Hardware-Software Contracts for Safe and Secure Systems

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The Need for New HW/SW Contracts

“Stone-age” Computing

Applications implemented data transformations:
e.g. payroll processing

Hardware:

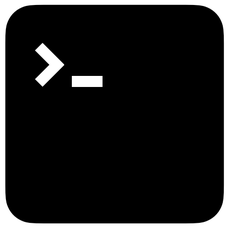
- isolated, on-site
- limited interaction with environment

IBM System 360/30

HW/SW Contract: Instruction set architecture (ISA)

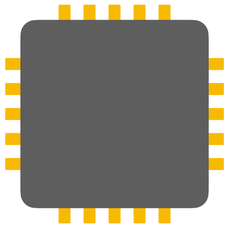
ISA: Benefits

High-level language



Instruction set architecture (ISA)

Microarchitecture



Can program **independently** of microarchitecture

Can implement **arbitrary optimizations** as long as ISA semantics are obeyed

“Modern” (?) Computing

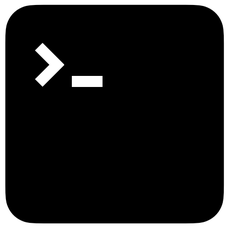
Applications are:

- ***Data-driven***: e.g. deep neural networks
- ***Distributed***: e.g. locally + in the cloud
- ***Open***: e.g. untrusted code in the browser 
- ***Real-time***: interacting with the physical environment 

What are the implications for HW/SW contracts?

Inadequacy of the ISA: Real-time Systems

High-level language



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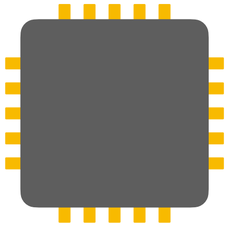


Impossible to program
real-time systems on top of ISA

Abstracts from time
No control over time

Can implement arbitrary
unpredictable optimizations as long
as ISA is implemented correctly

Wanted: Timed HW/SW Contracts

Programs have a **timed semantics** that is **efficiently predictable**
Programs have **control** over timing

Timed Instruction Set Architecture

Admit a **wide range** of **timing-predictable**, yet high-performance microarchitectural **implementations**

Wanted: Timed HW/SW Contracts

Some answers:

E. Lee, J. Reineke, and M. Zimmer:
Abstract PRET Machines
RTSS 2017

Determinism

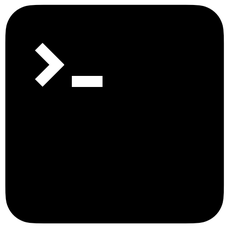
S. Hahn and J. Reineke:
Design and Analysis of SIC:
A Provably Timing-Predictable Pipelined Processor Core
RTSS 2018 (🥇 Best Student Paper Award)

Monotonicity

G. Stock, S. Hahn and J. Reineke:
Cache Persistence Analysis: Finally Exact
RTSS 2019 (🥇 Best Paper Award)

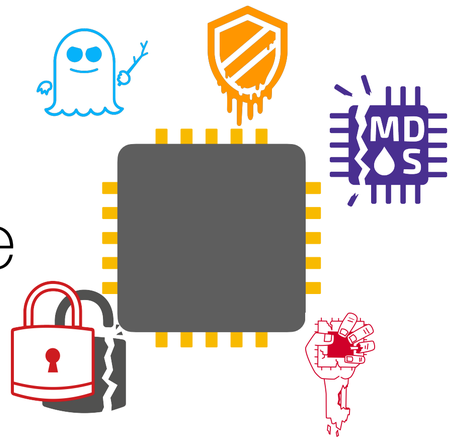
Inadequacy of the ISA: Side channels

High-level language



Instruction set architecture (ISA)

