ProSpeCT: Provably Secure Speculation for the Constant-Time Policy

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Under submission

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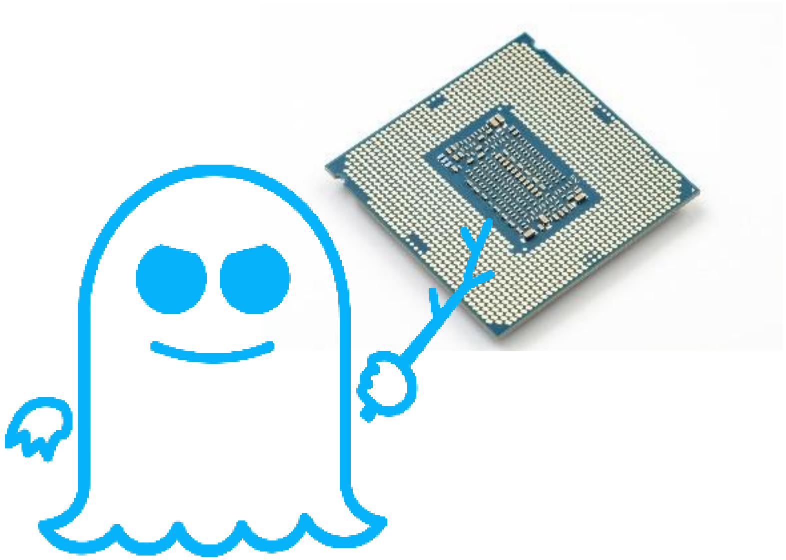
Spectre attacks

- Speculative out-of-order execution is powerful
- Speculation may lead to transient executions
- Transient executions are reverted at architectural level
- But *not the microarchitectural state* (e.g. cache)



Spectre attacks (2018)

Idea. *Force victim to encode secret data in cache during transient execution & recover them with microarchitectural attacks*

Hardware-Software Contracts

Hardware-Software Contracts for Secure Speculation

Marco Guarnieri*, Boris Köpf†, Jan Reineke‡, and Pepe Vila*
*IMDEA Software Institute †Microsoft Research ‡Saarland University

Formally reason about defenses & Enable hardware-software co-design

Foundational Framework

- Secure software design, verification and compilation
- *Formally express guarantees of hardware defenses*

Hardware-Software Contracts

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Marco Guarnieri[*], Boris Köpf[†], Jan Reineke[‡], and Pepe Vila[*]
[*]*IMDEA Software Institute* [†]*Microsoft Research* [‡]*Saarland University*

Formally reason about defenses & Enable hardware-software co-design

Foundational Framework

No hardware defense studied in the paper enables secure speculation for constant-time programs!

Secure Speculation for Constant-Time?

Constant-time Programming

Protection against (non-transient) microarchitectural attacks

- Used in many cryptographic implementations
- No secret-dependent control flow & memory accesses

Constant-Time in the Spectre Era

- Speculative semantics for software defenses
  → Hard to reason about & accommodate new speculation mechanisms?

- Hardware defense: disable speculation
  → Not acceptable

Secure Speculation for Constant-Time

Hardware defense

Efficient: enables speculation

Constant-time programs do not leak

Developer can ignore speculation

Hardware Secrecy Tracking

Hardware Secrecy Tracking (HST)

- Inform hardware of what is secret
- Track secret taint in hardware
- Do not leak tainted values during speculation

ConTExT: A Generic Approach for Mitigating Spectre

Michael Schwarz[1], Moritz Lipp[1], Claudio Canella[1], Robert Schilling[1,2], Florian Kargl[1], Daniel Gruss[1]
[1]Graz University of Technology [2]Know-Center GmbH

SpectreGuard: An Efficient Data-centric Defense Mechanism against Spectre Attacks

Jacob Fustos, University of Kansas
Farzad Farshchi, University of Kansas
Heechul Yun, University of Kansas

Speculative Privacy Tracking (SPT): Leaking Information From Speculative Execution Without Compromising Privacy

Rutvik Choudhary, UIUC, USA
Jiyong Yu, UIUC, USA
Christopher W. Fletcher, UIUC, USA
Adam Morrison, Tel Aviv University, Israel

