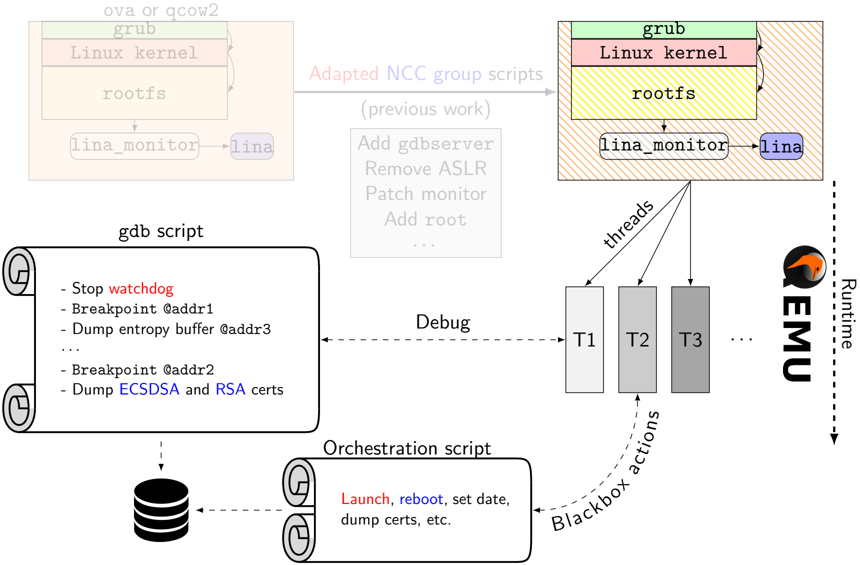
- From ≈ 100 MB in versions 9.8
  to ≈ 180 MB in recent 9.17
- More than 110k functions
- Multiple aggregated libraries (OpenSSL, etc.)
- Dedicated embedded Cavium firmware
- Redefintion of many low-level APIs (IOS era)

- Static analysis is complex
- Need for dynamic analysis and instrumentation

Instrumentation using gdb



Instrumentation using gdb



Instrumentation using qemu

- Limitations of gdb instrumentation:
  - Multi-threading ⇒ unitialized buffers values (MD_rand)
  - No ASLR impact analysis (this is also a source of entropy)
  - Breakpoints disturb entropy based on time!

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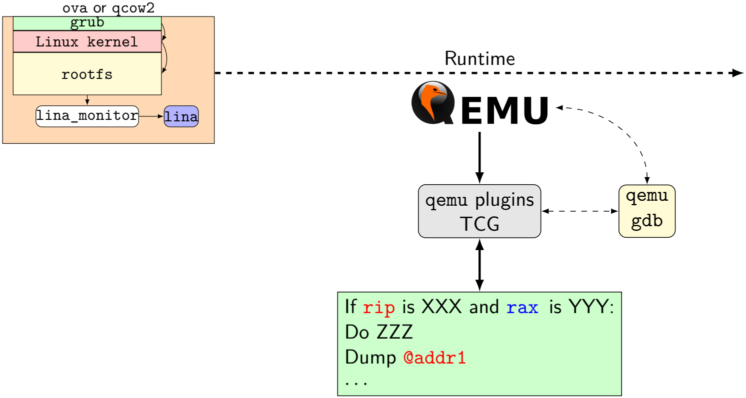
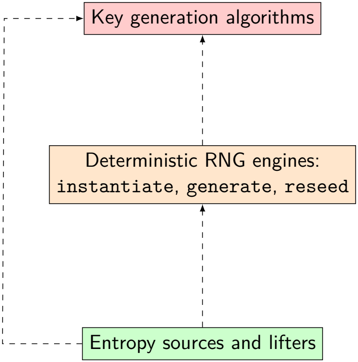
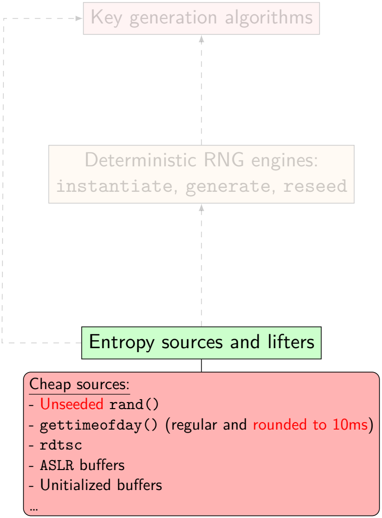


