Side-channel-free software, are we there yet?

Clémentine Maurice, CNRS, CRIStAL

17 June 2024—MPI-SP Symposium

Attacks on micro-architecture

- hardware usually modeled as an abstract layer behaving correctly

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  - side channels: observing side effects of hardware on computations

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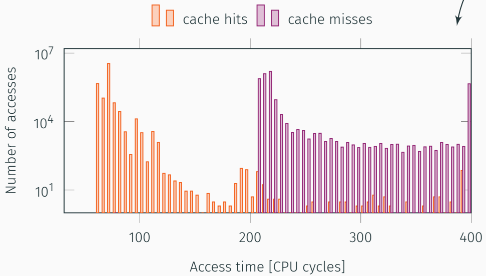

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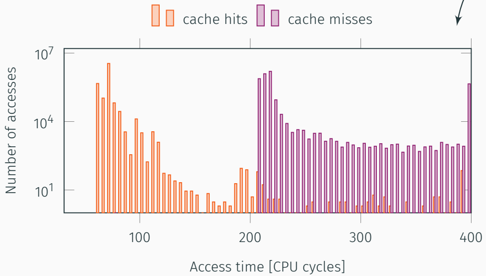
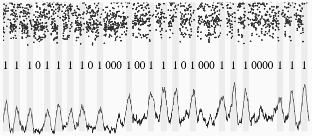


→

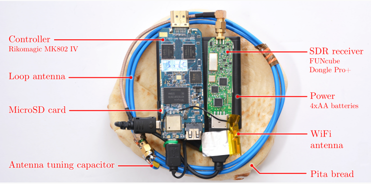
attack



- retrieving secret keys, keystroke timings
- bypassing OS security (ASLR)

Attacker model

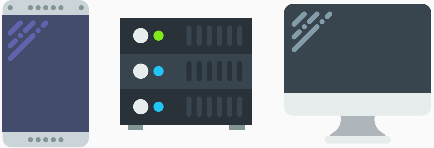
Hardware-based attacks
a.k.a physical attacks



Physical access to hardware
→ embedded devices

vs

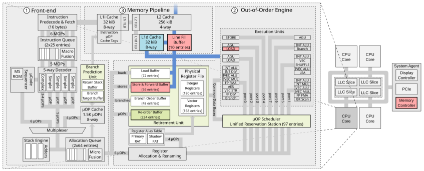
Software-based attacks
a.k.a micro-architectural attacks



Co-located or remote attacker
→ complex systems

Micro-architectural side-channel attacks: Two faces of the same coin

Hardware



&

Implementation

Algorithm 1: Square-and-multiply exponentiation

Input: base b, exponent e, modulus n

Output: $b^e \mod n$

$X \leftarrow 1$

for $i \leftarrow bitlen(e)$ **downto** 0 **do**

  $X \leftarrow \text{multiply}(X, X)$

  if $e_i = 1$ **then**

    $X \leftarrow \text{multiply}(X, b)$

  end

end

return X

We are more or less doomed on the hardware side

Translation look-aside buffer

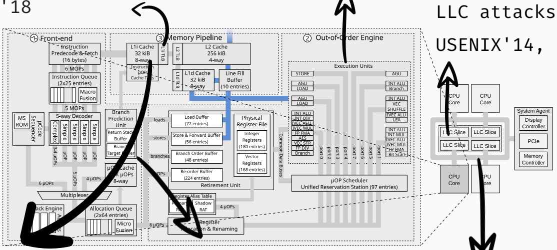
USENIX Sec'18

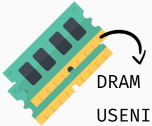
CPU Ports

S&P'19

LLC attacks

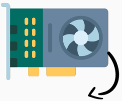
USENIX'14, S&P'15





DRAM

USENIX Sec'16



GPU

S&P'18

L1d, L1i, L2 cache

BSDCon'05, CT-RSA'06, ASIACCS'20

Branch Prediction

CT-RSA'07

Ring Interconnect

USENIX Sec'21, DIMVA'21

State of the art today: each component shared by two processes is a potential micro-architectural side-channel vector

GnuPG 1.4.13 RSA square-and-multiply exponentiation

GnuPG version 1.4.13 (2013)

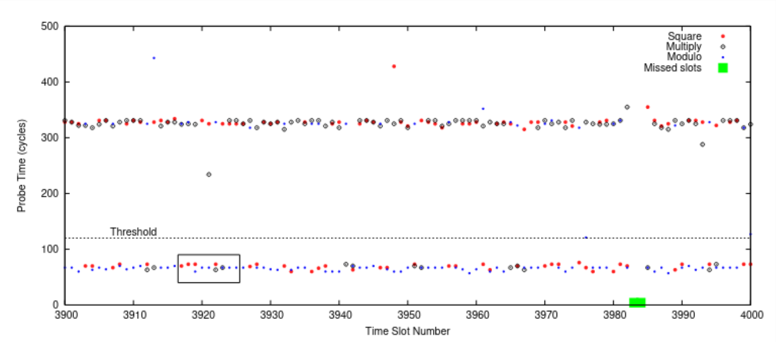
Algorithm 1: GnuPG 1.4.13 Square-and-multiply exponentiation

Input: base c, exponent d, modulus n
Output: $c^d \mod n$

$X \leftarrow 1$
for $i \leftarrow bitlen(d)$ **downto** 0 **do**
  $X \leftarrow \text{square}(X)$
  $X \leftarrow X \text{ mod } n$
  if $d_i = 1$ **then**
    $X \leftarrow \text{multiply}(X, c)$
    $X \leftarrow X \text{ mod } n$
  end
end
return X

