From Theory to Practice: Detecting and Preserving Constant-Time

A story of constant time, struggles, and betrayals

Clémentine Maurice, CNRS, CRIStAL

November 19, 2025 — C&ESAR Keynote

Attacks on micro-architecture

- hardware usually modeled as an abstract layer behaving correctly

Attacks on micro-architecture

- hardware usually modeled as an abstract layer behaving correctly, but possible attacks

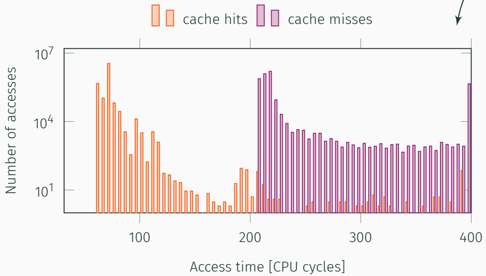
Attacks on micro-architecture

- hardware usually modeled as an abstract layer behaving correctly, but possible attacks
  - faults: bypassing software protections by causing hardware errors
  - side channels: observing side effects of hardware on computations

Attacks on micro-architecture

- hardware usually modeled as an abstract layer behaving correctly, but possible attacks
    - faults: bypassing software protections by causing hardware errors
    - side channels: observing side effects of hardware on computations

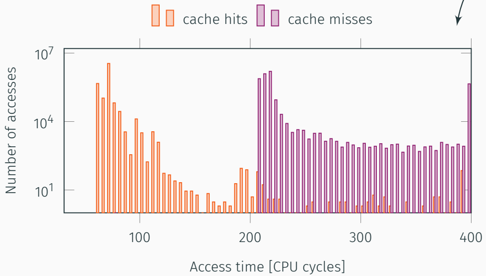
identification



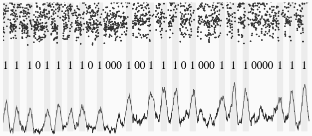
Attacks on micro-architecture

- hardware usually modeled as an abstract layer behaving correctly, but possible attacks
  - faults: bypassing software protections by causing hardware errors
  - side channels: observing side effects of hardware on computations

identification



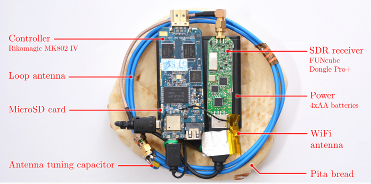
attack



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

Attacker model

Hardware-based attacks
a.k.a physical attacks

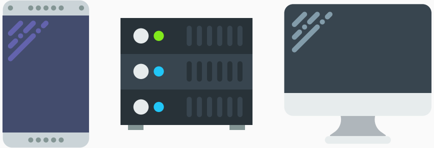


Physical access to hardware

→ embedded devices

VS

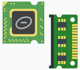
Software-based attacks
a.k.a micro-architectural attacks

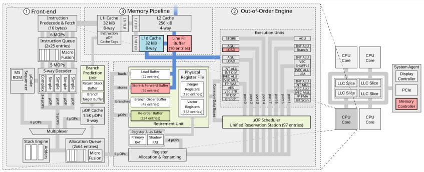


Co-located or remote attacker

→ 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 $i \leftarrow \mathit{bitlen}(e)$ **downto** 0 **do**
  $X \leftarrow \text{multiply}(X, X)$
  if $e_i = 1$ **then**
    $X \leftarrow \text{multiply}(X, b)$
  end
end
return X

Outline

- **Part 1** Small example: Flush+Reload on GnuPG v 1.4.13
- **Part 2** Constant-time: The Struggle
- **Part 3** Constant-time: The Betrayal

Part 1 Small example: Flush+Reload on GnuPG v 1.4.13

GnuPG 1.4.13 RSA square-and-multiply exponentiation

GnuPG version 1.4.13 (2013)

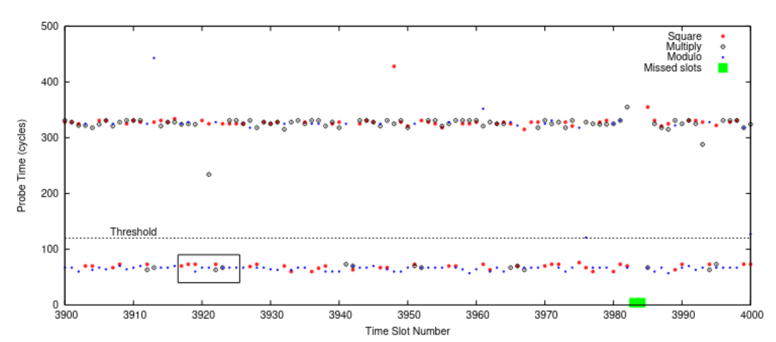
Algorithm 1: GnuPG 1.4.13 Square-and-multiply exponentiation

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

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

Attacking GnuPG 1.4.13 RSA exponentiation

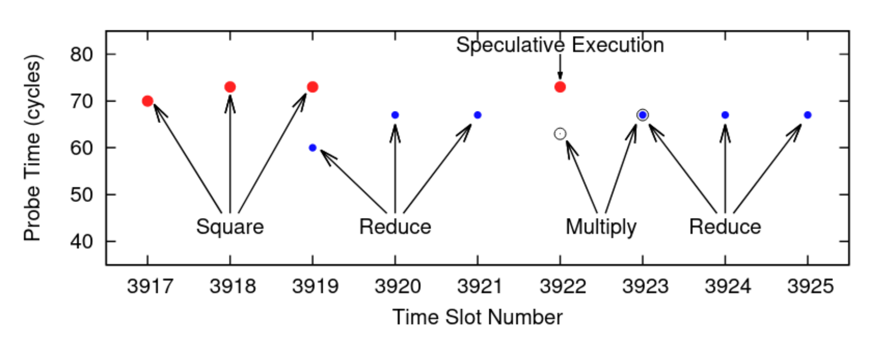
- monitor the square and multiply functions with Flush+Reload to recover the bits of the secret exponent



Y. Yarom and K. Falkner. “Flush+Reload: a High Resolution, Low Noise, L3 Cache Side-Channel Attack”. In: *USENIX Security Symposium*. 2014.

Attacking GnuPG 1.4.13 RSA exponentiation

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



Y. Yarom and K. Falkner. “Flush+Reload: a High Resolution, Low Noise, L3 Cache Side-Channel Attack”. In: *USENIX Security Symposium*. 2014.

Summary of the attack

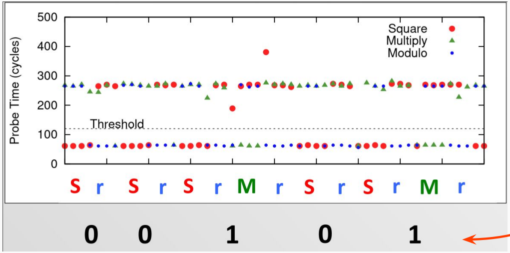
Algorithm 1: GnuPG 1.4.13 Square-and-multiply exponentiation

Input: base c, exponent d, modulus n

Output: $c^d \mod n$

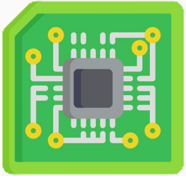
$X \leftarrow 1$
for $i \leftarrow bitlen(d)$ **downto** 0 **do**
  $X \leftarrow \text{square}(X)$
  $X \leftarrow X \bmod n$
  if $d_i = 1$ **then**
    $X \leftarrow \text{multiply}(X, c)$
    $X \leftarrow X \bmod n$
  end
end
return X

secret value!

