SemPat: From Hyperproperties to Attack Patterns for Scalable Analysis of Microarchitectural Security

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Example: Spectre V1 (BCB) Vulnerability

out-of-bound index i

```
void victimA (uint32_t i) {
  if (i < ARR_SIZE)
    temp_ = arr2[arr1[i] << CL_INDEX];
}
```

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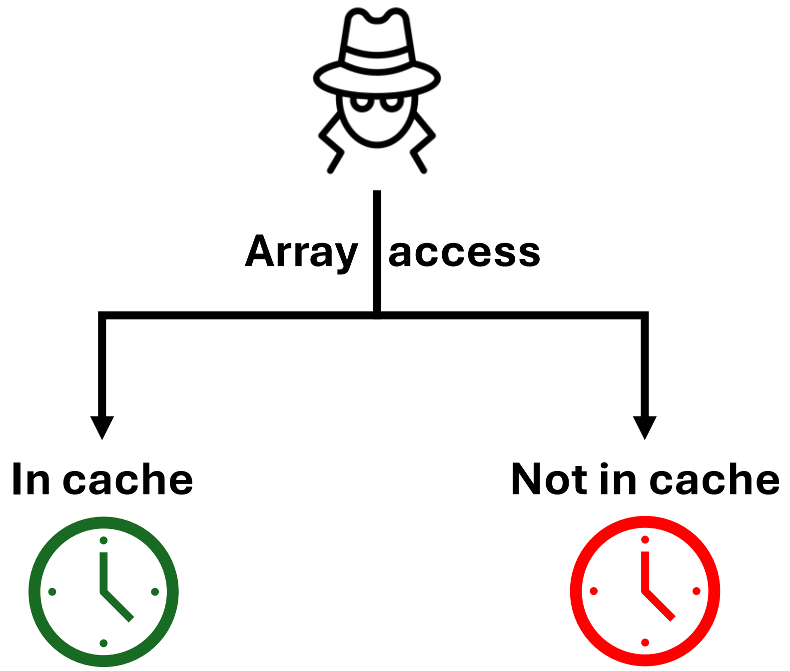

Cache-based timing side-channel

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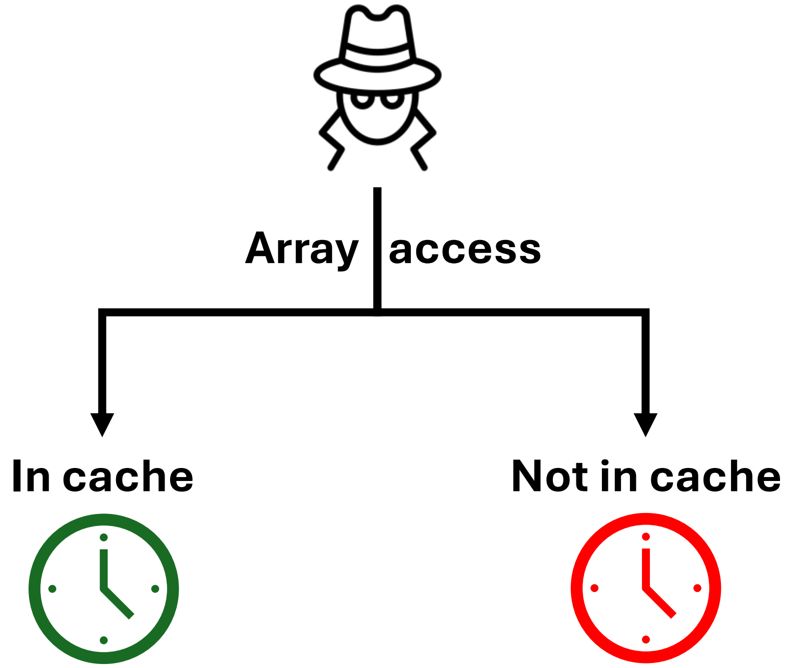

Cache-based timing side-channel

SW-verification for microarchitectural security:
Is SW program susceptible to such attacks?