Attacking GnuPG 1.4.13 RSA exponentiation

- monitor the square and multiply functions with Flush+Reload to recover the bits of the secret exponent



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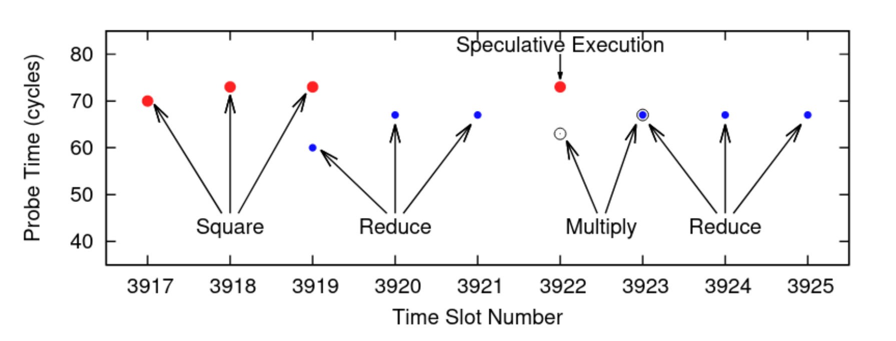

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mbedTLS 2.3.0 RSA square-and-multiply exponentiation

mbedTLS version 2.3.0 (2017), “fixes” the issue with a single operation multiply

Algorithm 2: mbedTLS 2.3.0 Square-and-multiply exponentiation

Input: base c, exponent d, modulus n

Output: $c^d \mod n$

$X \leftarrow 1$

for $i \leftarrow bitlen(d)$ **downto** 0 **do**

    $X \leftarrow \text{multiply}(X, X)$

    $X \leftarrow X \bmod n$

    if $d_i = 1$ **then**

        $X \leftarrow \text{multiply}(X, c)$

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    end

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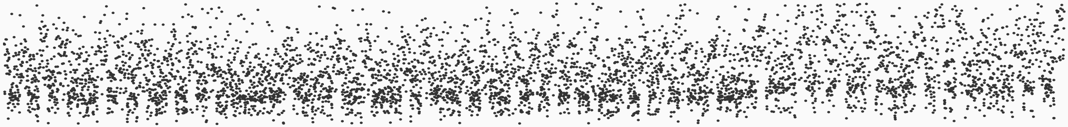
Attacking mbedTLS 2.3.0 RSA exponentiation

- raw Prime+Probe trace on the buffer holding the multiplier c



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Attacking mbedTLS 2.3.0 RSA exponentiation

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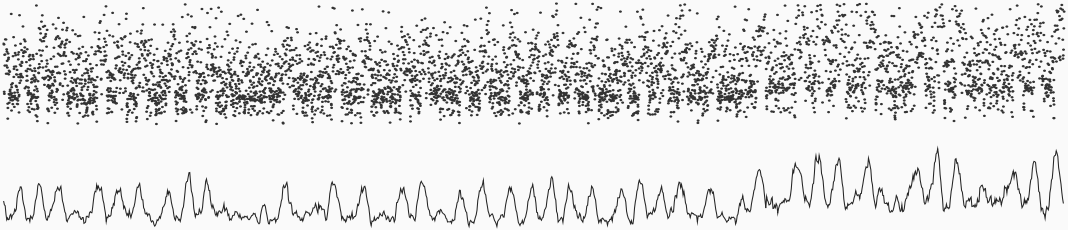
- processed with a simple moving average



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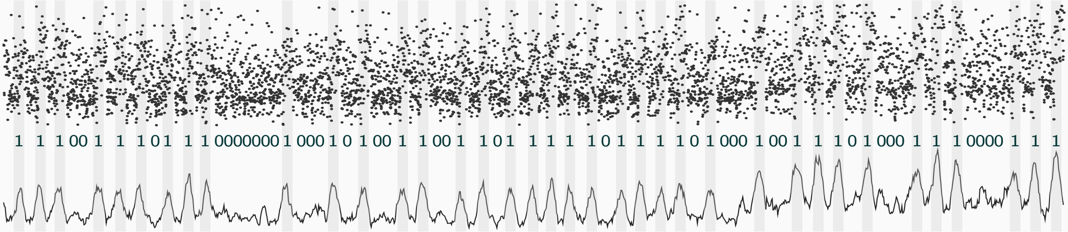
Attacking mbedTLS 2.3.0 RSA exponentiation

- raw Prime+Probe trace on the buffer holding the multiplier c
- processed with a simple moving average
- allows to clearly recover the bits of the secret exponent



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💣 Problem?

Side-channel vulnerability

Any branch or memory access that depends on a secret

Side-channel vulnerabilities and constant-time programming

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That's easy, right?... right?

So many attacks...