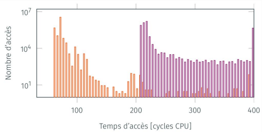


What just happened?

cache attack



exploits timing differences
of memory accesses



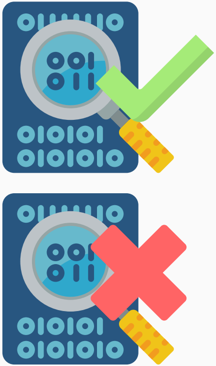
attacker monitors
lines accessed by the
victim, not the content

Part 2 Constant-time: The Struggle

Research Question: Which software implementation is vulnerable?

State of the art (more or less)

1. spend too much time reading OpenSSL code
2. find vulnerability
3. exploit it manually using known side channel
   $\rightarrow$ e.g. CPU cache
4. publish
5. goto step 1



💣 Problem?

Side-channel vulnerability

Any branch or memory access that depends on a secret

Side-channel vulnerabilities and constant-time programming

Problem?

Side-channel vulnerability

Any branch or memory access that depends on a secret

→

Solution!

Constant-time programming

No branch or memory access depends on a secret!

Side-channel vulnerabilities and constant-time programming

Problem?

Side-channel vulnerability

Any branch or memory access that depends on a secret

→

Solution!

Constant-time programming

No branch or memory access depends on a secret!

That's easy, right?

Side-channel vulnerabilities and constant-time programming

Problem?

Side-channel vulnerability

Any branch or memory access that depends on a secret

→

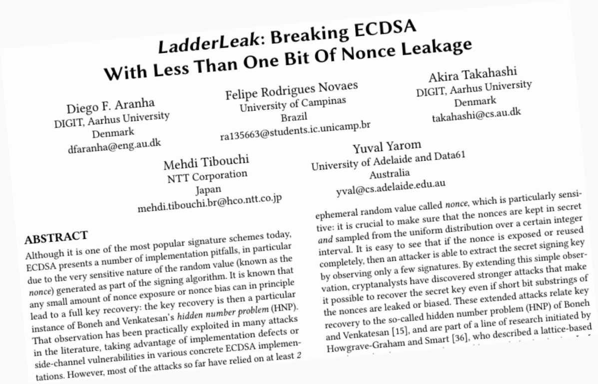
Solution!

Constant-time programming

No branch or memory access depends on a secret!

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

So many attacks...



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

Diego F. Aranha
DIGIT, Aarhus University
Denmark
dfaranha@eng.au.dk

Felipe Rodrigues Novaes
University of Campinas
Brazil
ra135663@students.ic.unicamp.br

Akira Takahashi
DIGIT, Aarhus University
Denmark
takahashi@cs.au.dk

Mehdi Tibouchi
NTT Corporation
Japan
mehdi.tibouchi.br@hco.ntt.co.jp

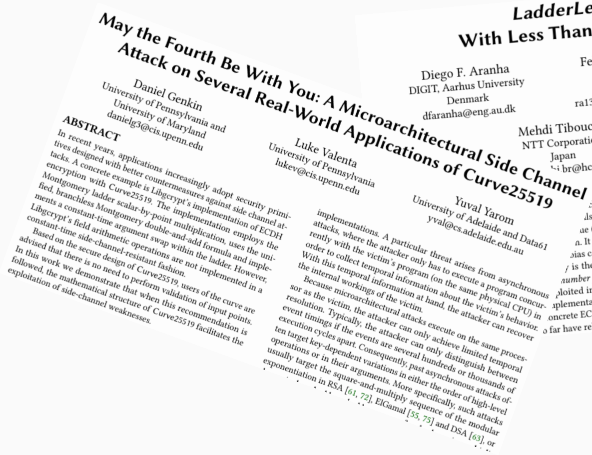
Yuval Yarom
University of Adelaide and Data61
Australia
yval@cs.adelaide.edu.au

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

So many attacks...



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

Daniel Genkin
University of Pennsylvania and
University of Maryland
danielg3@cis.upenn.edu

Luke Valenta
University of Pennsylvania
lukev@cis.upenn.edu

Yuval Yarom
University of Adelaide and Data61
yval@cs.adelaide.edu.au

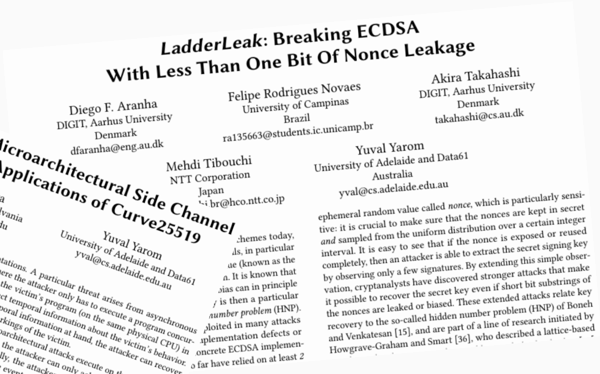
ABSTRACT

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

Diego F. Aranha
DIGIT, Aarhus University
Denmark
dfaranha@eng.au.dk

Felipe Rodrigues Novaes
University of Campinas
Brazil
ra135663@students.ic.unicamp.br

Akira Takahashi
DIGIT, Aarhus University
Denmark
takahashi@cs.au.dk

Mehdi Tibouchi
NTT Corporation
Japan
br@hco.ntt.co.jp

Yuval Yarom
University of Adelaide and Data61
Australia
yval@cs.adelaide.edu.au

chemes today, ls, in particular ue (known as the n. It is known that bias can in principle is then a particular number problem (HNP). ploited in many attacks plementation defects or oncrete ECDSA implemen- o 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

So many attacks...

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

Daniel Genkin
University of Pennsylvania and University of Maryland
danielg3@cis.upenn.edu

Luke Valenta
University of Pennsylvania
lukev@cis.upenn.edu

Yuval Yarom
University of Adelaide and Data61
yval@cs.adelaide.edu.au

ABSTRACT

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.