Microarchitecture

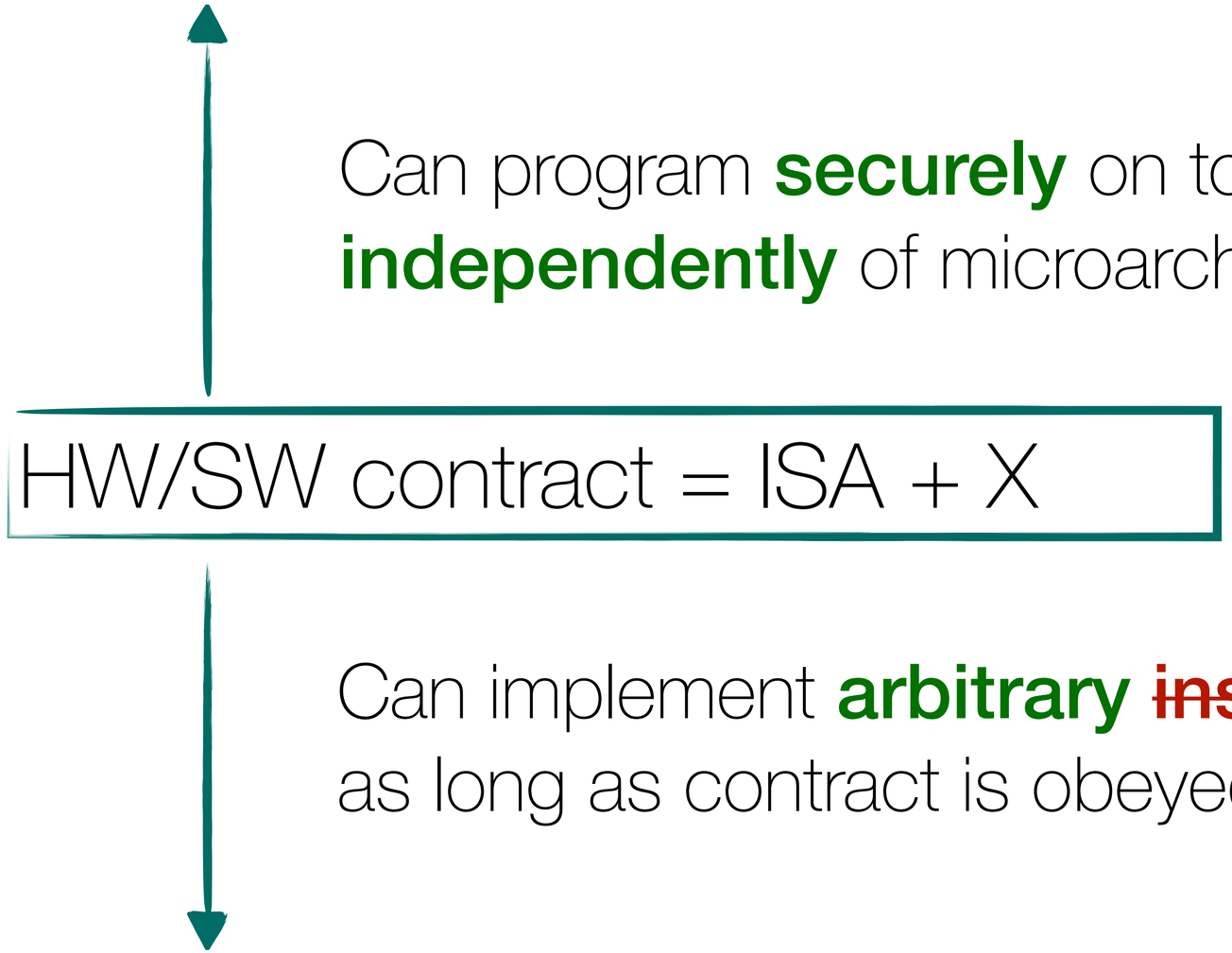


Impossible to program securely
cryptographic algorithms?
sandboxing untrusted code?