Two approach classes from previous work

Pattern-based

```
void victimA (uint32_t i) {

  if (i < ARR_SIZE) {

    temp1_ = arr1[i];

    temp_ = arr2[temp1_ << CL_INDEX];

  }
}
```

speculation

dependent load address

e.g., Ponce de Leon [S&P 2023],
Mosier et. al. [ISCA 2022]

Noninterference-based

Precondition: Φ_{pre}

```
void victimA (uint32_t i) {
  if (i < ARR_SIZE)
    temp_ = arr2[arr1[i] << CL_INDEX];
}
```

Postcondition: Φ_{post}

e.g., Cheang et. al. [CSF 2019],
Guarneri et. al. [S&P 2020]

This work: convert from NI to patterns

Pattern-based

```
void victimA (uint32_t i) {

  if (i < ARR_SIZE) {

    temp1_ = arr1[i];

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speculation

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This work

Noninterference (NI)-based

Precondition: Φ_{pre}

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 victimA (uint32_t i) {
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Pattern-based Analysis

```
void victimA (uint32_t i) {
  if (i < ARR_SIZE)
    temp_ = arr2[arr1[i] << CL_INDEX];
}
```

```
.victimA:
  ...
  bltu a5,a4,66004;  A1:Branch
                        ↓ spec.
  ...
  lw a5,a5,0;         A2:Load
                        ↓ addr. dep.
  ...
  lw a4,a5,0;         A3:Load
  ...
66004:  ←——— architectural
```

Execution embeds the pattern

A1:Branch —speculative→ **A2:Load** —address dependency→ **A3:Load**

Gadget variant

Variant

```
void victimA (uint32_t i) {
  if (i < ARR_SIZE)
    temp_ = arr2[arr1[i] << CL_INDEX];
}
```

```
void victimB (uint32_t i) {
  uint32_t temp1_ = arr1[i];
  if (i < ARR_SIZE)
    temp_ = arr2[temp1_ << CL_INDEX];
}
```

Embeds

Variant execution does not embed!

A1:Branch —speculative→ **A2:Load** —address dependency→ **A3:Load**

Gadget variant needs a new pattern

Patterns do not generalize well

Variant

```
void victimA (uint32_t i) {
  if (i < ARR_SIZE)
    temp_ = arr2[arr1[i] << CL_INDEX];
}
```

```
void victimB (uint32_t i) {
  uint32_t temp1_ = arr1[i];
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Embeds

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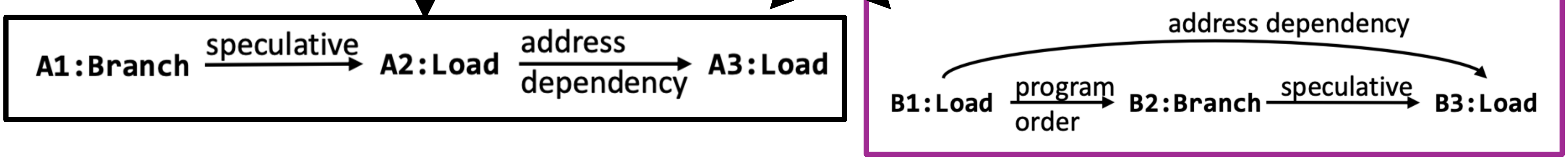
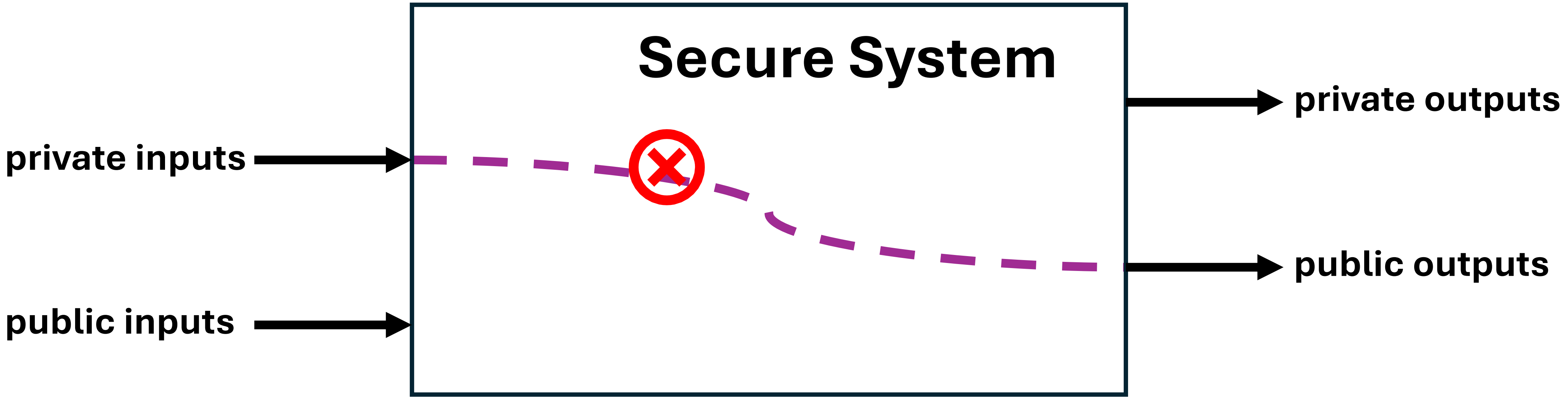