The RNG players in Cisco ASA



- Many primitives per layer
- Many combinations of these! (depending on ASA(v) version)
- Disclaimer: focus on important parts (not exhaustive)

Entropy sources and lifters



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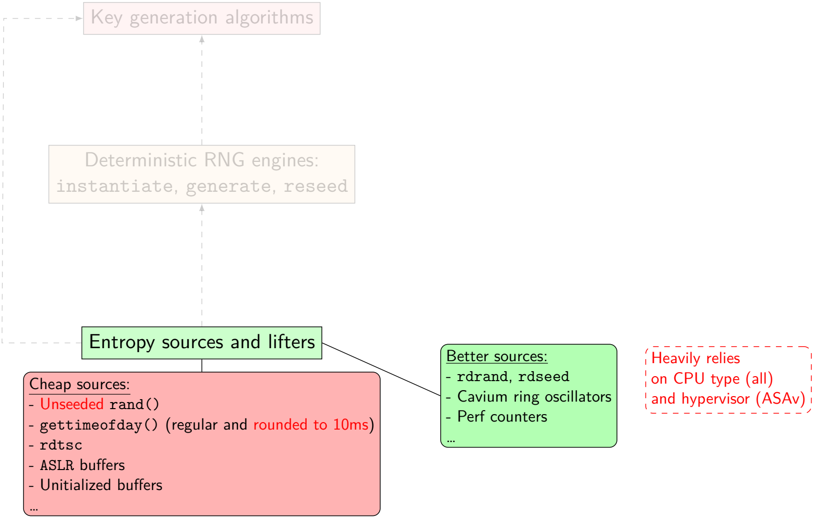

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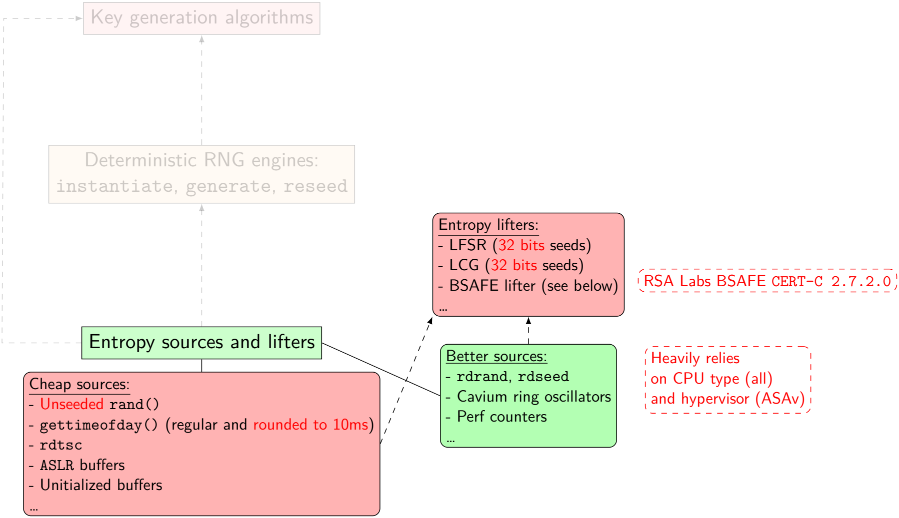
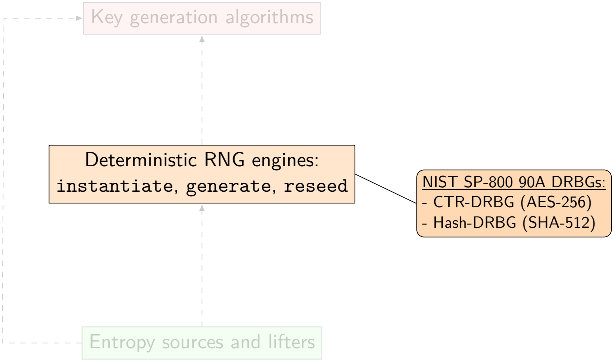