LadderLeak: Breaking ECDSA With Less Than One Bit Of Nonce Leakage

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ABSTRACT

Although it is one of the most popular signature schemes today, ECDSA presents a number of implementation pitfalls, in particular due to the very sensitive nature of the random value (known as the *nonce*) generated as part of the signing algorithm. It is known that any small amount of nonce exposure or nonce bias can in principle lead to a full key recovery: the key recovery is then a particular instance of Boneh and Venkatesan's *hidden number problem* (HNP). That observation has been practically exploited in many attacks in the literature, taking advantage of implementation defects or side-channel vulnerabilities in various concrete ECDSA implementations. However, most of the attacks so far have relied on at least 2

ephemeral random value called *nonce*, which is particularly sensitive: it is crucial to make sure that the nonces are kept in secret *and* sampled from the uniform distribution over a certain integer interval. It is easy to see that if the nonce is exposed or reused completely, then an attacker is able to extract the secret signing key by observing only a few signatures. By extending this simple observation, cryptanalysts have discovered stronger attacks that make it possible to recover the secret key even if short bit substrings of the nonces are leaked or biased. These extended attacks relate key recovery to the so-called hidden number problem (HNP) of Boneh and Venkatesan [15], and are part of a line of research initiated by Howgrave-Graham and Smart [36], who described a lattice-based

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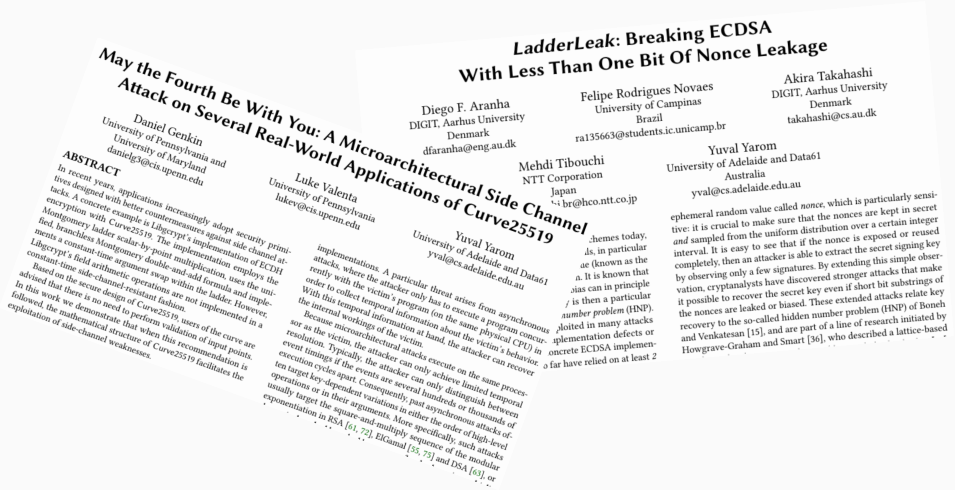

May the Fourth Be With You: A Microarchitectural Side Channel Attack on Several Real-World Applications of Curve25519

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In recent years, applications increasingly adopt security primitives designed with better countermeasures against side channel attacks. A concrete example is Libgcrypt's implementation of ECDH encryption with Curve25519. The implementation employs the Montgomery ladder scalar-by-point multiplication, uses the unified, branchless Montgomery double-and-add formula and implements a constant-time argument swap within the ladder. However, Libgcrypt's field arithmetic operations are not implemented in a constant-time side-channel-resistant fashion.

Based on the secure design of Curve25519, users of the curve are advised that there is no need to perform validation of input points. In this work we demonstrate that when this recommendation is followed, the mathematical structure of Curve25519 facilitates the exploitation of side-channel weaknesses.

implementations. A particular threat arises from asynchronous attacks, where the attacker only has to execute a program concurrently with the victim's program (on the same physical CPU) in order to collect temporal information about the victim's behavior. With this temporal information at hand, the attacker can recover the internal workings of the victim.

Because microarchitectural attacks execute on the same processor as the victim, the attacker can only achieve limited temporal resolution. Typically, the attacker can only distinguish between event timings if the events are several hundreds or thousands of execution cycles apart. Consequently, past asynchronous attacks often target key-dependent variations in either the order of high-level operations or in their arguments. More specifically, such attacks usually target the square-and-multiply sequence of the modular exponentiation in RSA [61, 72], ElGamal [55, 75] and DSA [63], or

LadderLeak: Breaking ECDSA With Less Than One Bit Of Nonce Leakage

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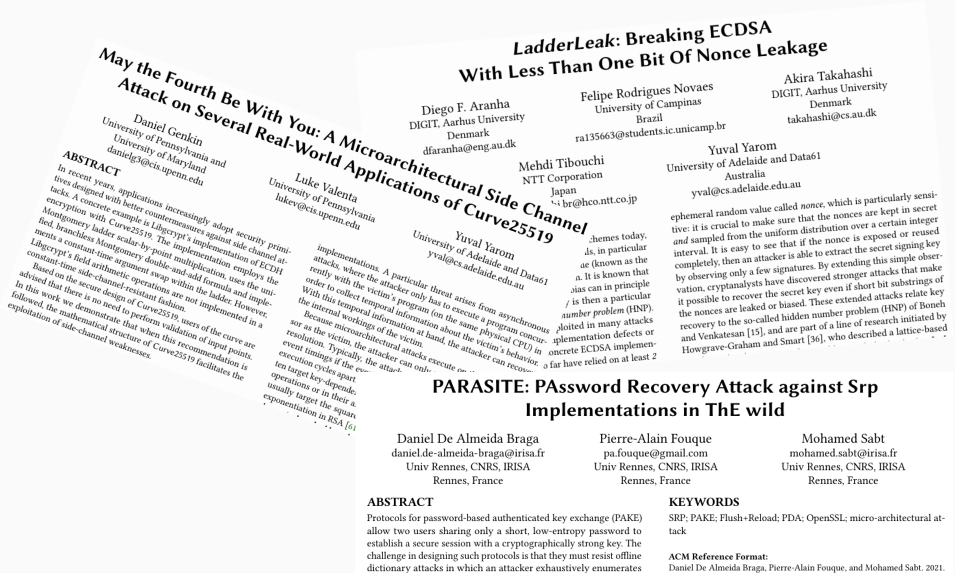

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PARASITE: PAssword Recovery Attack against Srp Implementations in ThE wild

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ABSTRACT

Protocols for password-based authenticated key exchange (PAKE) allow two users sharing only a short, low-entropy password to establish a secure session with a cryptographically strong key. The challenge in designing such protocols is that they must resist offline dictionary attacks in which an attacker exhaustively enumerates

KEYWORDS

SRP; PAKE; Flush+Reload; PDA; OpenSSL; micro-architectural attack

ACM Reference Format:
Daniel De Almeida Braga, Pierre-Alain Fouque, and Mohamed Sabt. 2021.