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

Diego F. Aranha
DIGIT, Aarhus University
Denmark
dfaranha@eng.au.dk

Felipe Rodrigues Novaes
University of Campinas
Brazil
ra135663@students.ic.unicamp.br

Akira Takahashi
DIGIT, Aarhus University
Denmark
takahashi@cs.au.dk

Mehdi Tibouchi
NTT Corporation
Japan
...br@hco.ntt.co.jp

Yuval Yarom
University of Adelaide and Data61
Australia
yval@cs.adelaide.edu.au

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

PARASITE: PAssword Recovery Attack against Srp Implementations in ThE wild

Daniel De Almeida Braga
daniel.de-almeida-braga@irisa.fr
Univ Rennes, CNRS, IRISA
Rennes, France

Pierre-Alain Fouque
pa.fouque@gmail.com
Univ Rennes, CNRS, IRISA
Rennes, France

Mohamed Sabt
mohamed.sabt@irisa.fr
Univ Rennes, CNRS, IRISA
Rennes, France

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

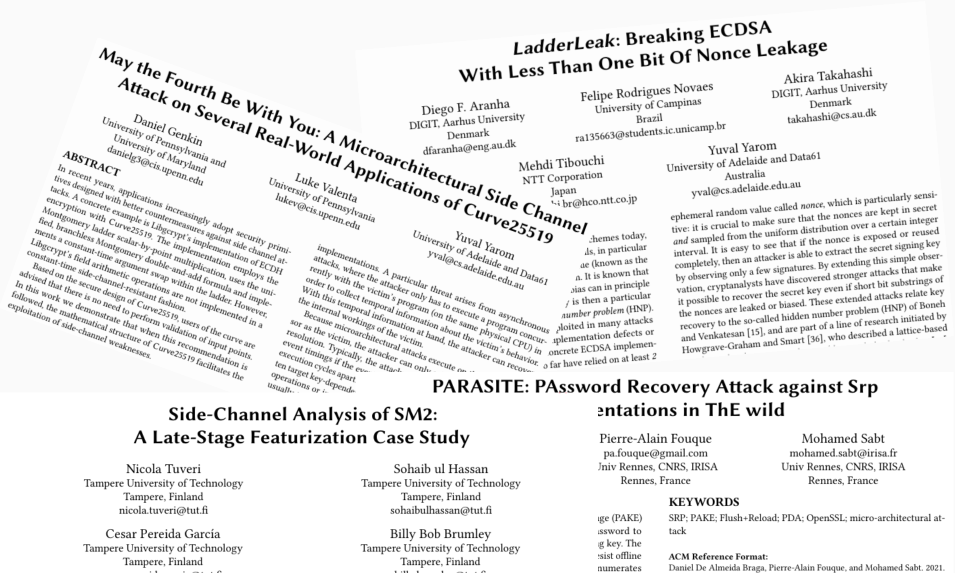
KEYWORDS

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

ACM Reference Format:

Daniel De Almeida Braga, Pierre-Alain Fouque, and Mohamed Sabt. 2021.

So many attacks...


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

Daniel Genkin
University of Pennsylvania and University of Maryland
danielg3@cis.upenn.edu

Luke Valenta
University of Pennsylvania
lukev@cis.upenn.edu

Yuval Yarom
University of Adelaide and Data61
yval@cs.adelaide.edu.au

ABSTRACT

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.

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

Diego F. Aranha
DIGIT, Aarhus University
Denmark
dfaranha@eng.au.dk

Felipe Rodrigues Novaes
University of Campinas
Brazil
ra135663@students.ic.unicamp.br

Akira Takahashi
DIGIT, Aarhus University
Denmark
takahashi@cs.au.dk

Mehdi Tibouchi
NTT Corporation
Japan

Yuval Yarom
University of Adelaide and Data61
Australia
yval@cs.adelaide.edu.au

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

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

Pierre-Alain Fouque
pa.fouque@gmail.com
Univ Rennes, CNRS, IRISA
Rennes, France

Mohamed Sabt
mohamed.sabt@irisa.fr
Univ Rennes, CNRS, IRISA
Rennes, France

KEYWORDS

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

ACM Reference Format:

Daniel De Almeida Braga, Pierre-Alain Fouque, and Mohamed Sabt. 2021.

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

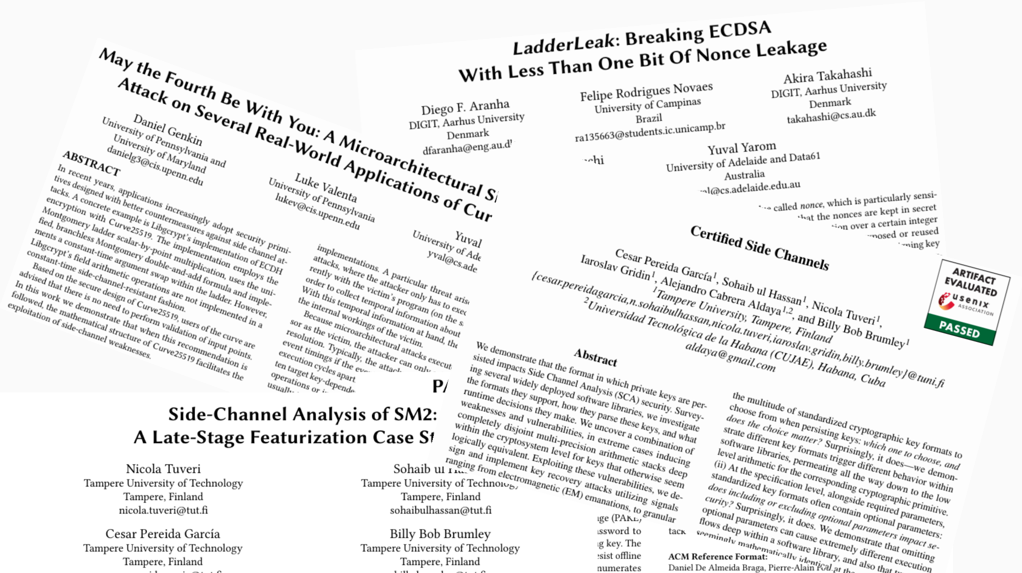
Nicola Tuveri
Tampere University of Technology
Tampere, Finland
nicola.tuveri@tut.fi

Sohaib ul Hassan
Tampere University of Technology
Tampere, Finland
sohaibulhassan@tut.fi

Cesar Pereida García
Tampere University of Technology
Tampere, Finland

Billy Bob Brumley
Tampere University of Technology
Tampere, Finland

So many attacks...


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

Diego F. Aranha
DIGIT, Aarhus University
Denmark
dfaranha@eng.au.d

Felipe Rodrigues Novaes
University of Campinas
Brazil
ra135663@students.ic.unicamp.br

Akira Takahashi
DIGIT, Aarhus University
Denmark
takahashi@cs.au.dk

Yuval Yarom
University of Adelaide and Data61
Australia
l@cs.adelaide.edu.au

May the Fourth Be With You: A Microarchitectural S
Attack on Several Real-World Applications of Cur

Daniel Genkin
University of Pennsylvania and
University of Maryland
danielg3@cis.upenn.edu

Luke Valenta
University of Pennsylvania
lukev@cis.upenn.edu

Yuval
University of Ade
yval@cs.ade

ABSTRACT

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.