Deterministic generators



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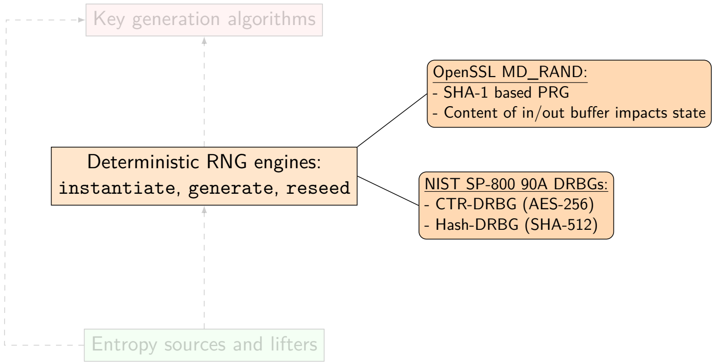

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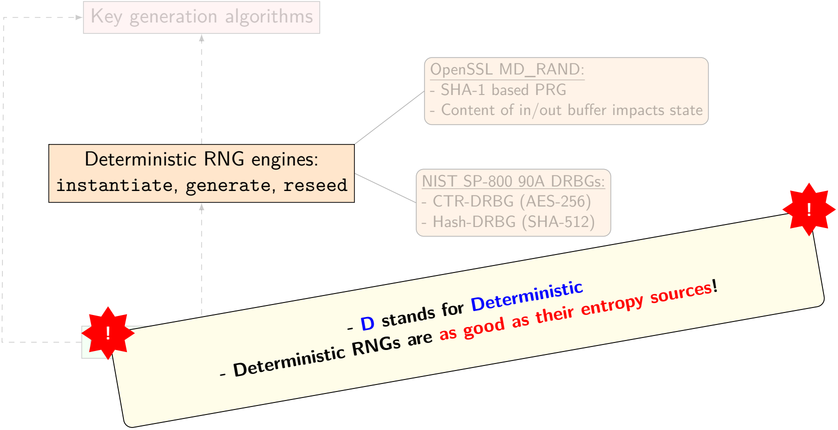
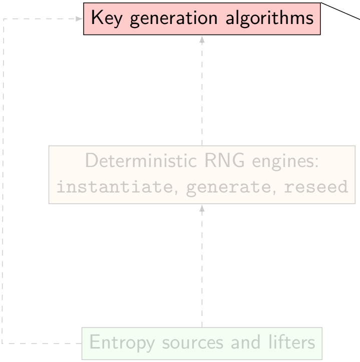


Key generation details



RSA key generation:
- FIPS 186-4 seeded generation of P and Q
- Seed of 28 bytes
- Explains why GCD attacks fail!

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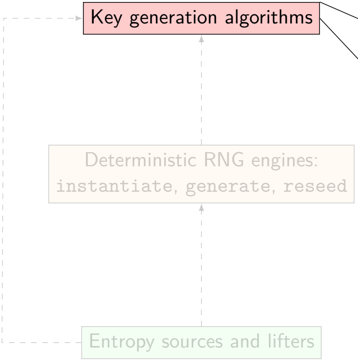