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Side-Channel Analysis of SM2: A Late-Stage Featurization Case Study

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PARASITE: PAssword Recovery Attack against Srp ...entations in ThE wild

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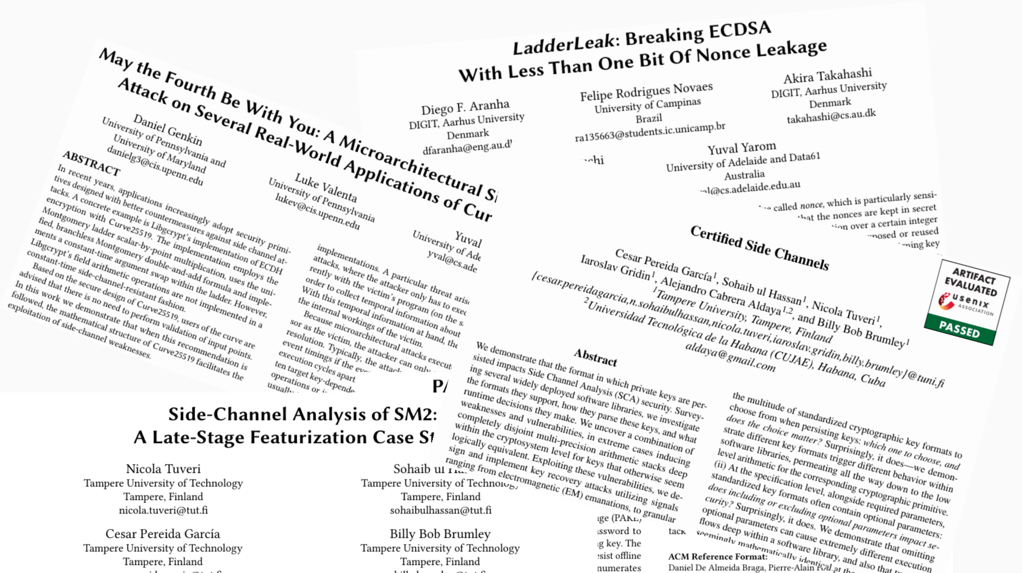

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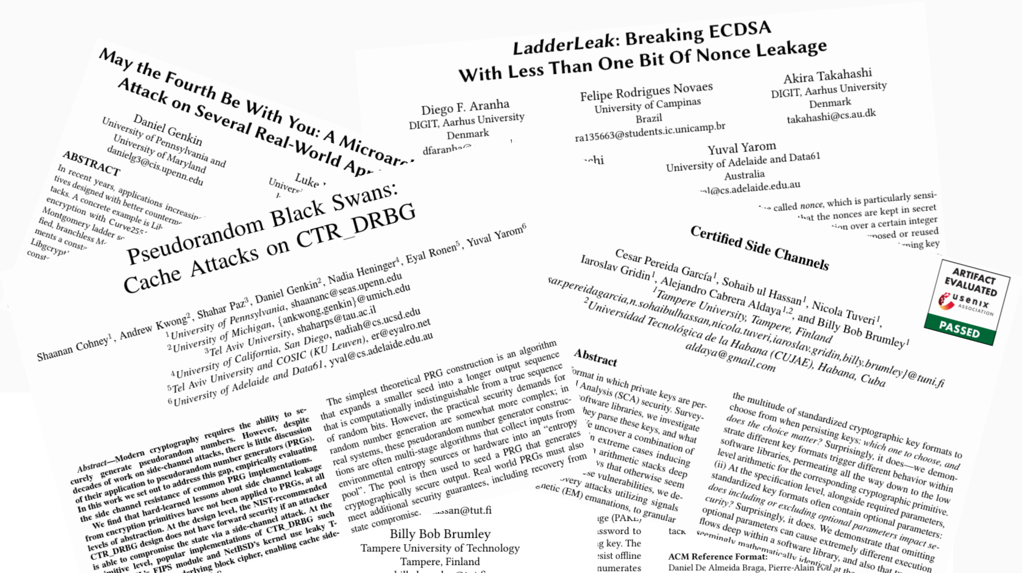

