Relative Security: Formally Modeling and (Dis)Proving Resilience Against Semantic Optimization Vulnerabilities

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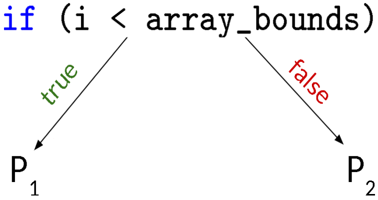

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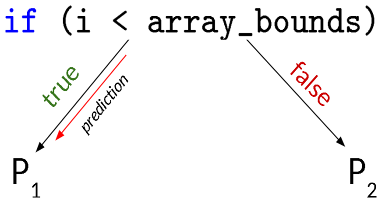

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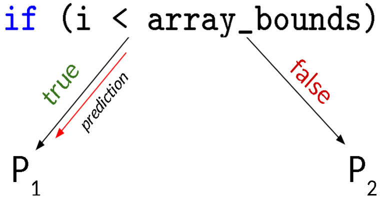

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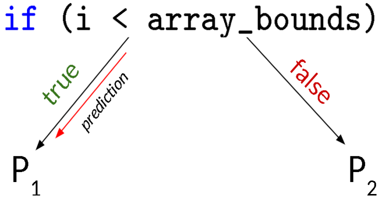

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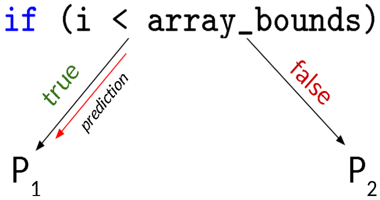

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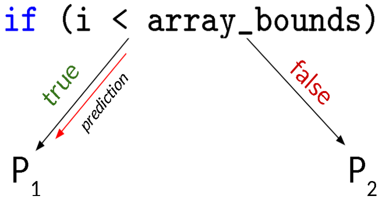

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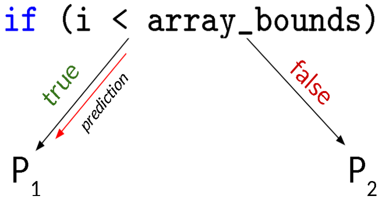

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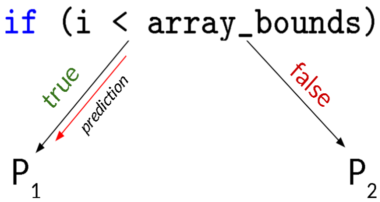

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- But side-channels can be exploited
    - Leaks data via CPU cache traces.

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History

1) Problem uncovered in 2018 affecting *all* major processors (big news)
2) Some variants, e.g., Meltdown / Foreshadow have been fixed via hardware / microcode patches (though older machines are still vulnerable)
3) Spectre believed to be unpatchable; new variants continue to be discovered (Retbleed, NetSpectre, Speculative Store Bypass ...)

There are **63** CVE Records that match your search.

A Dangerous Program

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uint8_t function_v01(unsigned i) {
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– Mistrains predictor

– Observes cache addresses

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SECRET IS REVEALED!

via probing cache address

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Spectre Mitigation via Fences

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FENCE HAS BEEN HIT!

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How can we:

(a) characterise Spectre vulnerabilities and

(b) prove their absence?

Related (and Inspiring) Work

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Conditional NI[1]	No	Restricted To Initial State
Speculative NI/Spectector[2]	No	Restricted To Initial State
TPOD[3]	Yes	Yes

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A comprehensive survey of the state-of-the-art:

S. Cauligi, C. Disselkoen, D. Moghimi, G. Barthe, D. Stefan: *SoK: Practical Foundations for Software Spectre Defenses*. IEEE S&P 2022.

Our Contributions

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General notion of information-flow security

– captures Spectre-like vulnerabilities

– works generally for transition systems (I/O automata)

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Verified Examples

– Instantiation to a C-like language with speculative semantics

– Case studies from the Spectre benchmark verified

– An Isabelle/HOL mechanization of the general framework and the case studies

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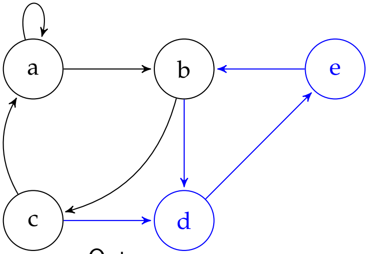
  A "vanilla" semantics and an "optimized" semantics (e.g. speculation)



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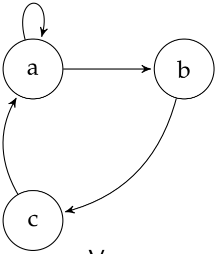

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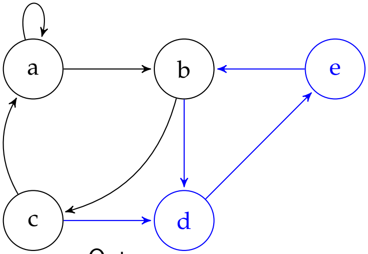