No guarantees about side channels

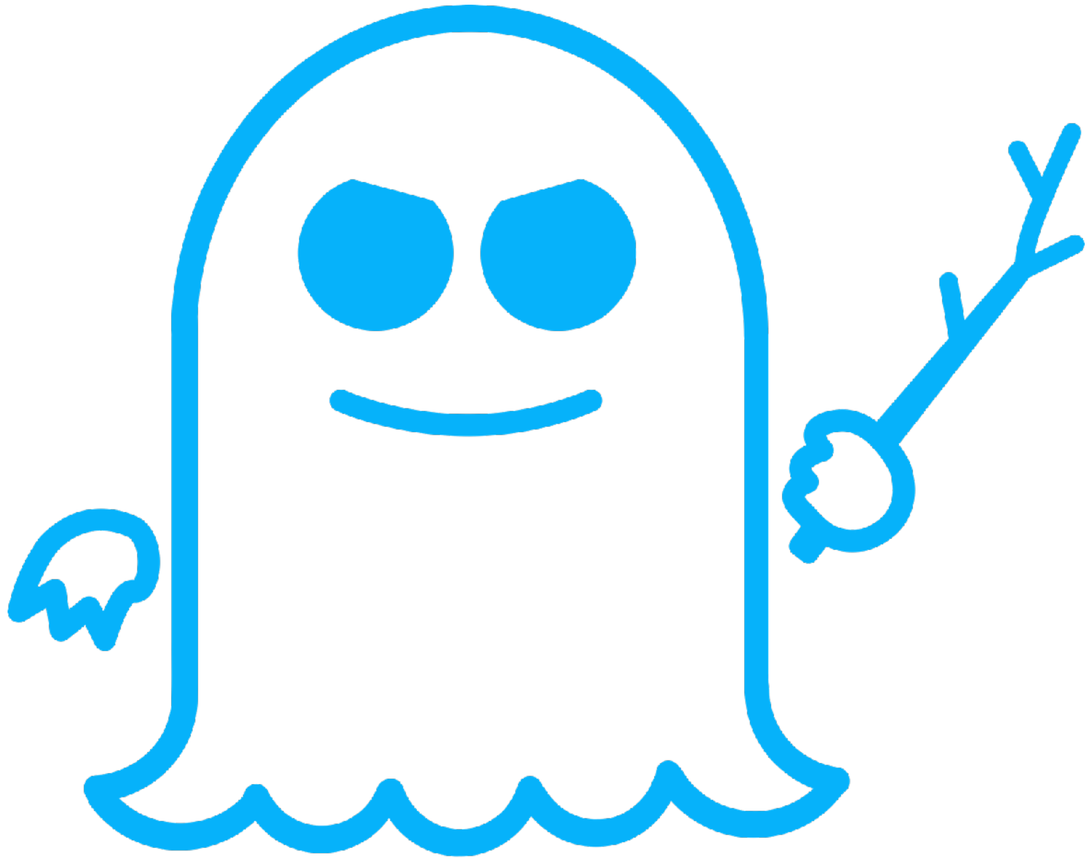
Can implement arbitrary **insecure** optimizations as long as ISA is implemented correctly