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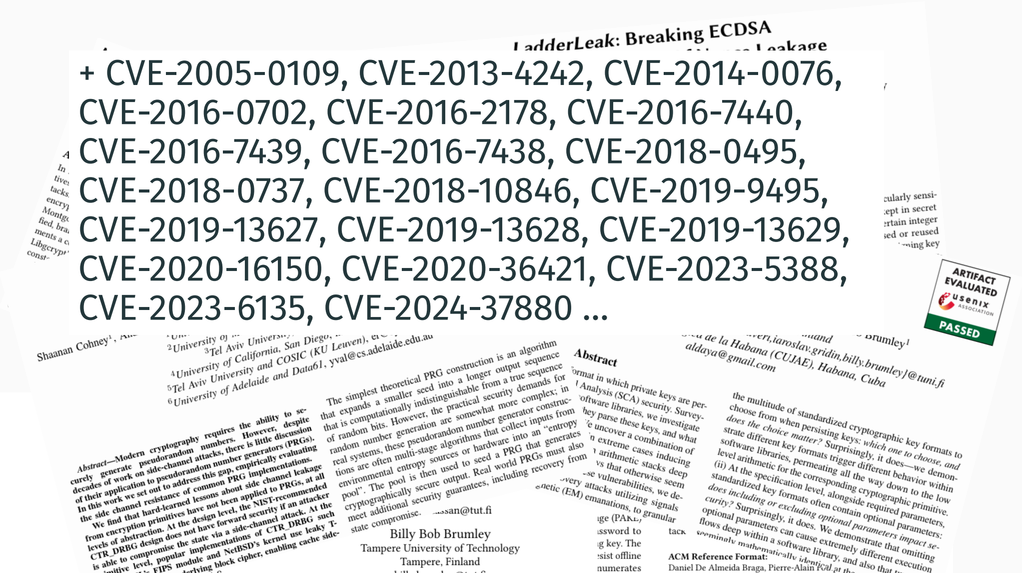

+ CVE-2005-0109, CVE-2013-4242, CVE-2014-0076, CVE-2016-0702, CVE-2016-2178, CVE-2016-7440, CVE-2016-7439, CVE-2016-7438, CVE-2018-0495, CVE-2018-0737, CVE-2018-10846, CVE-2019-9495, CVE-2019-13627, CVE-2019-13628, CVE-2019-13629, CVE-2020-16150, CVE-2020-36421, CVE-2023-5388, CVE-2023-6135, CVE-2024-37880 ...

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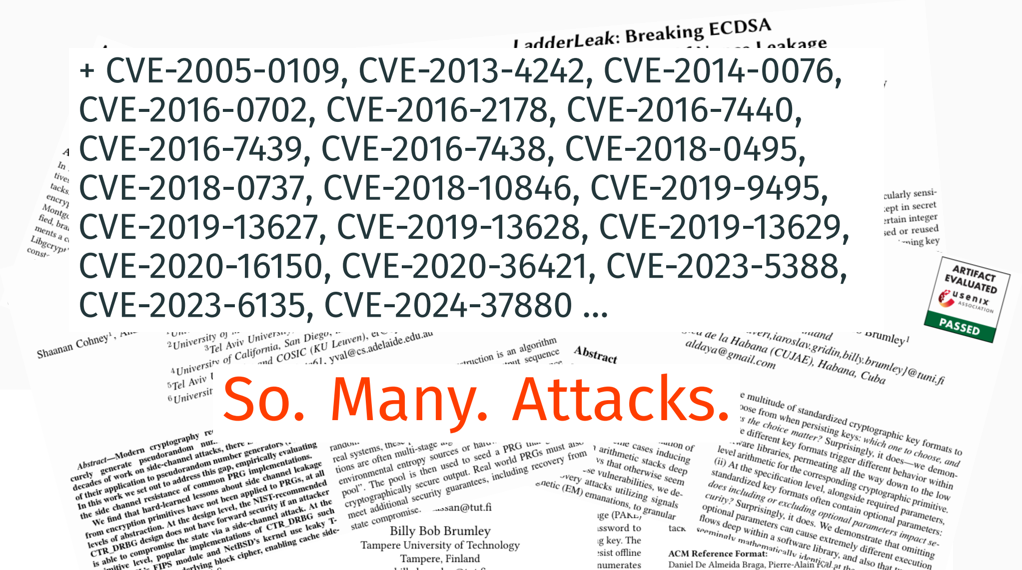
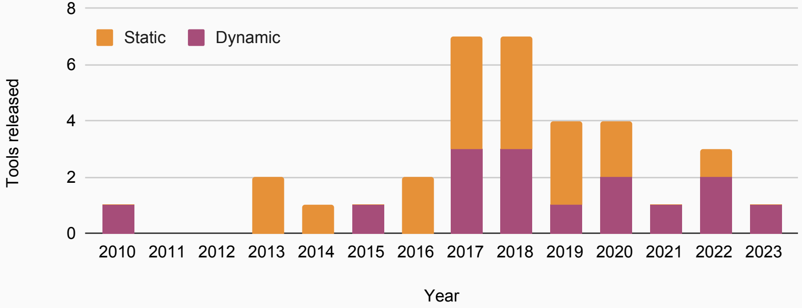


So. Many. Attacks.

So many detection frameworks, yet so many attacks... Why?



Many tools published from 2017, 67% of tools are open source (23 over 34)

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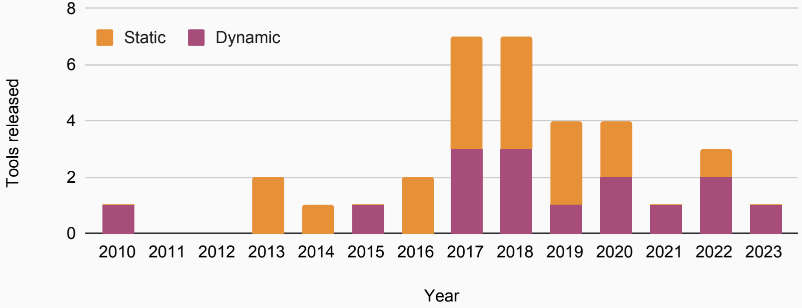

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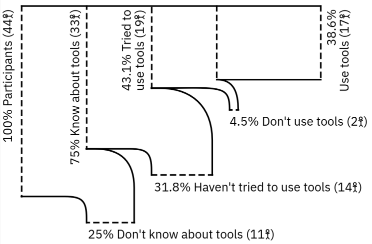
Why are so many attacks still manually found?