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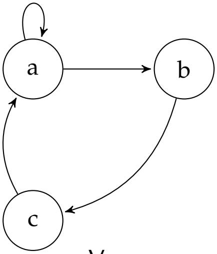

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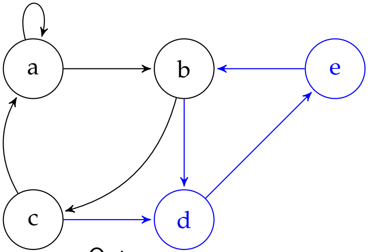

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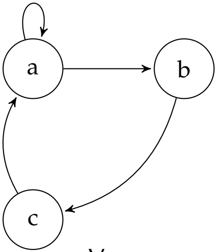

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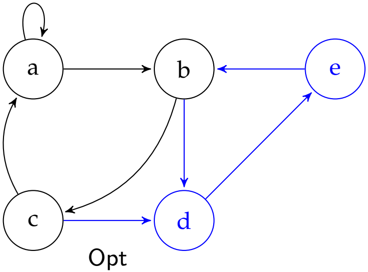

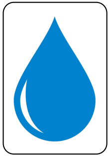

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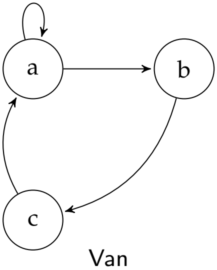

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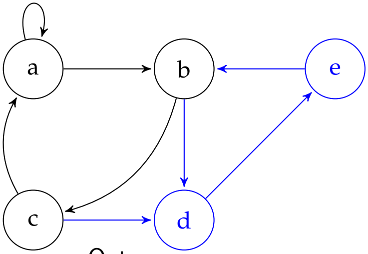

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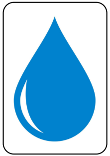

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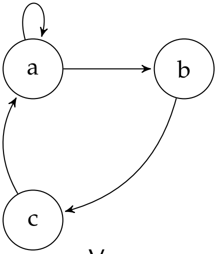

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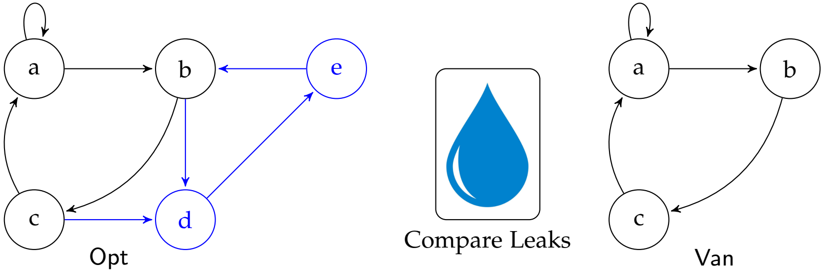
  There exist traces without Opt which produces the same leak



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$\mathcal{O}(\pi_1) \neq \mathcal{O}(\pi_2)$
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$$\mathcal{S}(\pi_1) = (s := 5)$$
$$\mathcal{S}(\pi_2) = (s := 4)$$
$$\mathcal{A}(\pi_1) = \mathcal{A}(\pi_2) = (x := 0)$$

```
input x
y ::= x + s
output y
```

$$\mathcal{O}(\pi_1) \neq \mathcal{O}(\pi_2)$$
$$5 \neq 4$$

Traces π_1 and π_2 produce the leak (sl_1, sl_2) iff...

$$\mathcal{S}(\pi_1) = sl_1 \ \wedge \ \mathcal{S}(\pi_2) = sl_2 \ \wedge \ \mathcal{A}(\pi_1) = \mathcal{A}(\pi_2) \ \wedge \ \mathcal{O}(\pi_1) \neq \mathcal{O}(\pi_2)$$

What is a leak?

A leak consists of two traces π_1 and π_2, such that an attacker can:

(a) distinguish between two secrets via observations while
(b) taking the same actions

$$\mathcal{S}(\pi_1) = (s := 5)$$
$$\mathcal{S}(\pi_2) = (s := 4)$$
$$\mathcal{A}(\pi_1) = \mathcal{A}(\pi_2) = (x := 0)$$

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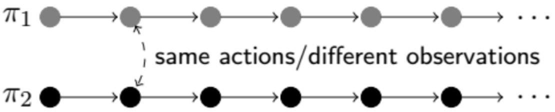
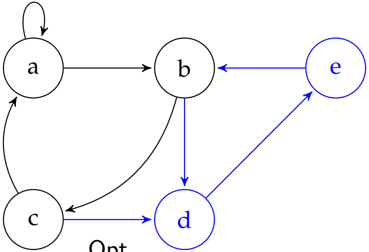
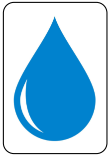