Certified Side Channels

Cesar Pereida García[1], Sohaib ul Hassan[1], Nicola Tuveri[1], Iaroslav Gridin[1], Alejandro Cabrera Aldaya[1,2], and Billy Bob Brumley[1]
[1]Tampere University, Tampere, Finland
[2]Universidad Tecnológica de la Habana (CUJAE), Habana, Cuba
{cesar.pereidagarcia,n.sohaibulhassan,nicola.tuveri,iaroslav.gridin,billy.brumley}@tuni.fi
aldaya@gmail.com

ARTIFACT EVALUATED
usenix ASSOCIATION
PASSED

Abstract

We demonstrate that the format in which private keys are persisted impacts Side Channel Analysis (SCA) security. Surveying several widely deployed software libraries, we investigate the formats they support, how they parse these keys, and what runtime decisions they make. We uncover a combination of weaknesses and vulnerabilities, in extreme cases inducing completely disjoint multi-precision arithmetic stacks deep within the cryptosystem level for keys that otherwise seem logically equivalent. Exploiting these vulnerabilities, we design and implement key recovery attacks utilizing signals ranging from electromagnetic (EM) emanations, to granular

the multitude of standardized cryptographic key formats to choose from when persisting keys: which one to choose, and does the choice matter? Surprisingly, it does—we demonstrate different key formats trigger different behavior within software libraries, permeating all the way down to the low level arithmetic for the corresponding cryptographic primitive. (ii) At the specification level, alongside required parameters, standardized key formats often contain optional parameters: does including or excluding optional parameters impact security? Surprisingly, it does. We demonstrate that omitting optional parameters can cause extremely different execution flows deep within a software library, and also that

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

Nicola Tuveri
Tampere University of Technology
Tampere, Finland
nicola.tuveri@tut.fi

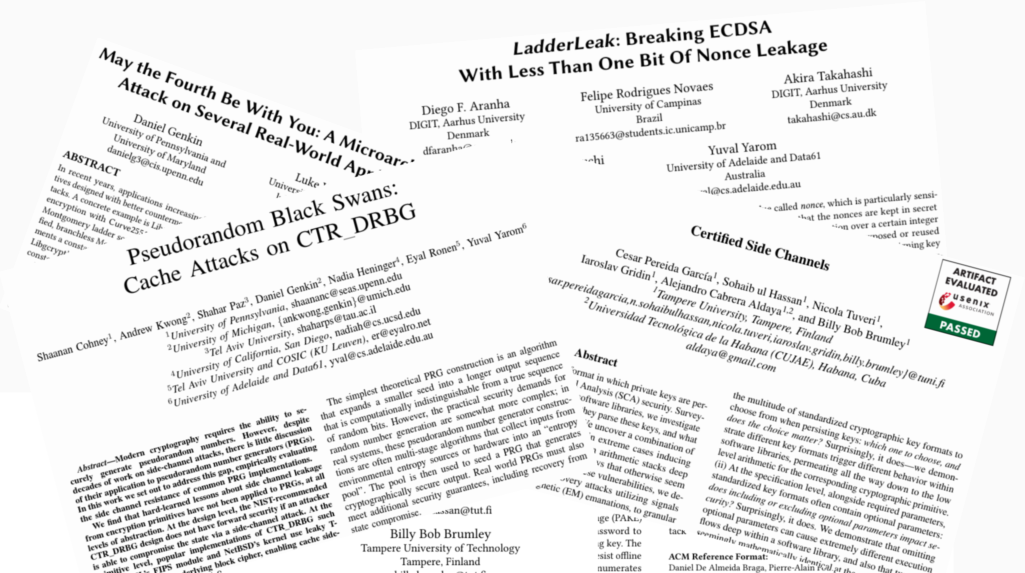
Sohaib ul Ha
Tampere University of Technology
Tampere, Finland
sohaibulhassan@tut.fi

Cesar Pereida García
Tampere University of Technology
Tampere, Finland

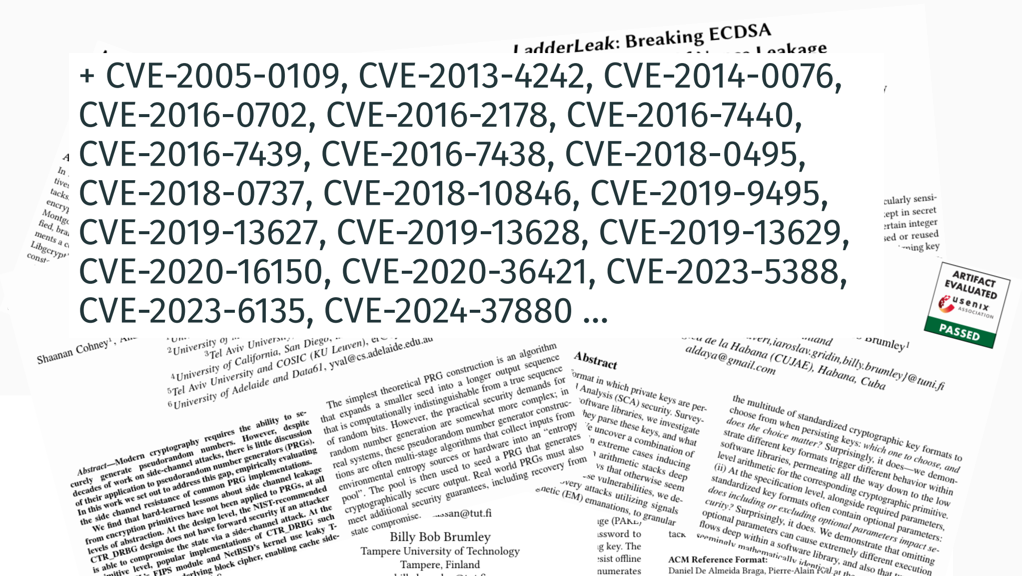
Billy Bob Brumley
Tampere University of Technology
Tampere, Finland

ACM Reference Format:
Daniel De Almeida Braga, Pierre-Alain

So many attacks...

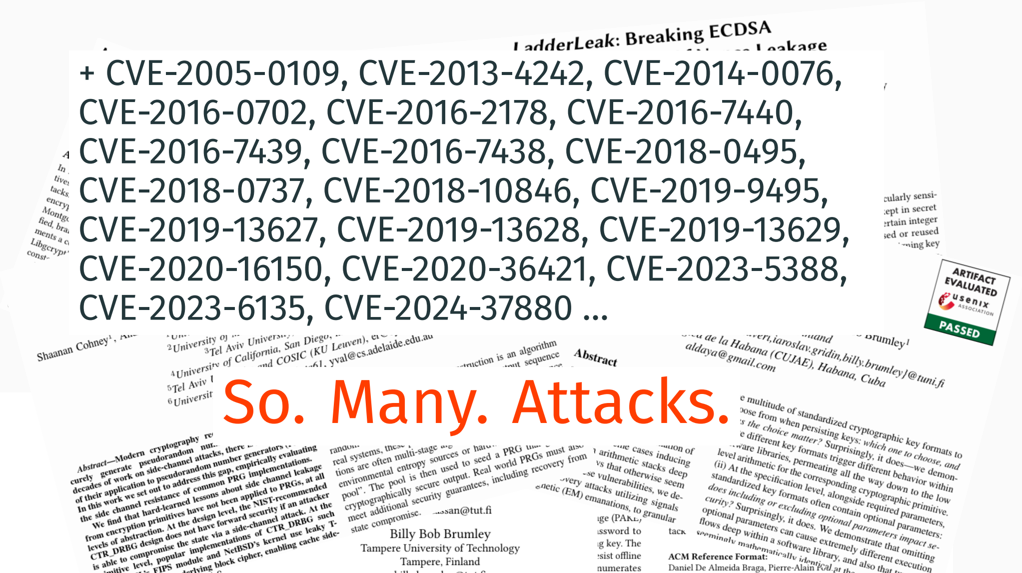


So many attacks...