Related Work

- do developers use CT tools? [S&P 2022]
  → most developers do not use them, or do not know about them
- how to improve the tool usability? [USENIX Sec 2024]
  → most developers find them really hard to use



J. Jancar et al. ""They're not that hard to mitigate": What Cryptographic Library Developers Think About Timing Attacks". In: *S&P*. 2022.
M. Fourné et al. ""These results must be false": A usability evaluation of constant-time analysis tools". In: *USENIX Security Symposium*. 2024.

Would the tools actually work to automatically find recent vulnerabilities?

Research questions

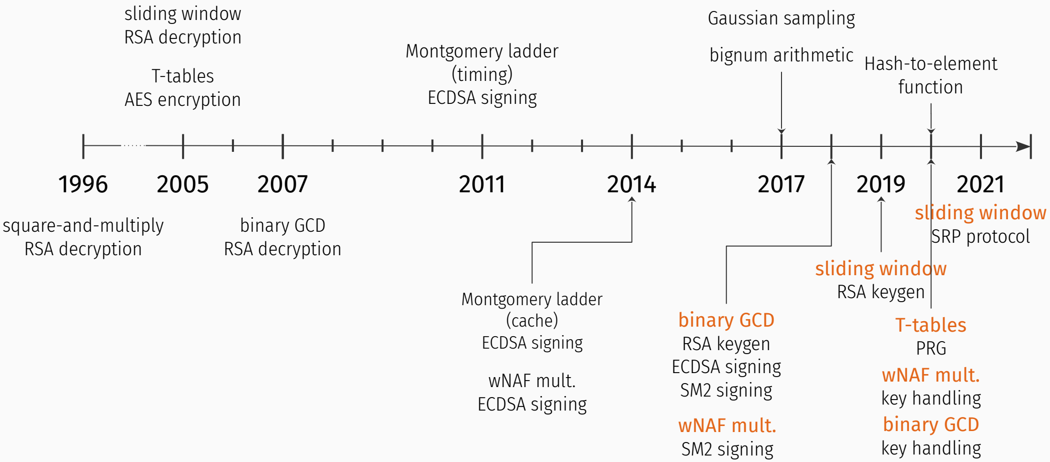
RQ1 How can we compare these tools?

RQ2 Could an existing one have detected these vulnerabilities?

RQ3 What features might be missing from existing tools?

Recent side-channel attacks

Comparing recent vulnerabilities (2017-2022) with past vulnerabilities



The SAME vulnerabilities keep resurfacing. Why? (1/2)

New contexts:

- Key generation [AsiaCCS 2018]
- Key parsing and handling [USENIX Sec 2020, S&P 2019]
- Random number generation [S&P 2020]

(Mostly OpenSSL) Vulnerable code stays in the library
and the CT flag is not correctly set

The SAME vulnerabilities keep resurfacing. Why? (2/2)

New libraries

- MbedTLS sliding window RSA implementation [DIMVA 2017]
- Bleichenbacher-like attacks in MbedTLS, s2n, or NSS [S&P 2019]

Vulnerability is found in OpenSSL but
patches are not propagated to other libraries

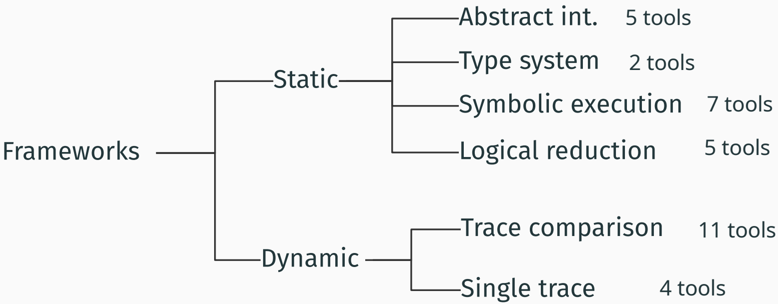
Most vulnerabilities stem from code
already known to be vulnerable

Side-channel vulnerability detection tools

Side-channel vulnerability detection tools (1/2)