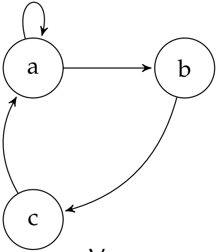
Relative Security

- Let $\mathsf{Trace}_{\mathbf{van}}, \mathsf{Trace}_{\mathbf{opt}}$ be the set of traces of the vanilla and *optimized* system
- Recall: $\mathcal{S}(\pi_1) = sl_1 \;\wedge\; \mathcal{S}(\pi_2) = sl_2 \;\;\wedge\;\; \mathcal{A}(\pi_1) = \mathcal{A}(\pi_2) \;\wedge\; \mathcal{O}(\pi_1) \neq \mathcal{O}(\pi_2)$



Opt


Compare Leaks



Van

Relative Security

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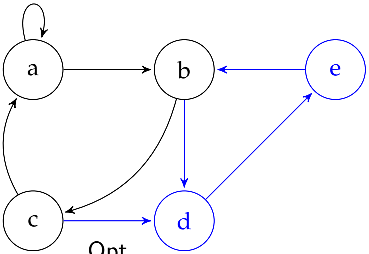
Definition (Relative Security)

For all possible leaks the semantics with Opt can produce

There exist traces without Opt which produces the same leak



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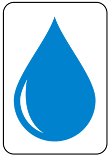
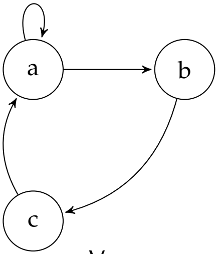


Compare Leaks



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- Let $\mathsf{Trace}_{\mathbf{van}}, \mathsf{Trace}_{\mathbf{opt}}$ be the set of traces of the vanilla and *optimized* system
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Definition (Relative Security)

$\forall (sl_1, sl_2) \in \mathsf{Leak}.$

$$\forall o_1, o_2 \in \mathsf{Trace}_{\mathbf{opt}}.\; \mathcal{S}(o_1) = sl_1 \;\wedge\; \mathcal{S}(o_2) = sl_2 \;\wedge\; \mathcal{A}(o_1) = \mathcal{A}(o_2) \wedge \mathcal{O}(o_1) \neq \mathcal{O}(o_2)$$

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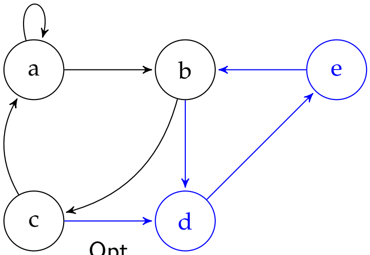
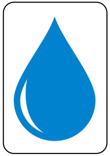
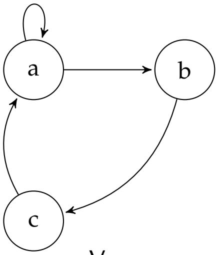


Opt


Compare Leaks



Van

Relative Security

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Definition (Relative Security)

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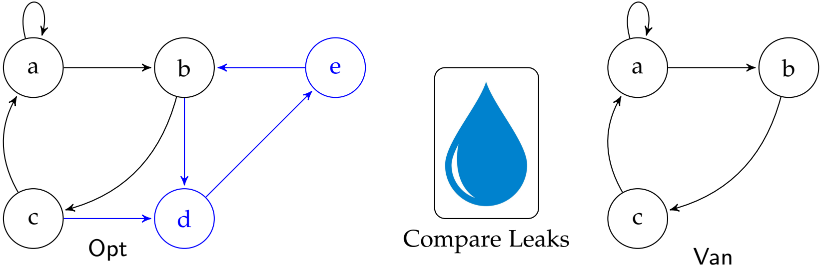

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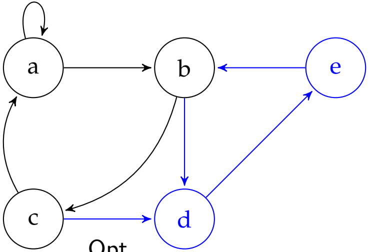

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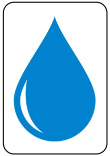

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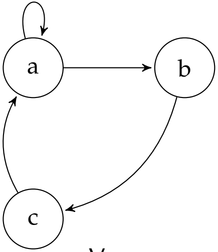

Van

Relative Security

Definition (Relative Security)

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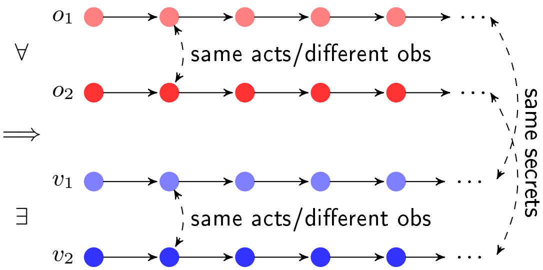

Proving Relative Security

Use an *unwinding relation* over the states of the vanilla and optimised systems

Joseph A. Goguen and José Meseguer. Unwinding and inference control. In *IEEE Symposium on Security and Privacy*, pages 75–87, 1984.