New pattern

Hyperproperty-based Analysis

Hyperproperties formally characterize semantic security

Non-interference (NI)/information-flow-control: *secret inputs do not affect public (observable) outputs*



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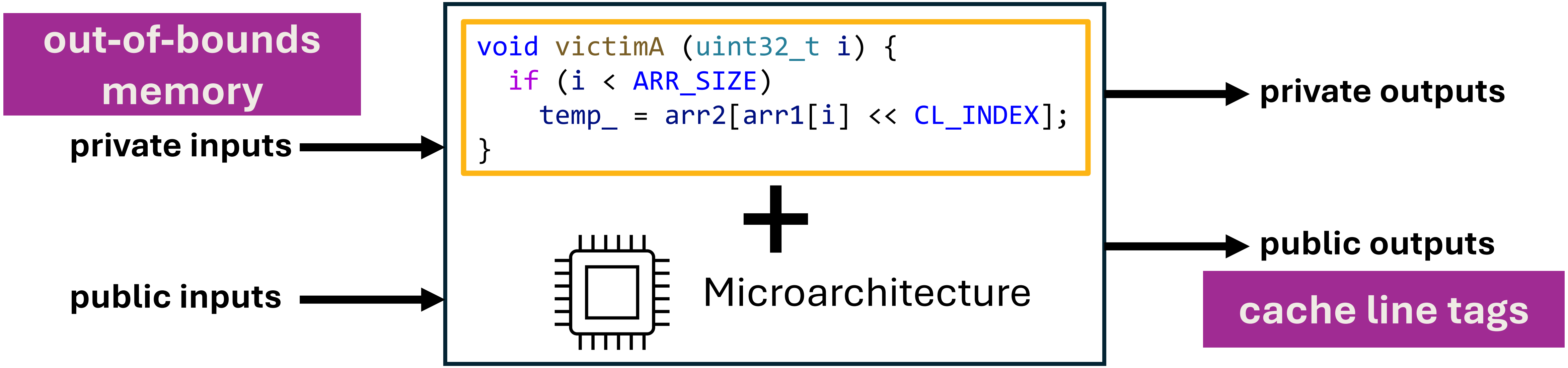

Same non-interference property applies to both variants

```
void victimA (uint32_t i) {
  if (i < ARR_SIZE)
    temp_ = arr2[arr1[i] << CL_INDEX];
}
```