Hardware Secrecy Tracking

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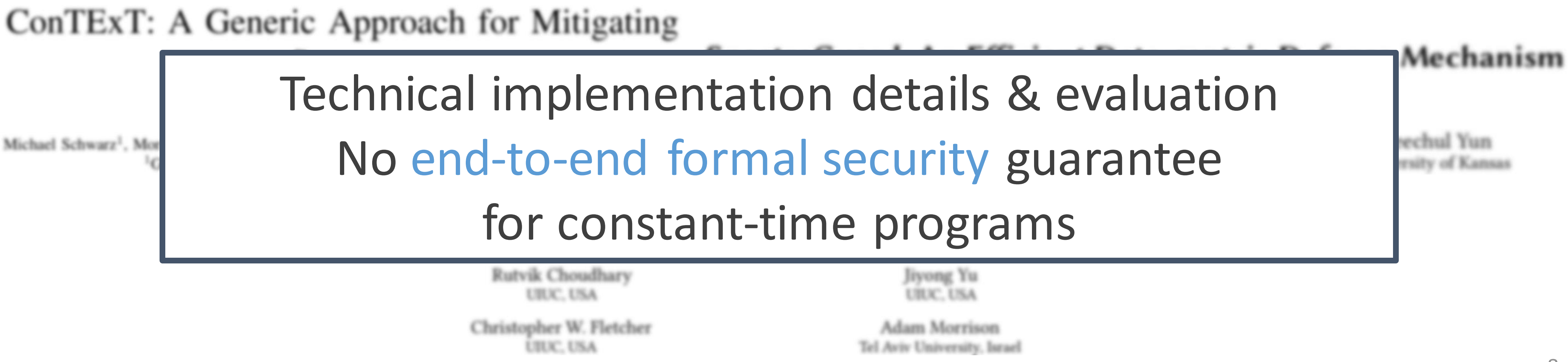

ConTExT: A Generic Approach for Mitigating

Mechanism

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Technical implementation details & evaluation
No end-to-end formal security guarantee
for constant-time programs

What we propose

ProSpeCT: Formal processor model with HST

- Generic: wide range of speculation mechanisms

Proof that CT programs do not leak secrets

- All Spectre variants + LVI
- Allows for *declassification*

First to consider Load Value Speculation

- Novel insight: sometimes need to rollback *correct* speculations for security

Implementation in a RISC-V microarchitecture

- First synthesizable implementation
- Evaluation: hardware cost, performance, annotations

ProSpeCT
Secure Speculation for Constant-Time

Illustration with Spectre-v1

Spectre-v1. Exploit branch prediction

```
char A[16]
char secret
if (idx < 16)
  x = load A[idx]
  leak(x)
```

Consider `idx = 16`

No defense

Mispredicted

`x = secret`

`secret` is transiently leaked !

Illustration with Spectre-v1

```
char A[16]  // public memory
char secret // secret memory
if (idx < 16)
  x = load A[idx]
  leak(x)
```

Consider `idx = 16`

ProSpeCT

Developer annotate secret memory

Mispredicted

`x = secret:H`

`secret` is not forwarded to `leak`

Illustration with LVI

LVI. Inject values at faulting loads

```
char A[16]
char secret
x = load idx
y = load A[x]
leak(y)
```

No defense

Attacker inject `x = 16`

`y = secret`

`secret` is transiently leaked!

Akin to Load Value Prediction

Illustration with LVI

```
char A[16]  // public memory
char secret // secret memory
x = load idx
y = load A[x]
leak(y)
```

Akin to Load Value Prediction

ProSpeCT

Developer annotate secret memory

Attacker inject `x = 16`

`y = secret:H`

`secret` is not forwarded to `leak`

Design Choices

Software side	Hardware side
• Label secret memory • Constant-time program • Secret written to public memory is declassified	• Track security labels • Secrets do not speculatively flow to insecure instructions • Predictions do not leak secrets

Code without secret $\Longrightarrow$ free speculation

Constant-time programs $\Longrightarrow$ only block mispredictions

ProSpeCT: Generic formal processor model for HST

Semantics of out-of-order speculative processor with HST

$$(a, \mu) \xrightarrow{d} (a', \mu')$$

- *declassification trace* (d)
- *microarchitectural context* (μ')
- *architectural state* (a')