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... A two player game!

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- Adversary controls optimized traces o_1 and o_2
- Protagonist build vanilla traces v_1 and v_2

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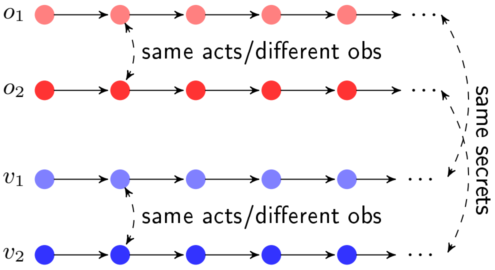

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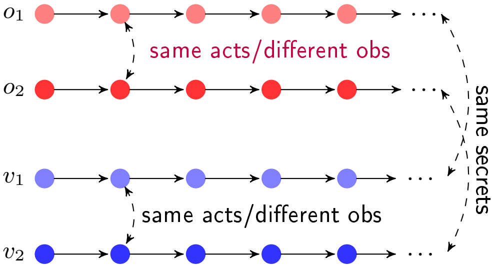

Assume: o_1 and o_2 – same acts/different obs

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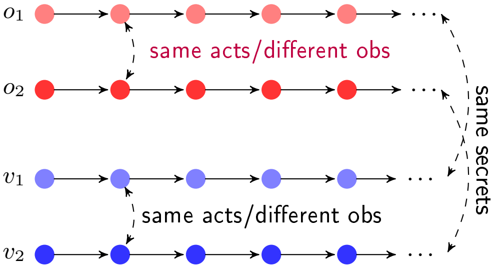

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Contracts:

Proving Relative Security

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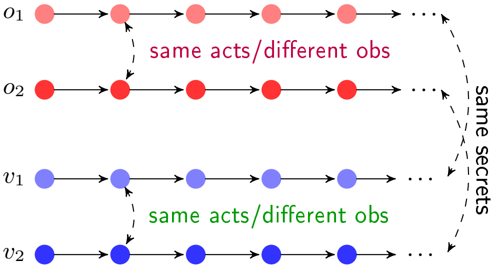

Assume: o_1 and o_2 – same acts/different obs

Contracts:

– *Interaction*: v_1 and v_2 – same acts/different obs

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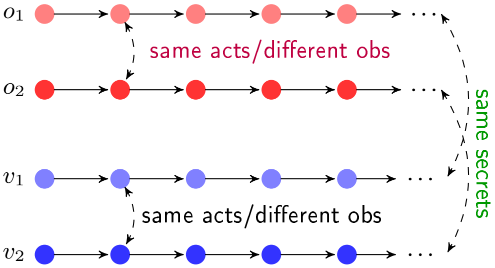

Assume: o_1 and o_2 – same acts/different obs

Contracts:

- *Interaction*: v_1 and v_2 – same acts/different obs
- *Secrecy*: same secrets for o_1, v_1 and o_2, v_2

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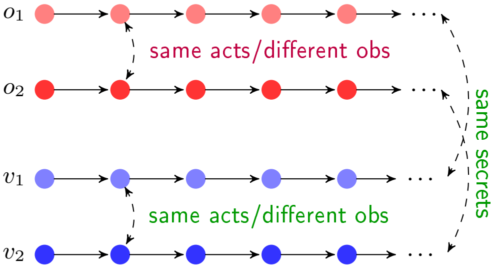

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Assumption + **Contracts** $\implies$ *Relative Security*

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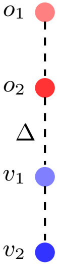
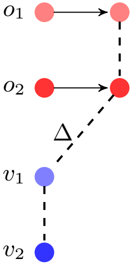


$\Delta \implies$ **Assumption + Contracts**

Proving Relative Security

Use an *unwinding relation* over the states of the vanilla and optimised systems
... A two player game!

- Adversary controls optimized traces o_1 and o_2
- Protagonist build vanilla traces v_1 and v_2 **... incrementally**



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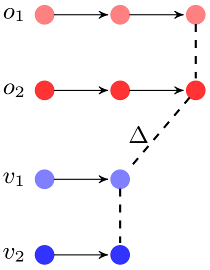

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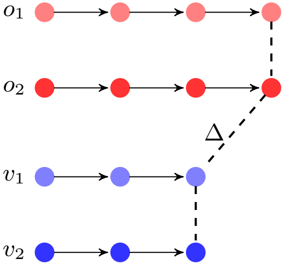

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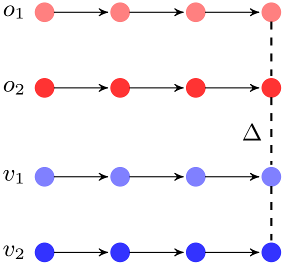

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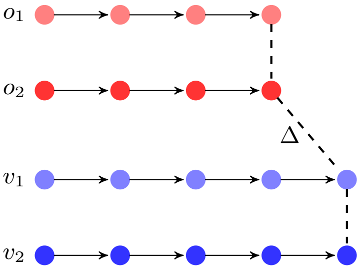

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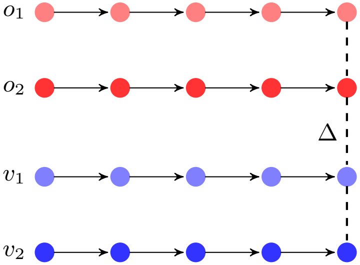

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....