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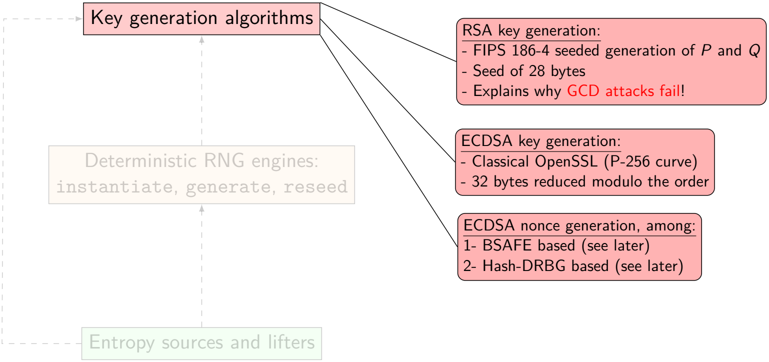
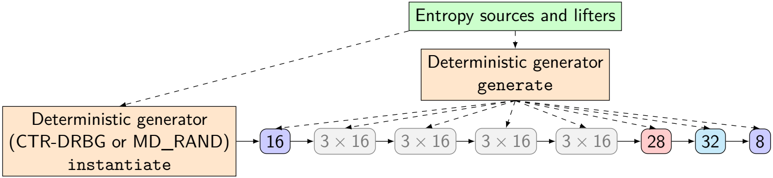
- Explains why GCD attacks fail!

ECDSA key generation:
- Classical OpenSSL (P-256 curve)
- 32 bytes reduced modulo the order

Key generation details



Calls to the DRBG and random generate



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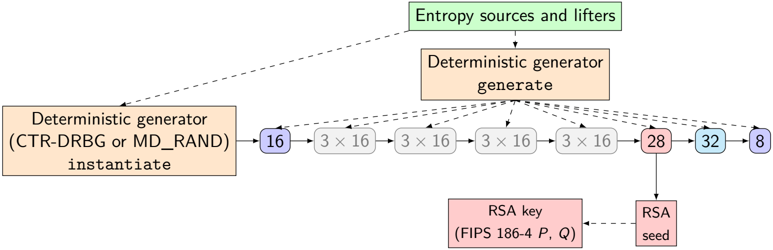

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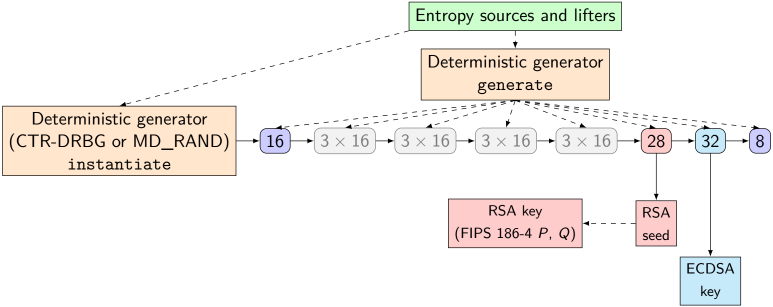