Abstract microarchitectural context μ
+ Functions $update, predict, next$

{ Observations of attacker
  Influence of attacker

At each step: μ is updated with *all* public values
→ predictions can depend on any public value

Secure Speculation for Constant-Time Policy

Security (no decl). *For all constant-time program (architectural semantics)*

if $a_0 =_{public} a'_0$ and $(a_0, \mu) \longrightarrow^n (a_n, \mu_n)$

then $(a'_0, \mu) \longrightarrow^n (a'_n, \mu'_n)$ and $\mu_n = \mu'_n$

Architectural semantics = hardware software security contract

Secure Speculation for Constant-Time Policy

Security (decl). *For all constant-time program up to declassification*

$$\text{if } a_0 =_{public} a_0' \text{ and } (a_0, \mu) \xrightarrow{d}{}^{n} (a_n, \mu_n)$$

$$\text{then } (a_0', \mu), d \hookrightarrow^{n} (a_n', \mu_n') \text{ and } \mu_n = \mu_n'$$

Declassify ciphertext while still protecting plaintext

Load Prediction: Rollback correct executions?

```
char secret // secret memory
x = load secret
y = x + 4
```

	Fetch	Predict 0	Resolve prediction	
secret=0	x = load secret y = x + 4	x = 0 y = 4	x = 0 y = 4	*Implicit resolution-based channel*
secret=1	x = load secret y = x + 4	x = 0 y = 4	x = 1	Commit / Rollback can be distinguished

Load Prediction: Rollback correct executions?

```
char secret // secret memory
x = load secret
y = x + 4
```

	Fetch	Predict 0	Resolve prediction
secret=0	x = load secret y = x + 4	x = 0 y = 4	x = 0:H
secret=1	x = load secret y = x + 4	x = 0 y = 4	x = 1:H

Always rollback when actual value is secret

Implementation and Evaluation

Implementation

Prototype Risc-V implementation

- On top of Proteus modular RiSC-V processor
- Will be open-sourced
- Limitation
  - Only branch prediction
  - Secrets not forwarded *at all* during speculation (conservative)

Evaluation

Preliminary Evaluation

- Hardware cost
- Labelling secrets
- Runtime overhead

Synthesized on FPGA

– LUTs: +9.6%

– Register: +4.8%

– Critical path: +3.3%

4 primitives (HACL*)

– Annotate public/secret

– Ensure no secret spilled

– Stack public in 3 cases

– Easy: ≤1h/primitive

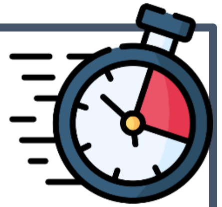
Runtime Overhead

Benchmark [1]

- Amount of secret
- Speculation-heavy public computations / crypto

spec/crypto	25/75	50/50	75/25	90/10
None	100%	100%	100%	100%
Secret	100%	100%	100%	100%
All	109%	125%	136%	145%

Conclusion



Results similar to [1]

Low overhead when secret annotation is precise and restricted part of code compute on secrets

[1] Jacob Fustos, Farzad Farshchi, and Heechul Yun. "SpectreGuard: An Efficient Data-Centric Defense Mechanism against Spectre Attacks". In: DAC. 2019

Conclusion

Hardware Secrecy Tracking

Software informs hardware about secret

Strong security guarantees

ProSpeCT ⟹ end-to-end security for constant-time programs

Low overhead

ProSpeCT ⟹ no runtime overhead on public data

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Backup

Future Work

Formal model

- Express details of existing HST defenses in our model

Compiler-support

- Separate secret from public memory
- Ensure no unintentional declassification

Validate RISC-V implementation

- Contract-based CPU testing (e.g., Revizor, Scam-V)?
- Hardware-fuzzing / Model checking?

Secure Speculation for Constant-Time Policy

Security without declassification:

If program is constant-time (sequential semantics), then secrets do not leak to μ in our hardware (speculative) semantics

Security with declassification

If program is constant-time up to declassification (sequential semantics), secrets do not leak to μ (speculative semantics).