Proving Relative Security

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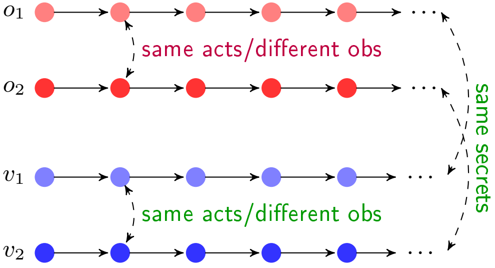


$\Delta \implies$ **Assumption + Contracts**

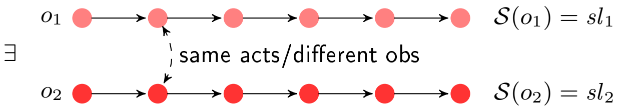
....

Assumption + Contracts $\implies$ *Relative Security*

Disproving Relative Security

Disproof

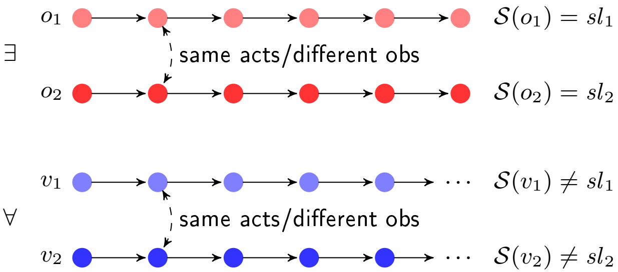
1) Provide traces (o_1, o_2) producing a concrete leak (sl_1, sl_2)



Disproving Relative Security

Disproof

1) Provide traces (o_1, o_2) producing a concrete leak (sl_1, sl_2)
2) An unwinding, showing that there is no related pair (v_1, v_2) producing the same secrets.



Relative Security for Speculative Execution

```
uint8_t function_v01(unsigned i) {
   if (i < N) {
     uint8_t v = a1[i];
     return a2[v];
   }
   return 0;}
```

Relatively Secure? (??)

Relative Security for Speculative Execution

```
uint8_t function_v01(unsigned i) {
   if (i < N) {
     uint8_t v = a1[i];
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```

Not Relatively Secure (👎)

Relative Security for Speculative Execution

```c
uint8_t function_v01(unsigned i) {
   if (i < N) {
     uint8_t v = a1[i];
     return a2[v];
   }
   return 0;}
```

Not Relatively Secure (👎)

```c
uint8_t v01_secure(unsigned i) {
   if (i < N) {
      _mm_lfence(); //resolve spec
      uint8_t v = a1[i];
      return a2[v];
   }
   return 0;}
```

Relatively Secure? (??)

Relative Security for Speculative Execution

```
uint8_t function_v01(unsigned i) {
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Relatively Secure!

Relative Security for Speculative Execution

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Not Relatively Secure ()

```
uint8_t v01_secure(unsigned i) {
  if (i < N) {
    _mm_lfence(); //resolve spec
    uint8_t v = a1[i];
    return a2[v];
  }
  return 0;}
```

Relatively Secure! ()

```
uint8_t v01_secure_2(unsigned i) {
  if (i < N) {
    uint8_t v = a1[i];
    _mm_lfence();//resolve spec
    return a2[v];
  }
  return 0;}
```

Relatively secure? (??)

Relative Security for Speculative Execution

```c
uint8_t function_v01(unsigned i) {
   if (i < N) {
     uint8_t v = a1[i];
     return a2[v];
   }
   return 0;}
```

Not Relatively Secure ()

```c
uint8_t v01_secure(unsigned i) {
   if (i < N) {
      _mm_lfence(); //resolve spec
      uint8_t v = a1[i];
      return a2[v];
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```

Relatively Secure! ()

```c
uint8_t v01_secure_2(unsigned i) {
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      uint8_t v = a1[i];
      _mm_lfence();//resolve spec
      return a2[v];
   }
   return 0;}
```

Relatively Secure! ()

Relative Security vs TPOD

```
uint8_t cond_secure(unsigned i) {
  if (i < N) {//Assuming N > 0...
    uint8_t v = a1[0]; //ind. of i
    return a2[v];
  }
  return 0;}
```

Relatively secure? (??) / TPOD (??)

Relative Security vs TPOD