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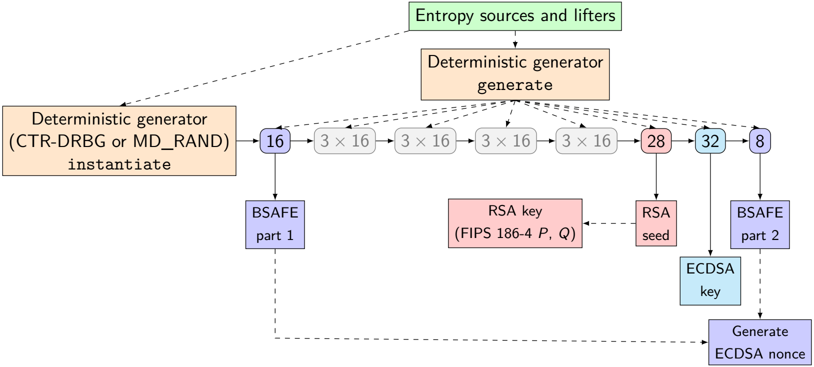
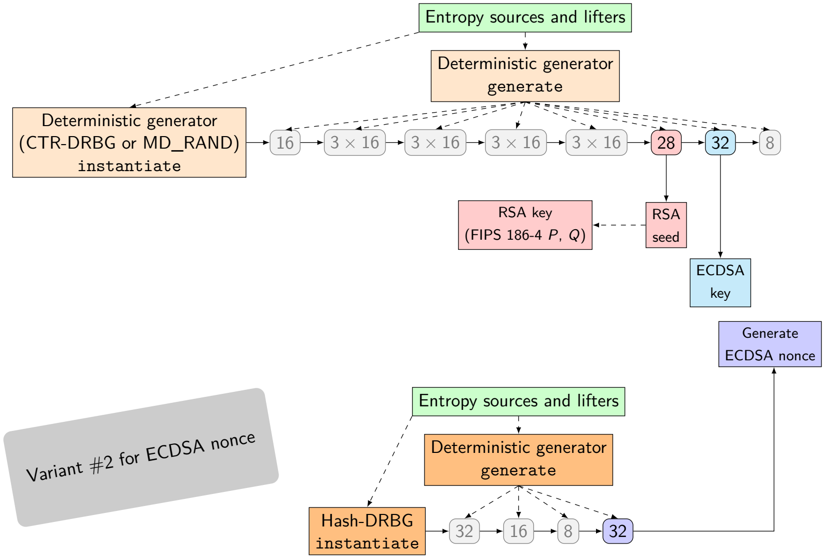
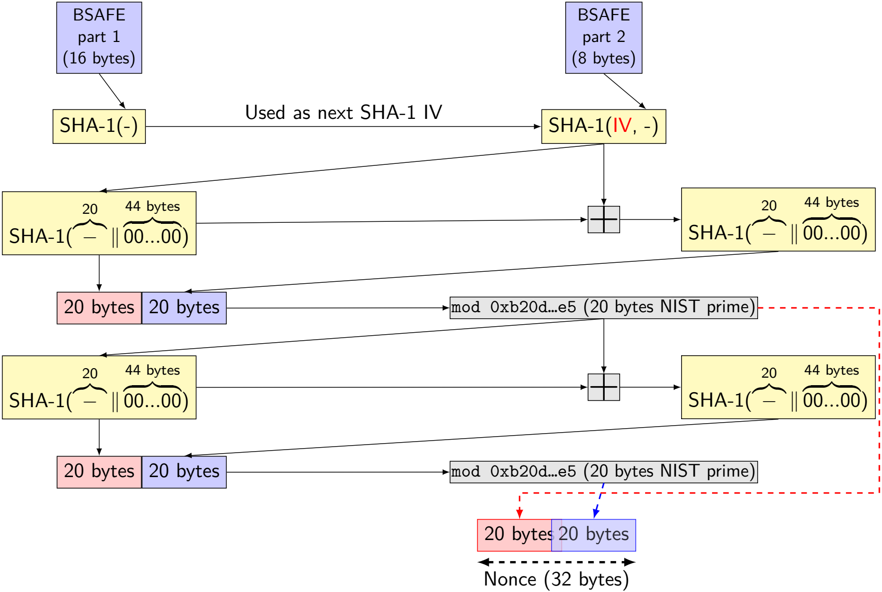