A Way Forward: HW/SW Security Contracts



Succinctly captures possible information leakage

A Concrete Challenge: Spectre



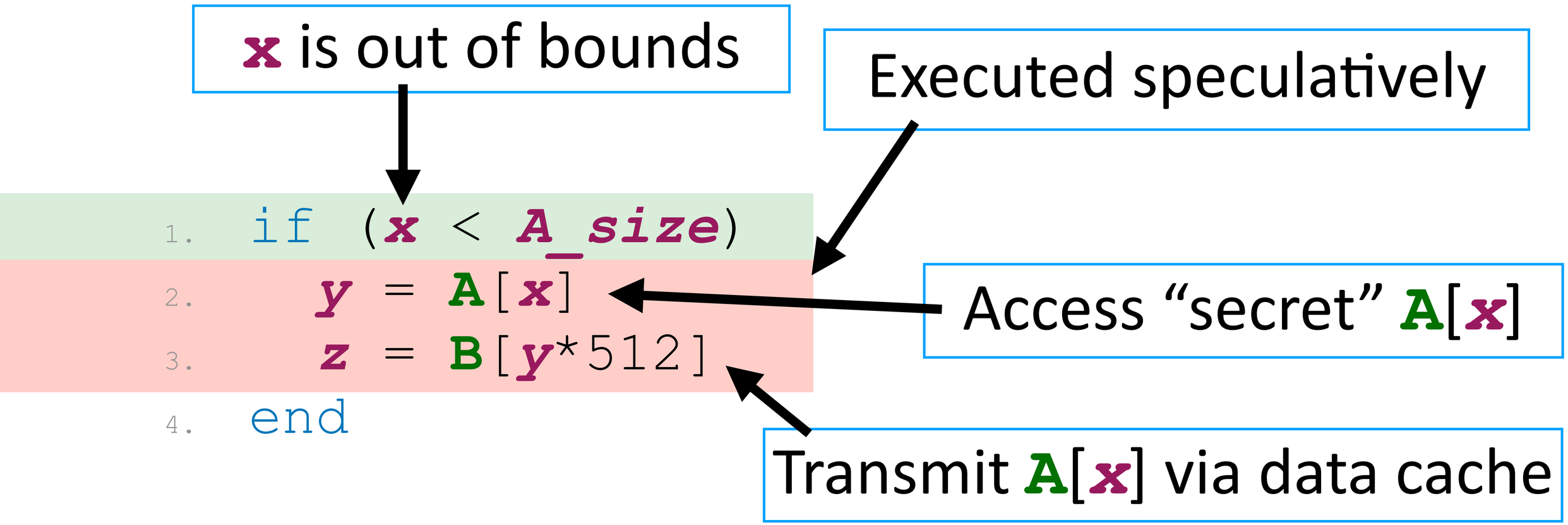
SPECTRE

Exploits *speculative execution*

Almost *all* modern *CPUs* are *affected*

P. Kocher, J. Horn, A. Fogh, D. Genkin, D. Gruss, W. Haas, M. Hamburg, M. Lipp, S. Mangard, T. Prescher, M. Schwarz, Y. Yarom — | Spectre Attacks: Exploiting Speculative Execution — S&P 2019

Example: Spectre v1 Gadget



Hardware Countermeasures

InvisiSpec: Making Speculative E
Invisible in the Cache

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NDA: Preventing Speculative Execution Attacks at Their Source

Kevin Loughlin
University of Michigan

Ian Neal
University of Michigan

Baris Kasikci
University of Michigan

Ofir Weisse
University of Michigan

Thomas F. Wenisch
University of Michigan

Efficient Invisible Speculative Execution through Selective Delay and Value Prediction

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CleanupSpec: An "Undo" Approach to Safe Speculation

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Speculative Taint Tracking (STT): A Comprehensive Protection for Speculatively Accessed Data

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Josep Torrellas

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Examples

```
1.  if (x < A_size)
2.      y = A[x]
3.      z = B[y*512]
4.  end
```

Delay loads until they can be retired

[Sakalis et al., ISCA'19]

Delay loads until they cannot be squashed

[Sakalis et al., ISCA'19]

Taint speculatively loaded data + delay tainted loads

[STT and NDA, MICRO'19]

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+ delay tainted loads
[STT and NDA, MICRO'19]

What security properties do HW countermeasures enforce?

How can we program securely?

Some Answers:

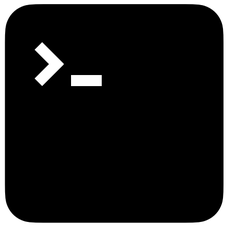
M. Guarnieri, B. Köpf, J. Reineke, and P. Vila

Hardware-Software Contracts for Secure Speculation

S&P (Oakland) 2021 (🏅 Best Paper Award)

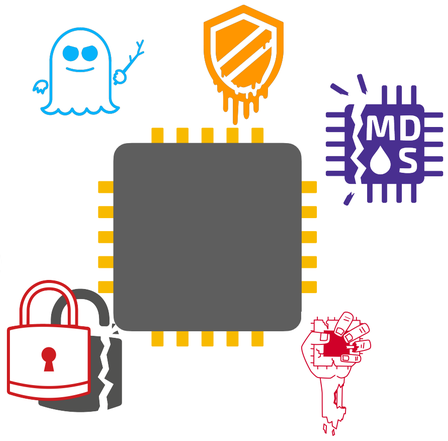
Research Landscape around HW/SW Contracts

High-level language



Hardware-Software Contracts

Microarchitecture



Program Analysis
Abstract Interpretation
Symbolic Execution

How to capture guarantees?

Verification SMT Solvers
+ Invariant Synthesis

Testing Fuzzing

Design Domain Specific Language

Happy to chat about PhD and internship opportunities

Thank you for your attention