+ 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 ...

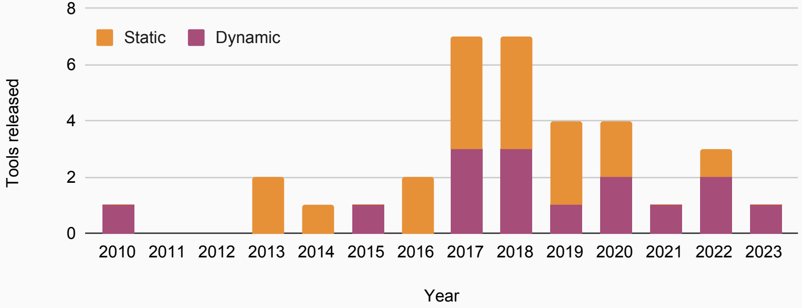
So many attacks...



+ 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 ...

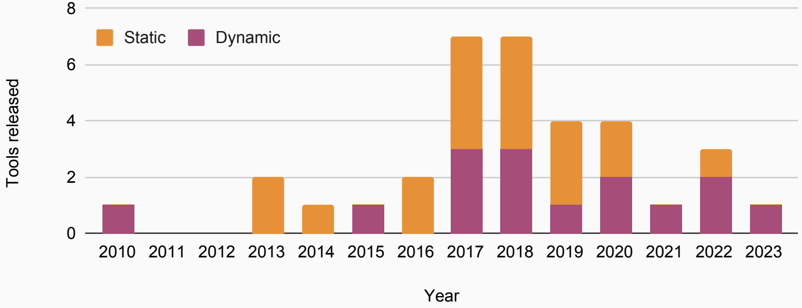
So. Many. Attacks.

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



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

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

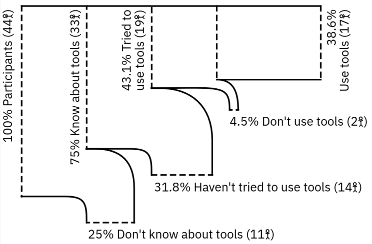


Many tools published from 2017, 67% of tools are open source (23 over 34)

Why are so many attacks still manually found?

Related Work

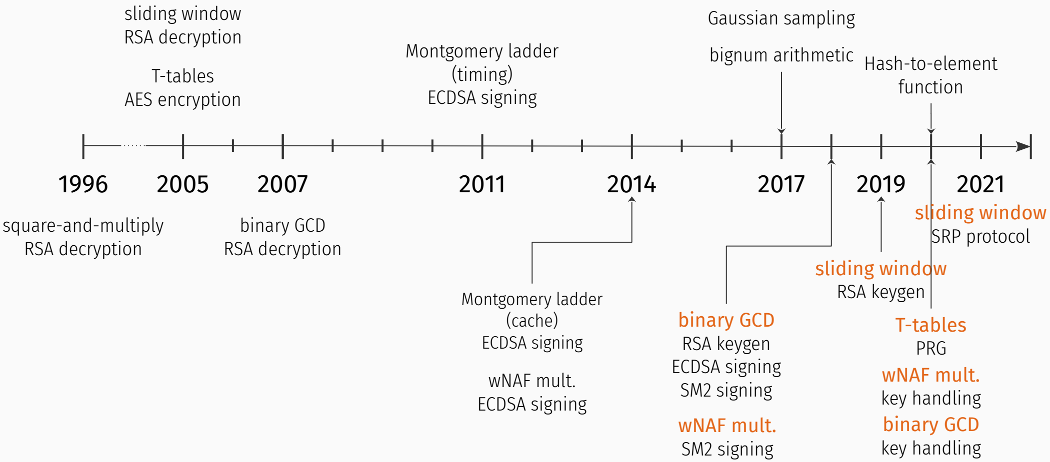
- do developers use CT tools? [S&P 2022]
  → most developers do not use them, or do not know about them
- how to improve the tool usability? [USENIX Sec 2024]
  → most developers find them really hard to use



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?

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]

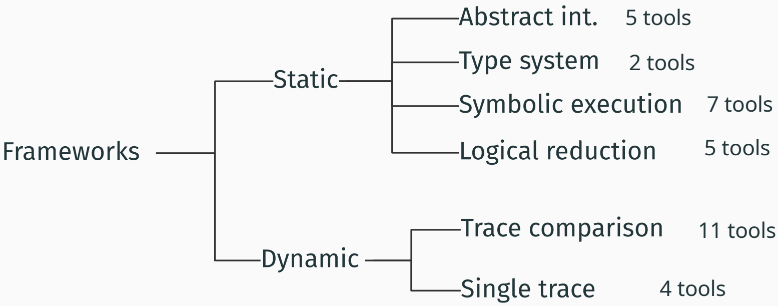
Vulnerability is found in OpenSSL but
patches are not propagated to other libraries

Most vulnerabilities stem from code
already known to be vulnerable

Side-channel vulnerability detection tools (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)



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 #V	Abacus #V	ctgrind #V	Microwalk #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

More details in our CCS 2023 paper!

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

Antoine Geimer
Univ. Lille, CNRS, Inria
Univ. Rennes, CNRS, IRISA
Lille, France

Mathéo Vergnolle
Université Paris-Saclay, CEA, List
Gif-sur-Yvettes, France

Frédéric Recoules
Université Paris-Saclay, CEA, List
Gif-sur-Yvettes, France

Lesly-Ann Daniel
KU Leuven, imec-DistriNet
Leuven, Belgium

Sébastien Bardin
Université Paris-Saclay, CEA, List
Gif-sur-Yvettes, France

Clémentine Maurice
Univ. Lille, CNRS, Inria
Lille, France

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-

Part 3: Constant-time: The Betrayal

Constant-time code $\neq$ constant-time binary (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/

Constant-time code ≠ constant-time binary (2/4)

Expanding a string into an array of integers, 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/

Constant-time code ≠ constant-time binary (3/4)

Expanding a string into an array of integers, 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/

Constant-time code ≠ constant-time binary (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
```

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

Constant-time code ≠ constant-time binary (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
```

```
expand_secure:  // x86 assembly
        [...]
.outer:
        [...]
.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/

Constant-time code ≠ constant-time binary (4/4)

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

```
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
```

```
expand_secure:  // x86 assembly
        [...]
.outer:
        [...]
.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/

Corollary

- constant-time code can produce non-constant-time binary
- any seemingly benign compiler update can break constant-time

L. Simon, D. Chisnall, and R. J. Anderson. "What You Get Is What You C: Controlling Side Effects in Mainstream C Compilers". In: *EuroS&P*. 2018.