Variant #1 for ECDSA nonce

Calls to the DRBG and random generate



BSAFE lifter for ECDSA nonce



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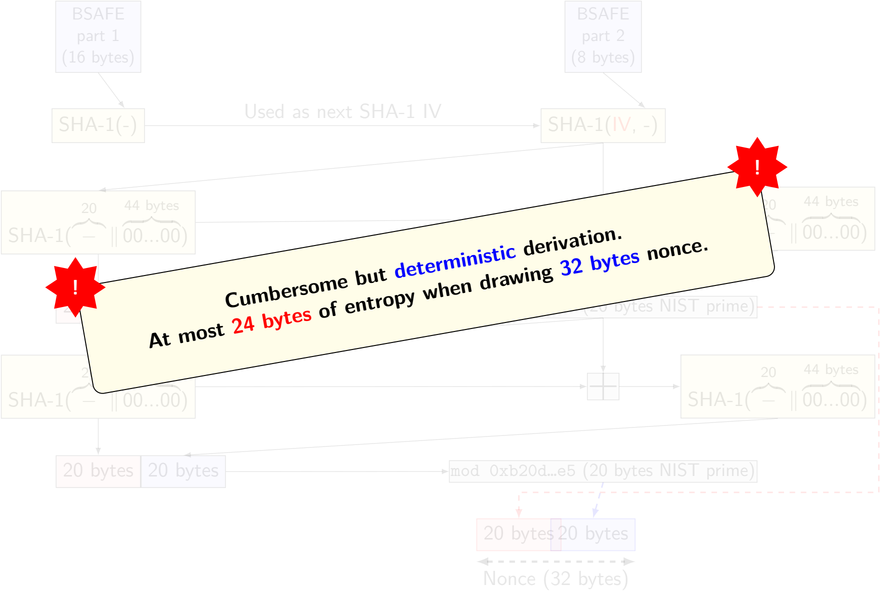


Cumbersome but deterministic derivation.
At most 24 bytes of entropy when drawing 32 bytes nonce.

ASAv v9.10.1.44

Overview of instantiated mechanisms

Used mechanisms

- CTR-DRBG used for RSA seed, ECDSA key
- ECDSA nonce using BSAFE with seeds from CTR-DRBG

CTR-DRBG Instantiate

- DRBG Personalization string:
  - Fixed `"CiscoSSL DRBG60"`
  - time from boot rounded to 10ms
- Entropy/nonce:
  - 40/20 bytes from MD_RAND …
  - … seeded by LFSR …
  - … seeded by 32 bits RDTSC.

CTR-DRBG Generate calls

- Addin: counter + time from boot rounded to 10ms

ASAv v9.10.1.44

Key aspects of a tricky keygenning

Estimated complexity

- 2^{32} possible LFSR seeds
- $\approx 2^{13}$ possible tuples for the 15 rounded time values

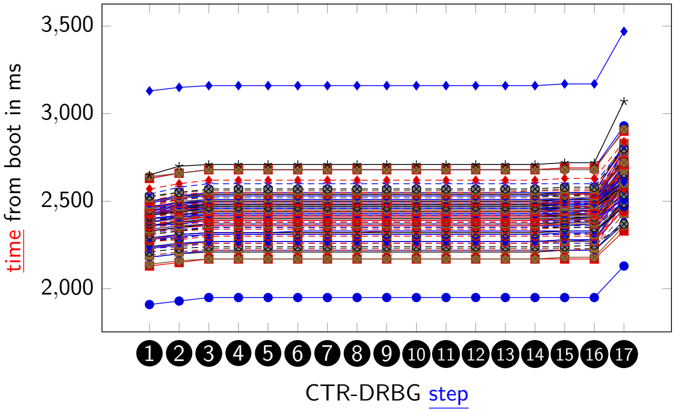
$\Rightarrow$ Exhaustive search for $\approx 2^{45}$ (w/ heavy DRBG calls)

Meet in the middle solution

- Patch the binary with a known fixed seed, do some stats on the timings as independent variables (valid approach)
- Take the most probable paths to reduce complexity, generate enough target certs and validate approach

ASAv v9.10.1.44

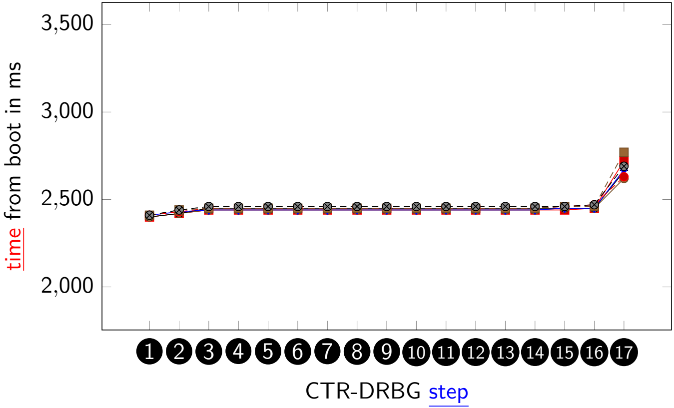
Timing statistics using patched binary (fixed seed)