```c
uint8_t cond_secure(unsigned i) {
  if (i < N) {//Assuming N > 0...
    uint8_t v = a1[0]; //ind. of i
    return a2[v];
  }
  return 0;}
```

Relatively Secure! () / TPOD ()

Conclusion

Relative Security

New correctness condition **Relative Security**, characterising Spectre-like vulnerabilities

- works generally for any optimization vulnerability
- accounts for interactive attackers and interactive uploading of secrets

Unwinding Proof Methodology

Incremental unwinding proofs to verify presence/absence of vulnerabilities

Verified Examples

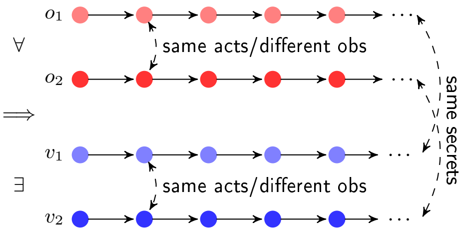
- Instantiation to a C-like language with speculative semantics
- Case studies from the Spectre benchmark verified
- An Isabelle/HOL mechanization of the general framework and the case studies

Contact me: jwright8@sheffield.ac.uk

Appendix

Relative Security vs TPOD

Relative Security



Relative Security vs TPOD

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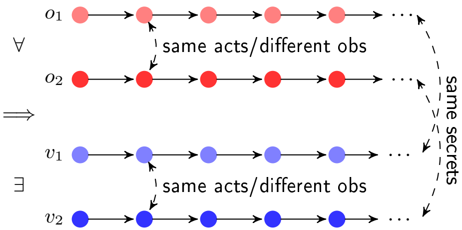
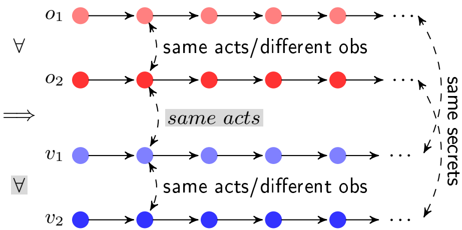


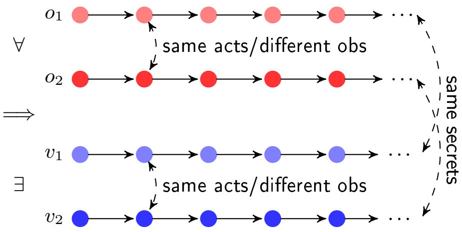
Trace-property dependent observational nondeterminism (TPOD)



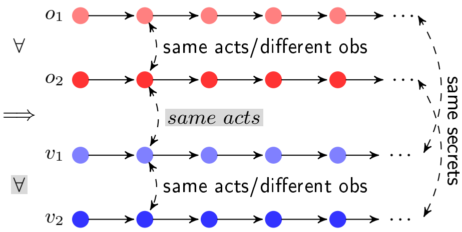
K. Cheang, C. Rasmussen, S. A. Seshia, and P. Subramanyan, "A formal approach to secure speculation," in CSF. IEEE, 2019

Relative Security vs TPOD

Relative Security



Trace-property dependent observational nondeterminism (TPOD)



Key differences:

- TPOD requires same actions between optimised *and* vanilla system
- Any leak of o_1, o_2 is reproduced not by *some* traces v_1, v_2 but all traces that share secrets

K. Cheang, C. Rasmussen, S. A. Seshia, and P. Subramanyan, "A formal approach to secure speculation," in CSF. IEEE, 2019

Relative Security vs. TPOD

```c
uint8_t cond_secure(unsigned i) {
  if (i < N) {//Assuming N > 0...
    uint8_t v = a1[0]; //ind. of i
    return a2[v];
  }
  return 0;}
```

Relatively secure? (??) / TPOD (??)

Relative Security vs. TPOD

```c
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  if (i < N) {//Assuming N > 0...
    uint8_t v = a1[0]; //ind. of i
    return a2[v];
  }
  return 0;}
```

Relatively Secure! () / TPOD ()

Example proof of security