M. Schneider et al. "Breaking Bad: How Compilers Break Constant-Time~Implementations". In: *ASIA CCS*. 2025.

L. Gerlach, R. Pietsch, and M. Schwarz. "Do Compilers Break Constant-time Guarantees?" In: *FC*. 2025.

Corollary

- constant-time code can produce non-constant-time binary
- any seemingly benign compiler update can break constant-time

Known problem... but few studies:

- either limited to short snippets or older i386 programs
- or providing only quantitative insights

L. Simon, D. Chisnall, and R. J. Anderson. “What You Get Is What You C: Controlling Side Effects in Mainstream C Compilers”. In: *EuroS&P*. 2018.

M. Schneider et al. “Breaking Bad: How Compilers Break Constant-Time~Implementations”. In: *ASIA CCS*. 2025.

L. Gerlach, R. Pietsch, and M. Schwarz. “Do Compilers Break Constant-time Guarantees?” In: *FC*. 2025.

Corollary

- constant-time code can produce non-constant-time binary
- any seemingly benign compiler update can break constant-time

Known problem... but few studies:

- either limited to short snippets or older i386 programs
- or providing only quantitative insights

→ lacking qualitative studies

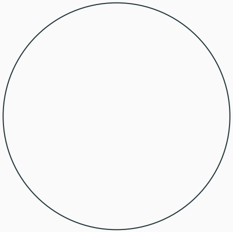
L. Simon, D. Chisnall, and R. J. Anderson. "What You Get Is What You C: Controlling Side Effects in Mainstream C Compilers". In: *EuroS&P*. 2018.
M. Schneider et al. "Breaking Bad: How Compilers Break Constant-Time~Implementations". In: *ASIA CCS*. 2025.
L. Gerlach, R. Pietsch, and M. Schwarz. "Do Compilers Break Constant-time Guarantees?" In: *FC*. 2025.

How do compilers break CT guarantees?

Challenge: lack of ground truth

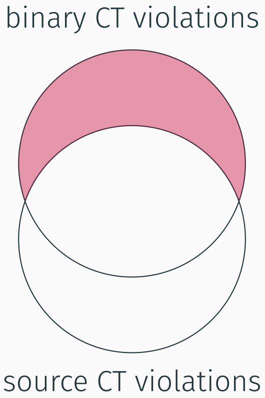
A two-fold problem:

binary CT violations



Challenge: lack of ground truth

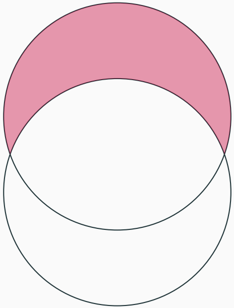
A two-fold problem:



Challenge: lack of ground truth

A two-fold problem:

binary CT violations



source CT violations

Potential solution: only analyze verified libraries

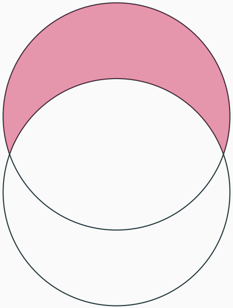
→ risks limiting experiment's scope

→ developers often use non-verified libraries

Challenge: lack of ground truth

A two-fold problem:

binary CT violations



source CT violations

Potential solution: only analyze verified libraries

→ risks limiting experiment's scope

→ developers often use non-verified libraries

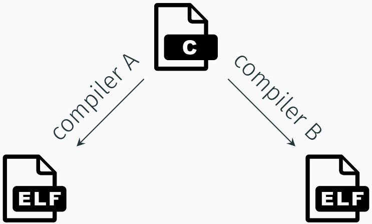
...or apply manual filtering?

→ done in Schneider et al.

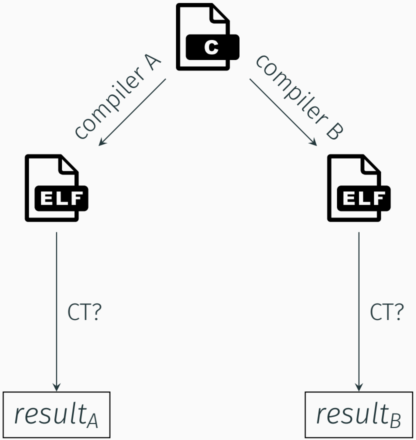
→ risks missing leakages

→ thwarted by function inlining

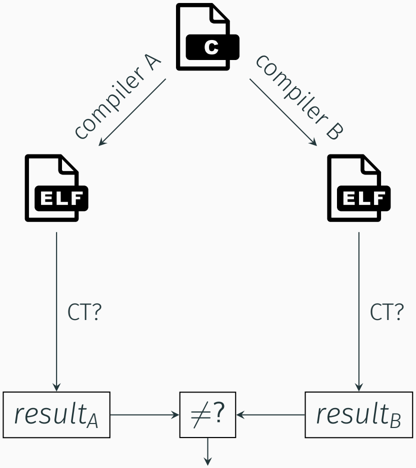
Our approach: differential testing



Our approach: differential testing

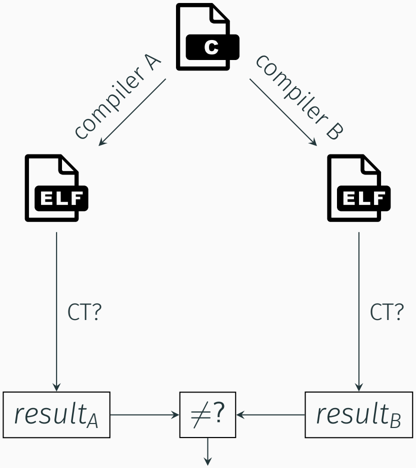


Our approach: differential testing



compiler-introduced CT violations

Our approach: differential testing



compiler-introduced CT violations

Source benchmarks

MbedTLS and BearSSL from previous works

Compilers

LLVM 12/18 and GCC 9/13, O3 and Os

CT detection

Dynamic approach: Microwalk

Results

Binaries	LLVM O3 v12	LLVM O3 v18	GCC O3 v9	GCC O3 v13
RSA-mbedtls (PKCS)	47	47	52	**48** ▼
RSA-mbedtls (OAEP)	46	**48** ▲	49	49
ECDSA-mbedtls	60	**64** ▲	61	**62** ▲
RSA-bearssl (OAEP)	0	**1** ▲	0	0
ECDSA-bearssl	0	**1** ▲	0	0
poly_frommsg	0	**1** ▲	0	0
jump_threading	0	0	1	1
loop_unswitching	1	1	1	1
path_splitting	0	0	1	1

Results

Binaries	LLVM O3 v12	LLVM O3 v18	GCC O3 v9	GCC O3 v13
RSA-mbedtls (PKCS)	47	47	52	**48** ▼
RSA-mbedtls (OAEP)	46	**48** ▲	49	49
ECDSA-mbedtls	60	**64** ▲	61	**62** ▲
RSA-bearssl (OAEP)	0	**1** ▲	0	0
ECDSA-bearssl	0	**1** ▲	0	0
poly_frommsg	0	**1** ▲	0	0
jump_threading	0	0	1	1
loop_unswitching	1	1	1	1
path_splitting	0	0	1	1