Variant

```
void victimB (uint32_t i) {
  uint32_t temp1_ = arr1[i];
  if (i < ARR_SIZE)
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}
```
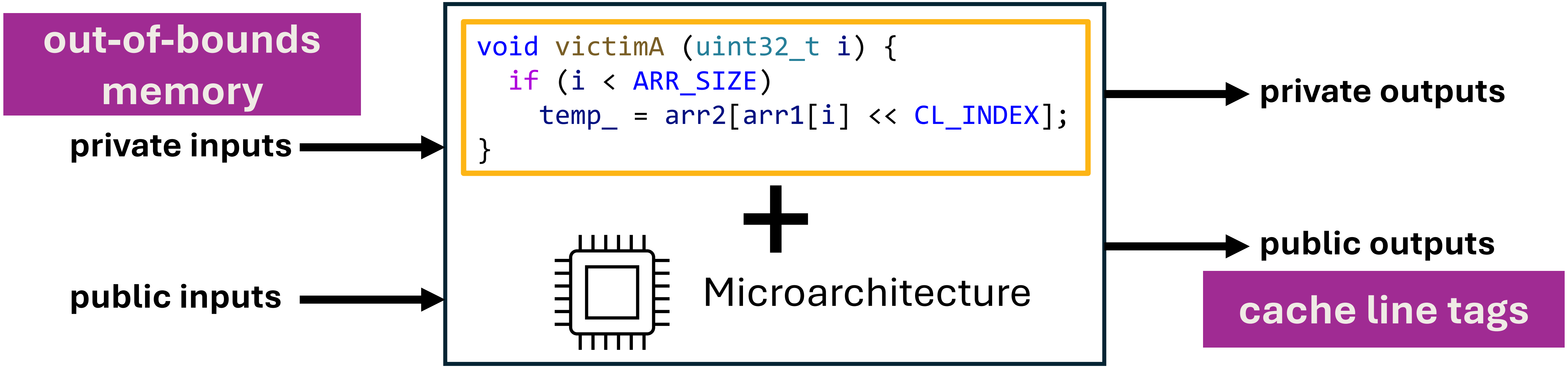



Motivation: Orthogonal Advantages

Approach	Pattern-based	Noninterference-based
Pros	Simpler ***verification*** queries, scalable	Uniform ***specification***, Robust
Cons	Sensitive to gadget structure	Scalability

Can we combine specification benefits of hyper-properties and scalable verification of patterns?

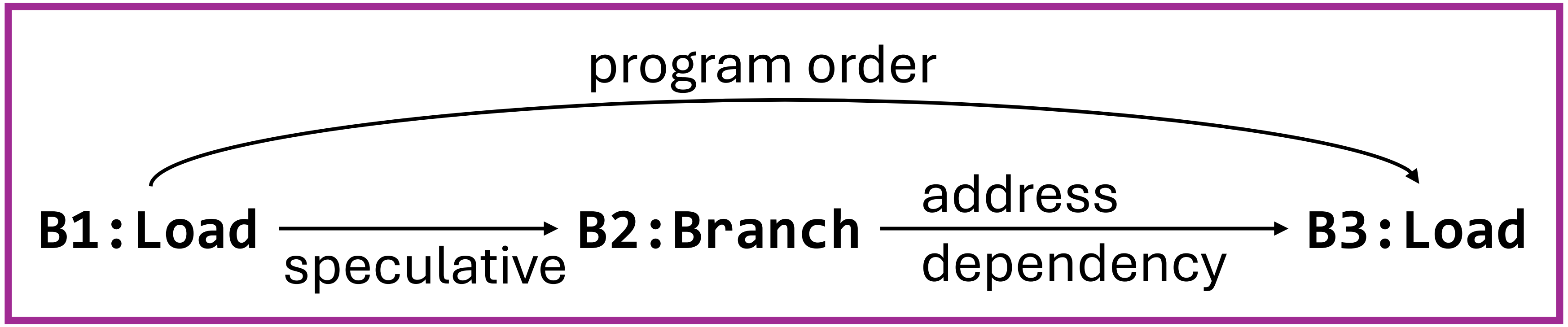
Contributions

- ***k*-completeness condition**: set of patterns covering all non-interference violations up to a size bound *k*
- **Pattern generation algorithm**: grammar-based search to produce a ***k*-complete set** of patterns
- **Evaluation:** (a) scalable pattern generation: **new patterns**, (b) verification: upwards of **100x** improvement over hyperproperties (for models considered)

Outline

- **Problem Formulation**
  - **Pattern Definition**
  - Pattern Generation Problem
- Pattern Generation Approach
- Theoretical Guarantee
- Implementation and Evaluation

A pattern is a pair (*w*, ϕ)



Pattern template (opcode sequence): *w*

(1: Load) -- (2: Branch) -- (3: Load)