- Pros: complexity reduced to $\approx 2^{13}$ for stats gathering

ASAv v9.10.1.44

Timing statistics using patched binary (fixed seed) + envelope reduction



- Pros: complexity reduced to $\approx 2^{37.5}$ for validation PoC on **unpatched** binary by reusing these envelope stats
- Cons: only 1.7% of possible certs remains accessible

ASAv v9.10.1.44

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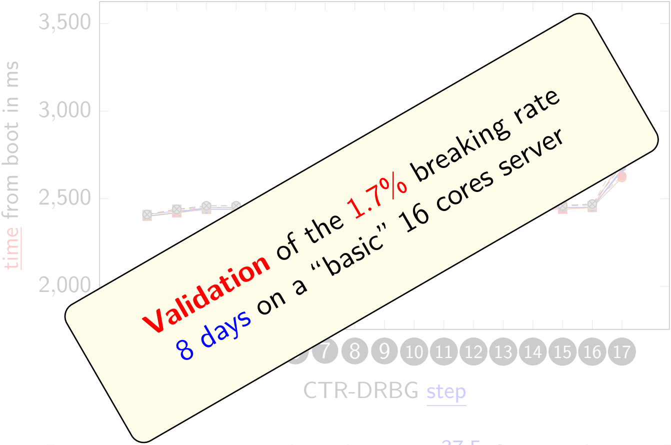

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ASAv firmware analysis: overview of results

Firmware	RSA modulus	ECDSA nonce	ECDSA key	Comment	Keygen time complexity
ASAv9.6.4-36	◗	●	◗ ▲	HASH-DRBG seeded by LFSR seeded by 32 bits rdtsc, used for nonce. CTR-DRBG is seeded by MD_RAND, itself seeded by HASH-DRBG itself seeded by a LFSR, itself seeded by rdtsc rounded to 32 bits	2^{32} (nonce)
ASAv9.8.1		●	▲	CTR-DRBG "saved" by addin with true gettimeofday(), HASH-DRBG seeded by a LFSR itself seeded by rdtsc rounded to 32 bits	2^{32} (nonce)
ASAv9.8.2	●	●	●	MD_RAND seeded by rand(), ASLR in input buffers for MD_RAND (nonce), BSAFE seeded by MD_RAND	$\approx 2^{33}$
ASAv9.8.3	●	●	●	CTR-DRBG seeded by rand() BSAFE seeded by CTR_DRBG	$\approx 2^{16}$
ASAv9.9.1	●	●	●	MD_RAND seeded by rand(), ASLR in input buffers for MD_RAND (nonce), BSAFE seeded by MD_RAND	$\approx 2^{33}$
ASAv9.10.1-44	● (red)	● (red)	● (red)	CTR-DRBG seeded by MD_RAND seeded by LFSR seeded by 32 bits rdtsc. Bad gettimeofday is also used.	Full: $\approx 2^{45}$ PoC: $\approx 2^{37.5}$

Legend:
- ● Fully broken with a PoC **keygen**
- ● (red) Broken with a PoC **keygen** with higher time complexity
- ◗ **Fragile** entropy sources, harder to exploit (but seems feasible)
- ▲ Broken as a side effect of nonce breaking