Ref	Year	**Tool**	Type	Methods	Scal.	Policy	Sound	Input	L	W	E	B	Available
[85]	2010	ct-grind	Dynamic	Tainting	●	**CT**	◐	**Binary**	✓				✓
[15]	2013	Almeida et al.	Static	Deductive verification	○	**CT**	●	C source					
[55]	2013	CacheAudit	Static	Abstract interpretation	○	CO	◐	**Binary**			✓		✓
[22]	2014	VirtualCert	Static	Type system	○	**CT**	●	C source			✓		✓
[70]	2015	Cache Templates	Dynamic	Statistical tests	○	CO	○	**Binary**	✓				✓
[13]	2016	ct-verif	Static	Logical verification	◐	**CT**	●	LLVM					✓
[107]	2016	FlowTracker	Static	Type system	◐	**CT**	●	LLVM	✓				✓
[56]	2017	CacheAudit2	Static	Abstract interpretation	○	**CT**	●	**Binary**			✓		
[28]	2017	Blazy et al.	Static	Abstract interpretation	◐	**CT**	●	C source					
[17]	2017	Blazer	Static	Decomposition	◐	CR	●	Java		✓			
[48]	2017	Themis	Static	Logical verification	◐	CR	●	Java	✓	✓			
[127]	2017	CacheD	Dynamic	DSE	◐	CO	○	**Binary**	✓	✓			
[136]	2017	STACCO	Dynamic	Trace diff	◐	CR	○	**Binary**	✓				✓
[106]	2017	dudect	Dynamic	Statistical tests	◐	CC	○	**Binary**					✓
[117]	2018	CANAL	Static	SE	○	CO	◐	LLVM		✓			✓
[47]	2018	CacheFix	Static	SE	◐	CO	◐	C	✓	✓			✓
[34]	2018	CoCo-Channel	Static	SE, tainting	●	CR	◐	Java		✓			
[19]	2018	SideTrail	Static	Logical verification	○	CR	●	LLVM	✓	✓	✓		✓
[114]	2018	Shin et al.	Dynamic	Statistical tests	◐	CO	○	**Binary**	✓				
[132]	2018	DATA	Dynamic	Statistical tests	◐	**CT**	○	**Binary**	✓			✓	✓
[133]	2018	MicroWalk	Dynamic	MIA	●	**CT**	○	**Binary**	✓		✓		✓
[110]	2019	STAnalyzer	Static	Abstract interpretation	●	**CT**	●	C	✓				✓
[95]	2019	DifFuzz	Dynamic	Fuzzing	◐	CR	○	Java		✓			✓
[126]	2019	CacheS	Static	Abstract interpretation, SE	●	**CT**	○	**Binary**	✓	✓			
[35]	2019	CaSym	Static	SE	◐	CO	●	LLVM	✓	✓			
[54]	2020	Pitchfork	Static	SE, tainting	●	**CT**	◐	LLVM	✓	✓			✓
[66]	2020	ABSynthe	Dynamic	Genetic algorithm, RNN	◐	CR	○	C source	✓				✓
[72]	2020	ct-fuzz	Dynamic	Fuzzing	◐	**CT**	○	**Binary**	✓	✓			✓
[51]	2020	Binsec/Rel	Static	SE	●	**CT**	◐	**Binary**	✓	✓			✓
[20]	2021	Abacus	Dynamic	DSE	●	**CT**	◐	**Binary**	✓		✓		✓
[74]	2022	CaType	Dynamic	Type system	◐	CO	●	**Binary**	✓			✓	
[134]	2022	MicroWalk-CI	Dynamic	MIA	●	**CT**	○	**Binary**, JS	✓		✓		✓
[140]	2022	ENCIDER	Static	SE	●	**CT**	◐	LLVM	✓	✓			✓
[141]	2023	CacheQL	Dynamic	MIA, NN	●	**CT**	○	**Binary**	✓		✓	✓	✓†

Side-channel vulnerability detection tools (2/2)



Side-note: Why you want to detect vulnerabilities at the binary level (1/4)

- the compiler is not your friend, it just wants to make stuff fast
- recent example: Kyber implementation, CVE-2024-37880, June 03, 2024

https://pqshield.com/pqshield-plugs-timing-leaks-in-kyber-ml-kem-to-improve-pqc-implementation-maturity/

Side-note: Why you want to detect vulnerabilities at the binary level (2/4)

Expanding a string into an array of integer, the wrong way

```
void expand_insecure(int16_t r[256], uint8_t *msg){
    for(i=0;i<16;i++) {                 // outer loop: every byte of msg
        for(j=0;j<8;j++) {              // inner loop: every bit in byte
            if ((msg[i] >> j) & 0x1)    // branch on j-th msg bit
                r[8*i+j] = CONSTANT;
            else
                r[8*i+j] = 0;
        }
    }
}
```

https://pqshield.com/pqshield-plugs-timing-leaks-in-kyber-ml-kem-to-improve-pqc-implementation-maturity/

Side-note: Why you want to detect vulnerabilities at the binary level (3/4)

Expanding a string into an array of integer, the right way

```
void expand_secure(int16_t r[256], uint8_t *msg){
    for(i=0;i<16;i++) {
        for(j=0;j<8;j++) {
            mask = -(int16_t)((msg[i] >> j) & 0x1);
            r[8*i+j] = mask & CONSTANT;                 // no branch
        }
    }
}
```

https://pqshield.com/pqshield-plugs-timing-leaks-in-kyber-ml-kem-to-improve-pqc-implementation-maturity/

Side-note: Why you want to detect vulnerabilities at the binary level (4/4)

Now, what does the compiler do with your code?

```
expand_insecure:    // x86 assembly
        xor     eax, eax
.outer:
        xor     ecx, ecx
.inner:
        movzx   r8d, byte ptr [rsi + rax]
        xor     edx, edx
        bt      r8d, ecx    // LSB test on (m[i] >> j)
        jae     .skip       // unsafe branch
        mov     edx, 1665   // load of CONSTANT (may be skipped)
.skip:
        mov     word ptr [rdi + 2*rcx], dx
        inc     rcx
        cmp     rcx, 8
        jne     .inner      // safe branch: inner loop
        inc     rax
        add     rdi, 16
        cmp     rax, 32
        jne     .outer      // safe branch: outer loop
        ret
```