A boolean formula constraint: ϕ

addrdep ((1: Load), (3: Load)) && speculative ((2: Branch))

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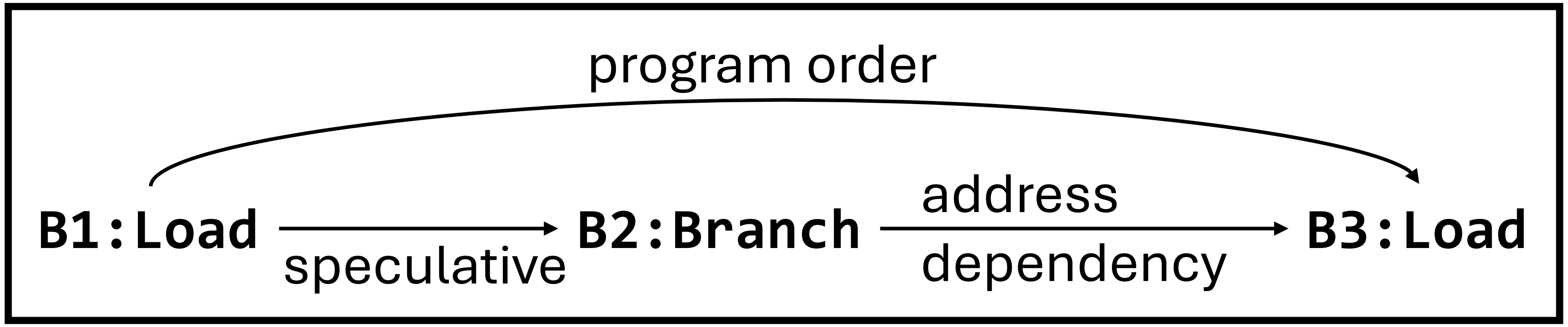

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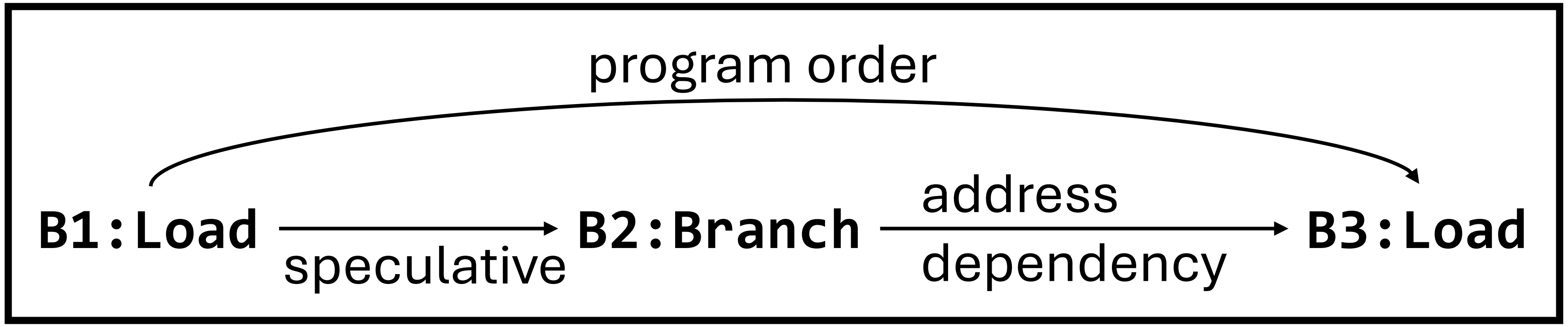