→ LLVM: general increase in newer versions

Results

Binaries	LLVM O3 v12	LLVM O3 v18	GCC O3 v9	GCC O3 v13
RSA-mbedtls (PKCS)	47	47	52	**48** ▼
RSA-mbedtls (OAEP)	46	**48** ▲	49	49
ECDSA-mbedtls	60	**64** ▲	61	**62** ▲
RSA-bearssl (OAEP)	0	**1** ▲	0	0
ECDSA-bearssl	0	**1** ▲	0	0
poly_frommsg	0	**1** ▲	0	0
jump_threading	0	0	1	1
loop_unswitching	1	1	1	1
path_splitting	0	0	1	1

- → LLVM: general increase in newer versions
- → not so much for GCC
- → both compilers can break CT

Pass analysis (1)

We analyzed the detected CT violations using **Compiler Explorer**:

→ OptPipeline tool allows us to isolate problematic passes

→ GCC and LLVM break CT in different ways: code patterns and optimizations

→ Limitation: manual analysis

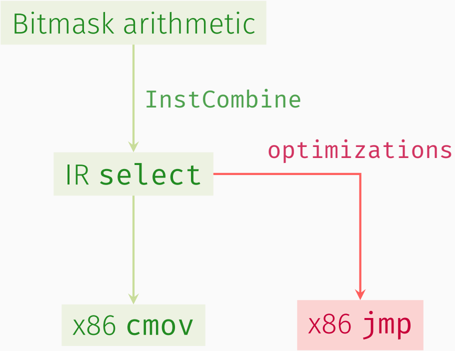
Pass analysis (2)

Different pathways to breaking CT…

Pass analysis (2)

Different pathways to breaking CT...

in LLVM:

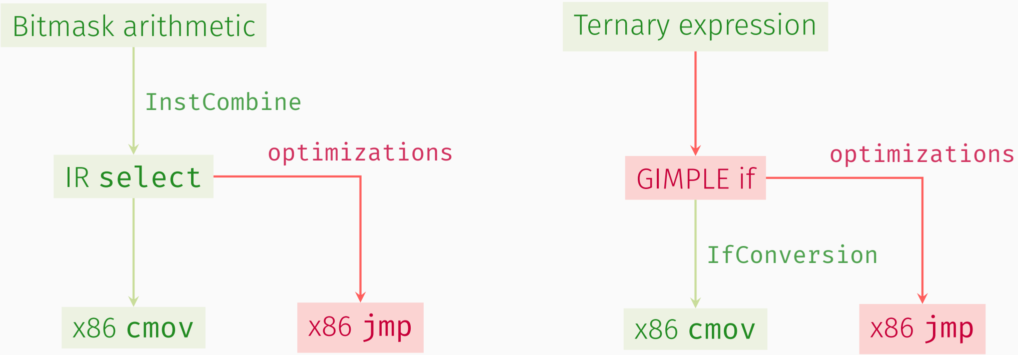


Pass analysis (2)

Different pathways to breaking CT...

in LLVM:

in GCC:



Example: RSA-bearssl in LLVM (1)

Goal: perform a CT array access for windowed RSA modular exponentiation

```
for (int u = 1; u < N; u++) {
  uint32_t m;

  m = -EQ(u, secret);
  for (int v = 1; v < M; v++) {
    t2[v] |= m & base[v];
  }
  base += M;
}
```

C source

Example: RSA-bearssl in LLVM (1)

Goal: perform a CT array access for windowed RSA modular exponentiation

```c
for (int u = 1; u < N; u++) {
  uint32_t m;

  m = -EQ(u, secret);
  for (int v = 1; v < M; v++) {
    t2[v] |= m & base[v];
  }
  base += M;
}
```

C source

Inlining

InstCombine

```c
for (int u = 1; u < N; u++) {
  uint32_t m;

  m = (u == secret);
  for (int v = 1; v < M; v++) {
    t2[v] |= select(m, base[v], 0);
  }
  base += M;
}
```

LLVM IR (represented as C for clarity)

Example: RSA-bearssl in LLVM (2)

This transformation *by itself* is safe...

```
for (int u = 1; u < N; u++) {
  uint32_t m;

  m = (u == secret);
  for (int v = 1; v < M; v++) {
    t2[v] |= select(m, base[v], 0);
  }
  base += M;
}
```

Example: RSA-bearssl in LLVM (2)

This transformation *by itself* is safe... but allows further unsafe optimizations!

```
for (int u = 1; u < N; u++) {
  uint32_t m;

  m = (u == secret);
  for (int v = 1; v < M; v++) {
    t2[v] |= select(m, base[v], 0);
  }
  base += M;
}
```

LoopUnswitch

```
for (int u = 1; u < k; u++) {
  uint32_t m;

  m = (u == secret);
  if (m) {
    for (int v = 1; v < M; v++) {
      t2[v] |= base[v];
    }
  }
  base += M;
}
```

Example: RSA-bearssl in LLVM (2)

This transformation *by itself* is safe... but allows further unsafe optimizations!

```
for (int u = 1; u < N; u++) {
  uint32_t m;

  m = (u == secret);
  for (int v = 1; v < M; v++) {
    t2[v] |= select(m, base[v], 0);
  }
  base += M;
}
```

CmovConversion

```
for (int u = 1; u < k; u++) {
  uint32_t m;

  m = (u == secret);
  for (int v = 1; v < M; v++) {
    if (m) {
      t2[v] |= base[v];
    }
  }
  base += M;
}
```

What can we do about it?

high-assurance cryptography (e.g., Jasmin) → requires a change in language

What can we do about it?

😱	high-assurance cryptography (e.g., Jasmin)	→ requires a change in language
😫	specialized compilers (e.g., CompCert)	→ requires a change in compiler

What can we do about it?

😱	high-assurance cryptography (e.g., Jasmin)	→ requires a change in language
😫	specialized compilers (e.g., CompCert)	→ requires a change in compiler
😬	code modifications and assembly	→ can break with compiler updates, portability issues

Mitigations

We investigate a simple mitigation: disabling problematic optimizations

- → using (sometimes undocumented) compiler flags
- → GCC: we disable loop unswitching, jump threading and path splitting
- → LLVM: we disable loop unswitching, loop vectorization and cmov conversion

Mitigations

We investigate a simple mitigation: disabling problematic optimizations

- → using (sometimes undocumented) compiler flags
- → GCC: we disable loop unswitching, jump threading and path splitting
- → LLVM: we disable loop unswitching, loop vectorization and cmov conversion

Evaluation

- → effectiveness: rerun our benchmarks compiled with the mitigating flags
- → performance: reusing the libraries' existing performance benchmarks

Results

Binaries \ Mitig.?	LLVM O3 No	LLVM O3 Yes	GCC O3 No	GCC O3 Yes
RSA-mbedtls (PKCS)	47	**46** ▼	48	**50** ▲
RSA-mbedtls (OAEP)	48	**46** ▼	49	49
ECDSA-mbedtls	64	**61** ▼	62	62
RSA-bearssl (OAEP)	1	**0** ▼	0	0
ECDSA-bearssl	1	**0** ▼	0	0
poly_frommsg	1	**0** ▼	0	0
jump_threading	0	0	1	**0** ▼
loop_unswitching	1	**0** ▼	1	**0** ▼
path_splitting	0	0	1	**0** ▼