```c
uint8_t v01_secure(unsigned i) {
  if (i < N) {
    _mm_lfence();//resolve spec
    uint8_t v = a1[i];
    return a2[v];
  }
  return 0;}
```

Δ_0

	Spec.	$v_1 = v_2 = o_1^0 = o_2^0$	$o_1^1 = o_2^1$	Memory invariants	Read locs. invariants
Δ_0	No	1	–	$\mathcal{S}(v_1) = \mathcal{S}(o_1) \wedge \mathcal{S}(v_2) = \mathcal{S}(o_2)$	$v_1 = o_1 \wedge v_2 = o_2$

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$$\Delta_0 \longrightarrow \Delta_1$$

	Spec.	$v_1 = v_2 = o_1^0 = o_2^0$	$o_1^1 = o_2^1$	Memory invariants	Read locs. invars ($\mathcal{O}$)
Δ_0	No	1	–	$\mathcal{S}(v_1) = \mathcal{S}(o_1) \wedge$ $\mathcal{S}(v_2) = \mathcal{S}(o_2)$	$v_1 = o_1 \wedge$ $v_2 = o_2$
Δ_1	No	2–7	–	$\cdots \wedge$ $v_1 =_i o_1$	$\cdots$

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```

$$\Delta_0 \longrightarrow \Delta_1 \longrightarrow \Delta_e$$

	Spec.	$v_1 = v_2 = o_1^0 = o_2^0$	$o_1^1 = o_2^1$	Memory invariants	Read locs. invars ($\mathcal{O}$)
Δ_0	No	1	–	$\mathcal{S}(v_1) = \mathcal{S}(o_1) \wedge$ $\mathcal{S}(v_2) = \mathcal{S}(o_2)$	$v_1 = o_1 \wedge$ $v_2 = o_2$
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$$\begin{tikzcd} \Delta_0 \arrow[r] & \Delta_1 \arrow[r] \arrow[dr] & \Delta_e \\ & & \color{purple}{\Delta_2} \end{tikzcd}$$

	Spec.	$v_1 = v_2 =$ $o_1^0 = o_2^0$	$o_1^1 = o_2^1$	Memory invariants	Read locs. invars ($\mathcal{O}$)
Δ_0	No	1	–	$\mathcal{S}(v_1) = \mathcal{S}(o_1) \wedge$ $\mathcal{S}(v_2) = \mathcal{S}(o_2)$	$v_1 = o_1 \wedge$ $v_2 = o_2$
Δ_1	No	2–7	–	$\cdots \wedge$ $v_1 =_i o_1$	$\cdots$
Δ_2	Yes	3	7	$\cdots$	$\cdots$
Δ_e	No	return	–	$\cdots$	$\cdots$

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	Spec.	$v_1 = v_2 = o_1^0 = o_2^0$	$o_1^1 = o_2^1$	Memory invariants	Read locs. invars ($\mathcal{O}$)
Δ_0	No	1	–	$\mathcal{S}(v_1) = \mathcal{S}(o_1) \wedge \mathcal{S}(v_2) = \mathcal{S}(o_2)$	$v_1 = o_1 \wedge v_2 = o_2$
Δ_1	No	2–7	–	$\cdots \wedge v_1 =_i o_1$	$\cdots$
Δ_2	Yes	3	7	$\cdots$	$\cdots$
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Example proof of security

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$$\begin{tikzcd}
 & & \Delta_3 \\
\Delta_0 \arrow[r] & \Delta_1 \arrow[ur] \arrow[r] \arrow[dr] & \Delta_e \\
 & & \Delta_2 \arrow[ul, bend left]
\end{tikzcd}$$

	Spec.	$v_1 = v_2 = o_1^0 = o_2^0$	$o_1^1 = o_2^1$	Memory invariants	Read locs. invars ($\mathcal{O}$)
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Δ_1	No	2–7	–	$\cdots \wedge$ $v_1 =_i o_1$	$\cdots$
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Δ_e	No	return	–	$\cdots$	$\cdots$

Example proof of security

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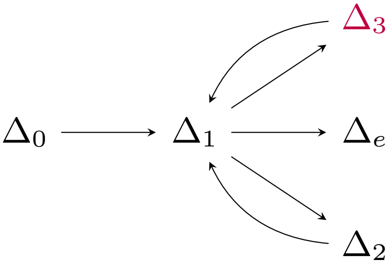

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Δ_2	Yes	3	7	$\cdots$	$\cdots$
Δ_3	Yes	7	3	$\cdots$	$\cdots$
Δ_e	No	return	–	$\cdots$	$\cdots$

A simple language with speculative semantics - Syntax

$$\mathsf{Exp} ::= \mathsf{Lit} \mid \mathsf{Var} \mid \mathsf{Exp\ Op\ Exp} \mid \ \ldots$$

$$\mathsf{BExp} ::= \mathsf{true} \mid \mathsf{false} \mid \mathsf{not\ BExp} \mid \ \ldots$$

$$\mathsf{Com} ::= \mathsf{Fence} \mid \mathsf{IfJump}\ \ \mathsf{BExp}\ \ \mathsf{pc}\ \ \mathsf{pc} \mid \ \mathsf{I/O} \ldots$$

A simple language with speculative semantics - State

Configuration:

- Program Counter
- Variable memory
- Array Memory
- Heap
- Pointer