Versions highlighted are vulnerable and NOT concerned by previous CVE-2019-1715

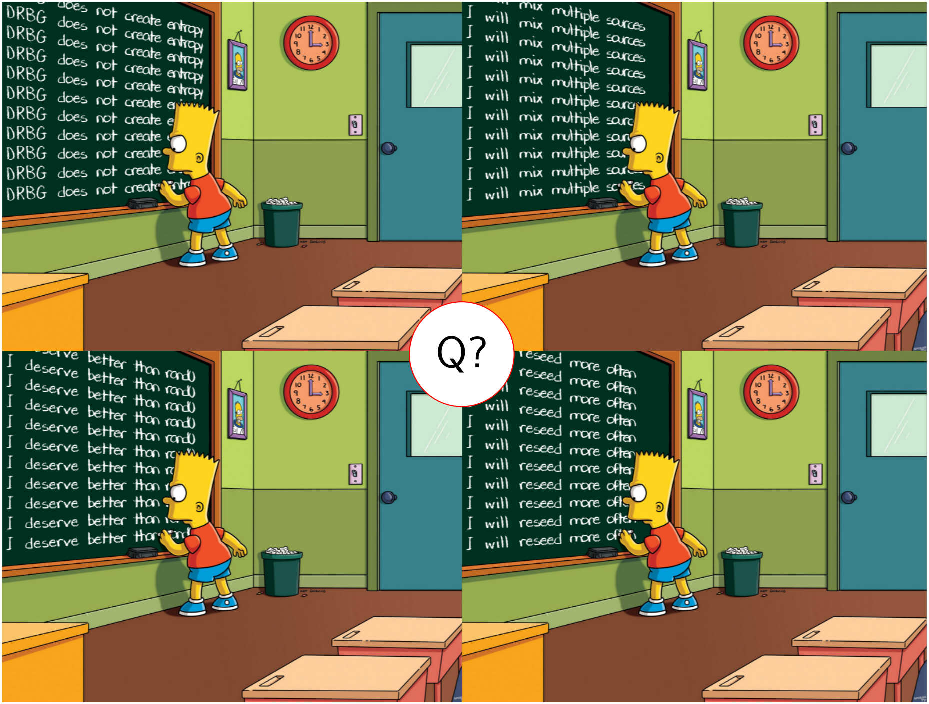
Conclusion

What we ~~learned~~ already knew.

- Fail instead of fallback to a bad entropy source
- Consider worst code path, remove if unacceptable/unsure
- Mix multiple sources instead of using a single one
- DRBG specific
  - DRBG security depends on `instantiate()` source
  - Poor addins for `DRBG generate()` calls is risky
  - Reseeding often is a requirement [DRBG-ANALYSIS]

Final thoughts

- Good looking keys, etc $\not\Rightarrow$ good random
- Good DRBG/PRNG $\not\Rightarrow$ good random
- Full 50 pages article in SSTIC proceedings


DRBG does not create entropy
I will mix multiple sources
I deserve better than rand()
I will reseed more often
Q?

- Ryad Benadjila, Arnaud Ebalard, Jean-Pierre Flori **“libecc: an ecc-based signature mechanisms library”**. Available at https://github.com/libecc/libecc.
- Arnaud Ebalard **“x509-parser: a RTE-free X.509 parser”**. Available at https://github.com/ANSSI-FR/x509-parser. More details at https://www.sstic.org/2019/presentation/journey-to-a-rte-free-x509-parser/
- Nils Schneider **“Recovering Bitcoin private keys using weak signatures from the blockchain”**, Blog entry, 28 January 2013, http://www.nilsschneider.net/2013/01/28/recovering-bitcoin-private-keys.html, broken link use https://archive.org.
- Nadia Heninger and Zakir Durumeric and Eric Wustrow and J. Alex Halderman **“Mining Your Ps and Qs: Detection of Widespread Weak Keys in Network Devices”**, https://www.usenix.org/system/files/conference/usenixsecurity12/sec12-final228.pdf.

- Luciano Bello, "**DSA-1571-1 openssl – predictable random number generator**" available at https://www.debian.org/security/2008/dsa-1571.
- failoverflow, https://web.archive.org/web/20150627235425/https://events.ccc.de/congress/2010/Fahrplan/attachments/1780_27c3_console_hacking_2010.pdf, 29 December 2010
- Cisco Adaptive Security Appliance Software and Firepower Threat Defense Software Low-Entropy Keys Vulnerability, https://tools.cisco.com/security/center/content/CiscoSecurityAdvisory/cisco-sa-20190501-asa-ftd-entropy, May 2019
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