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        [...]
.inner:
        movzx   r8d, byte ptr [rsi + rax]
        xor     edx, edx
        bt      r8d, ecx
        jae     .skip       // still here :(
        mov     edx, 1665
.skip:
        [...]
        ret
```

https://pqshield.com/pqshield-plugs-timing-leaks-in-kyber-ml-kem-to-improve-pqc-implementation-maturity/

Side-note: Why you want to detect vulnerabilities at the binary level (4/4)

Now, what does the compiler do with your code? Yes, it ✨ optimizes it ✨

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expand_insecure:    // x86 assembly
        xor     eax, eax
.outer:
        xor     ecx, ecx
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        inc     rcx
        cmp     rcx, 8
        jne     .inner      // safe branch: inner loop
        inc     rax
        add     rdi, 16
        cmp     rax, 32
        jne     .outer      // safe branch: outer loop
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Benchmarks

Benchmark: cryptographic operations

Unified benchmark representative of cryptographic operations:

- 5 tools: Binsec/Rel, Abacus, ctgrind, dudect, Microwalk-CI
- 25 benchmarks from 3 libraries (OpenSSL, MbedTLS, BearSSL)
- cryptographic primitives: symmetric, AEAD schemes, asymmetric

---

L. Daniel, S. Bardin, and T. Rezk. "Binsec/Rel: Efficient Relational Symbolic Execution for Constant-Time at Binary-Level". In: *S&P*. 2020.

Q. Bao et al. "Abacus: Precise Side-Channel Analysis". In: *ICSE*. 2021.

https://github.com/agl/ctgrind

O. Reparaz, J. Balasch, and I. Verbauwhede. "Dude, is my code constant time?" In: *DATE*. 2017.

J. Wichelmann et al. "Microwalk-CI: Practical Side-Channel Analysis for JavaScript Applications". In: *CCS*. 2022.

Benchmark results: cryptographic operations (selection)

	Binsec/Rel2	Abacus	ctgrind	Microwalk
	#V	#V	#V	#V
AES-CBC-bearssl (T)	36	36	36	36
AES-CBC-bearssl (BS)	0	0	0	0
AES-GCM-openssl (EVP)	0	0	70	8
RSA-bearssl (OAEP)	2 (⌛)	💣	87	0
RSA-openssl (PKCS)	1 (⌛)	0	321	46
RSA-openssl (OAEP)	1 (⌛)	💣	546	61

- timeout limit (⌛): 1 hour
- tools generally agree on symmetric crypto, but disagree on asymmetric crypto
- takeaway: support for vector instructions is essential

Benchmark: recent vulnerabilities

Replication of published vulnerabilities:

- 7 vulnerable functions from 3 publications
- both the function itself and its context are targeted
- total: 11 additional benchmarks

Benchmark results: recent vulnerabilities (selection)

	Binsec/Rel2		Abacus		ctgrind		Microwalk	
	V	T(s)	V	T(s)	V	T(s)	V	T(s)
RSA valid. (MbedTLS)		⌛		490.01	✓	0.40	✓	278.94
GCD		⌛		37.74		0.21	✓	22.96
modular inversion		⌛		242.10	✓	0.24	✓	141.82
RSA keygen (OpenSSL)		0.17	💣	8.66		6.36	✓	842.02
GCD	✓	⌛		⌛	✓	0.19	✓	3.61
modular inversion		⌛		⌛	✓	0.21	✓	5.96

- some vulnerabilities are missed because of implicit flows
- most tools do not support tainting internal secrets

Recommendations

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#2 Support for indirect flows

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#2 Support for indirect flows

#3 Support for internally generated secrets (e.g. key generation)

#4 Promote usage of a standardized benchmark

#5 Improve usability for static tools (e.g. core-dump initialization)

#6 Make libraries more static analysis friendly

Perspectives & Conclusion

tl;dr

Side-channel free software, are we there yet?

Nope!

Beyond constant time

Other microarchitectural vulnerabilities:

- transient execution, e.g., Spectre, LVI
- data memory-dependent prefetchers, e.g., GoFetch
- dynamic voltage and frequency scaling (DVFS), e.g., Hertzbleed

$\rightarrow$ code that is ”constant-time” (and considered secure until recently) can be vulnerable too!

Conclusion

- first paper by Kocher in 1996: 25 years of research in this area
- so many detection tools, yet, so many vulnerabilities (manually) found
- most vulnerabilities stem from code already known to be vulnerable
- we introduced a benchmark for fair tool comparison
- we identified limitations in the current literature and issued recommendations for the community

https://github.com/ageimer/sok-detection/

More details in our CCS 2023 paper!

A Systematic Evaluation of Automated Tools for Side-Channel Vulnerabilities Detection in Cryptographic Libraries

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Abstract

To protect cryptographic implementations from side-channel vulnerabilities, developers must adopt constant-time programming practices. As these can be error-prone, many side-channel detection tools have been proposed. Despite this, such vulnerabilities are still manually found in cryptographic libraries. While a recent paper by Jancar et al. shows that developers rarely perform side-channel detection, it is unclear if existing detection tools could have found these vulnerabilities in the first place.

To answer this question we surveyed the literature to build a classification of 34 side-channel detection frameworks. The classification we offer compares multiple criteria, including the methods used, the scalability of the analysis or the threat model considered.

1 Introduction

Implementing cryptographic algorithms is an arduous task. Beyond functional correctness, the developers must also ensure that their code does not leak potentially secret information through side channels. Since Paul Kocher's seminal work [82], the research community has combed through software and hardware to find vectors allowing for side-channel attacks, from execution time to electromagnetic emissions. The unifying principle behind this class of attacks is that they do not exploit the algorithm *specification* but rather *physical characteristics* of its execution. Among the aforementioned attack vectors, the processor microarchitecture is of particular interest, as it is a shared resource between multiple programs. By observing the target execution through microarchitec-

Thank you!

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Side-channel-free software, are we there yet?

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