Predictor:

- Mispred
- Resolve
- Update

Normal Semantics – (Config, InputBuffer, ReadLocations)

A simple language with speculative semantics - State

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- Update

Normal Semantics – (Config, InputBuffer, ReadLocations)

Speculative Semantics = *Normal Semantics* + **Predictor** + **Speculative Configs**

A simple language with speculative semantics - Semantics

STARTORFENCEOROUTPUT

$$\frac{c_{pc} \in \{\mathsf{Start}, \mathsf{Fence}\} \cup \{\mathsf{Output}_{och}\ e \mid e \in \mathsf{Exp}\}}{((pc, \mu), inp) \Rightarrow_B ((pc+1, \mu), inp)}$$

VARASSIGN

$$\frac{c_{pc} = (x = e)}{((pc, \mu), inp) \Rightarrow_B ((pc+1, \mu[x \leftarrow [\![e]\!](\mu)]), inp)}$$

AVARASSIGN

$$\frac{c_{pc} = (a[e] = e')}{((pc, \mu), inp) \Rightarrow_B ((pc+1, \mu[(a, [\![e]\!](\mu)) \leftarrow [\![e']\!](\mu)]), inp)}$$

INPUT

$$\frac{c_{pc} = (\mathsf{Input}_{ich}\ x) \qquad inp_{ich} = i \cdot is'}{((pc, \mu), inp) \Rightarrow_B ((pc+1, \mu[x \leftarrow i]), inp[ich \leftarrow is'])}$$

JUMP

$$\frac{c_{pc} = (\mathsf{Jump}\ pc')}{((pc, \mu), inp) \Rightarrow_B ((pc', \mu), inp)}$$

IFJUMP

$$\frac{\begin{array}{c} c_{pc} = (\mathsf{IfJump}\ b\ pc_1\ pc_2) \\ pc' = (\mathsf{if}\ [\![b]\!](\mu)\ \mathsf{then}\ pc_1\ \mathsf{else}\ pc_2) \end{array}}{((pc, \mu), inp) \Rightarrow_B ((pc', \mu), inp)}$$

A simple language with speculative semantics - Extended Semantics

IfJumpMispred

$$\frac{c_{pc} = (\mathsf{IfJump}\ b\ pc_1\ pc_2) \qquad pc' = (\mathsf{if}\ [\![b]\!](\mu)\ \mathsf{then}\ pc_2\ \mathsf{else}\ pc_1)}{((pc, \mu), inp) \Rightarrow_M ((pc', \mu), inp)}$$

Standard

$$\frac{\neg\,\mathsf{isCond}(cfg_k) \lor \neg\,\mathsf{mispred}(ps, pcs) \qquad (k > 0 \longrightarrow \neg\,\mathsf{isIOorFence}(cfg_k) \land \neg\,\mathsf{resolve}(ps, pcs)) \qquad (cfg_k, inp) \Rightarrow_B (cfg', inp') \qquad C' = cfg_0 \cdot \ldots \cdot cfg_{k-1} \cdot cfg' \qquad L' = L \cup \mathsf{readLocs}(cfg_k)}{(ps, cfg_0 \cdot \ldots \cdot cfg_k, inp, L) \Rightarrow_S (ps, C', inp', L')}$$

Mispred

$$\frac{\mathsf{isCond}(cfg_k) \qquad \mathsf{mispred}(ps, pcs) \qquad (cfg_k, inp) \Rightarrow_B (cfg', inp') \qquad (cfg_k, inp) \Rightarrow_M (cfg'', inp'') \qquad C' = cfg_0 \cdot \ldots \cdot cfg_{k-1} \cdot cfg' \cdot cfg'' \qquad L' = L \cup \mathsf{readLocs}(cfg_k)}{(ps, cfg_0 \cdot \ldots \cdot cfg_k, inp, L) \Rightarrow_S (\mathsf{update}(ps, pcs), C', inp', L')}$$

Resolve

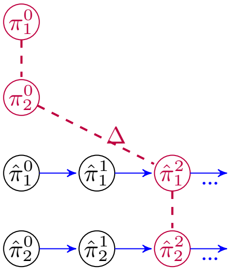
$$\frac{k > 0 \qquad \mathsf{resolve}(ps, pcs) \qquad C' = cfg_0 \cdot \ldots \cdot cfg_{k-1}}{(ps, cfg_0 \cdot \ldots \cdot cfg_k, inp, L) \Rightarrow_S (\mathsf{update}(ps, pcs), C', inp, L)}$$

Fence

$$\frac{k > 0 \qquad \neg\,\mathsf{resolve}(ps, pcs) \qquad \mathsf{isFence}(cfg_k)}{(ps, cfg_0 \cdot \ldots \cdot cfg_k, inp, L) \Rightarrow_S (pcs, cfg_0, inp, L)}$$

A problem with infinite traces

What if the player makes infinite independent steps?



Joseph A. Goguen and José Meseguer. Unwinding and inference control. In *IEEE Symposium on Security and Privacy*, pages 75–87, 1984.

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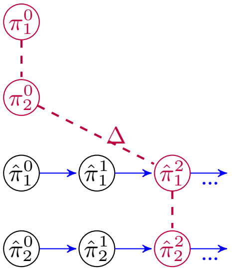

We include a timer in our unwinding which decreases with every proactive step (and resets to ∞ when reacting)

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