Results

Binaries \ Mitig.?	LLVM O3 No	LLVM O3 Yes	GCC O3 No	GCC O3 Yes
RSA-mbedtls (PKCS)	47	**46** ▼	48	**50** ▲
RSA-mbedtls (OAEP)	48	**46** ▼	49	49
ECDSA-mbedtls	64	**61** ▼	62	62
RSA-bearssl (OAEP)	1	**0** ▼	0	0
ECDSA-bearssl	1	**0** ▼	0	0
poly_frommsg	1	**0** ▼	0	0
jump_threading	0	0	1	**0** ▼
loop_unswitching	1	**0** ▼	1	**0** ▼
path_splitting	0	0	1	**0** ▼

- Decrease in vulnerability
- CT binaries remain CT

Results

Binaries \ Mitig.?	LLVM O3 No	LLVM O3 Yes	GCC O3 No	GCC O3 Yes
RSA-mbedtls (PKCS)	47	**46** ▼	48	**50** ▲
RSA-mbedtls (OAEP)	48	**46** ▼	49	49
ECDSA-mbedtls	64	**61** ▼	62	62
RSA-bearssl (OAEP)	1	**0** ▼	0	0
ECDSA-bearssl	1	**0** ▼	0	0
poly_frommsg	1	**0** ▼	0	0
jump_threading	0	0	1	**0** ▼
loop_unswitching	1	**0** ▼	1	**0** ▼
path_splitting	0	0	1	**0** ▼

- Decrease in vulnerability
- CT binaries remain CT
- Negligible performance impact
  - → BearSSL: −3.30% (GCC), −0.43% (LLVM)
  - → MbedTLS: −0.71% (GCC), −1.14% (LLVM)

What can we do about it? (cont'd)

😱 high-assurance cryptography (e.g., Jasmin)	→ requires a change in language
😫 specialized compilers (e.g., CompCert)	→ requires a change in compiler
😬 code modifications and assembly	→ can break with compiler updates, portability issues
😌 disabling compiler optimizations with flags	→ developers can focus on their core expertise

More details in our arXiv pre-print!

Fun with flags: How Compilers Break and Fix Constant-Time Code

Antoine Geimer
Univ. Lille, CNRS, Inria
Univ. Rennes, CNRS, IRISA
antoine.geimer@inria.fr

Clémentine Maurice
Univ. Lille, CNRS, Inria
clementine.maurice@inria.fr

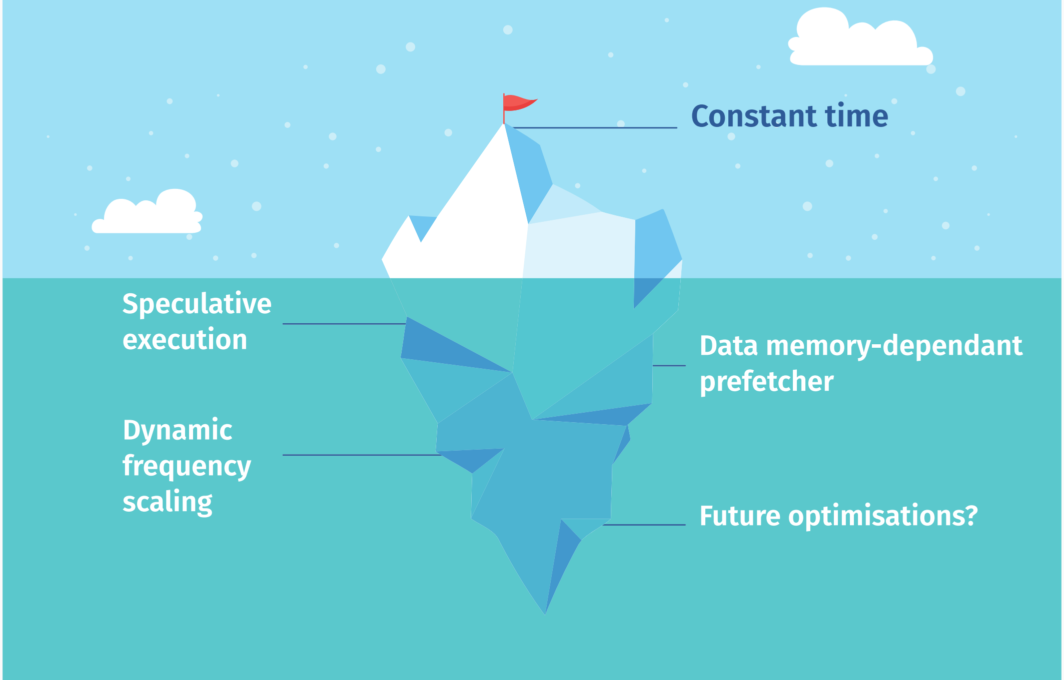
***Abstract*—Developers rely on constant-time programming to prevent timing side-channel attacks. But these efforts can be undone by compilers, whose optimizations may silently reintroduce leaks. While recent works have measured the extent of such leakage, they leave developers without actionable insights: which optimization passes are responsible, and how to disable them without modifying the compiler remains unclear.**

In this paper, we conduct a *qualitative* analysis of how compiler optimizations break constant-time code. We construct a dataset of compiler-introduced constant-time violations and analyze the internals of two widely used compilers, GCC and LLVM, to identify the specific optimization passes responsible. Our key

can re-implement critical functions in assembly snippets for each targeted architecture – a time-consuming task that risk introducing more bugs. On the other hand they can purposefully complexify their code to counter the compiler's optimizations – hardly a resilient approach as compilers improve.

Problem. While a mix of both approaches is generally applied in cryptographic libraries, compiler-introduced side-channel vulnerabilities are still regularly found [8], [41]. In fact, recent studies showed that such vulnerabilities might be much more common than previously thought [42], [27]. Newer

Perspectives & Conclusion


Constant time
Speculative execution
Data memory-dependant prefetcher
Dynamic frequency scaling
Future optimisations?

Code that is ”constant-time”

(and considered secure until recently)

can be vulnerable too!

Conclusions

- first paper by Kocher in 1996: almost 30 years of research in this area

Conclusions

- first paper by Kocher in 1996: almost 30 years of research in this area
- domain still in expansion: increasing number of papers published since 2015

Conclusions

- first paper by Kocher in 1996: almost 30 years of research in this area
- domain still in expansion: increasing number of papers published since 2015
- micro-architectural attacks & defenses require a:
    - low-level understanding of hardware → micro-architecture, reverse-engineering
    - low-level understanding of software → program analysis, compilation, cryptography...

→ work across all abstraction layers!

Thank you!

Contact

clementine.maurice@inria.fr

From Theory to Practice: Detecting and Preserving Constant-Time

A story of constant time, struggles, and betrayals

Clémentine Maurice, CNRS, CRIStAL

November 19, 2025 — C&ESAR Keynote

Recommendations

#1 Support for vector instructions

#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