Pattern template (opcode sequence): *w*

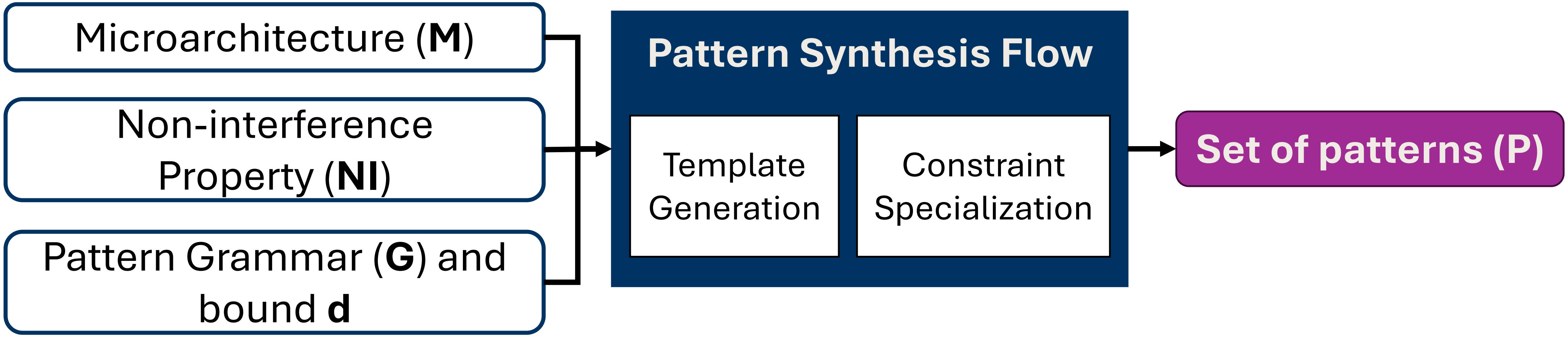
(1: Load) -- (2: Branch) -- (3: Load)

constraint is a conjunction of predicates: p1 && p2 && p3 ...

A boolean formula constraint: ϕ

addrdep ((1: Load), (3: Load)) && speculative ((2: Branch))

Pattern Generation Problem



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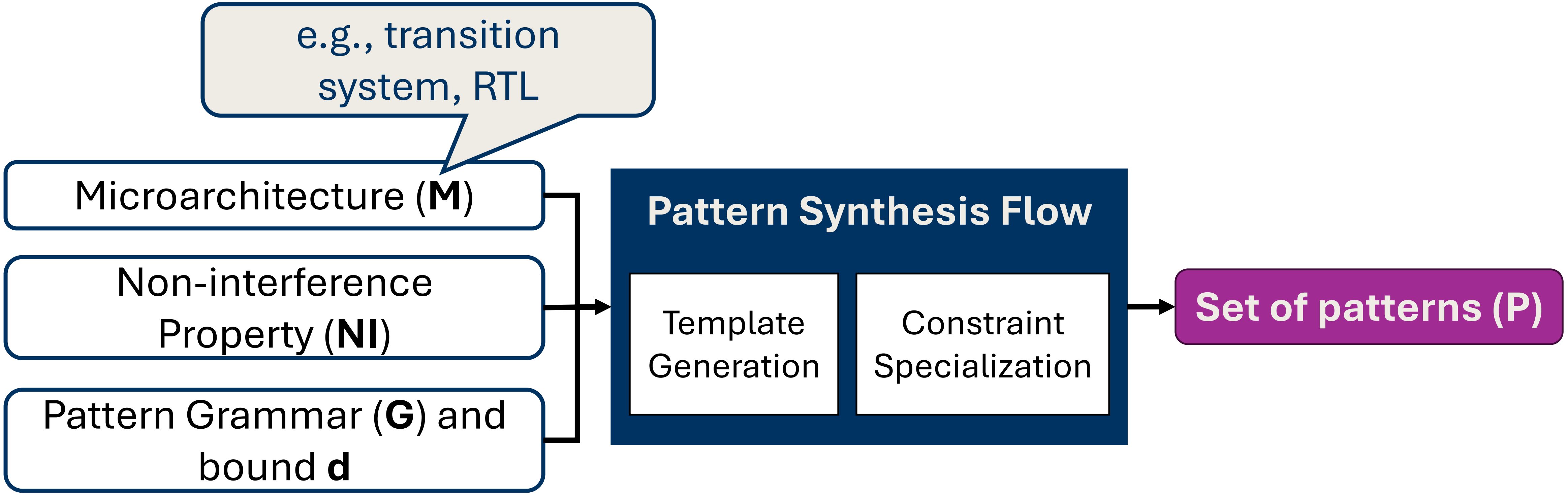

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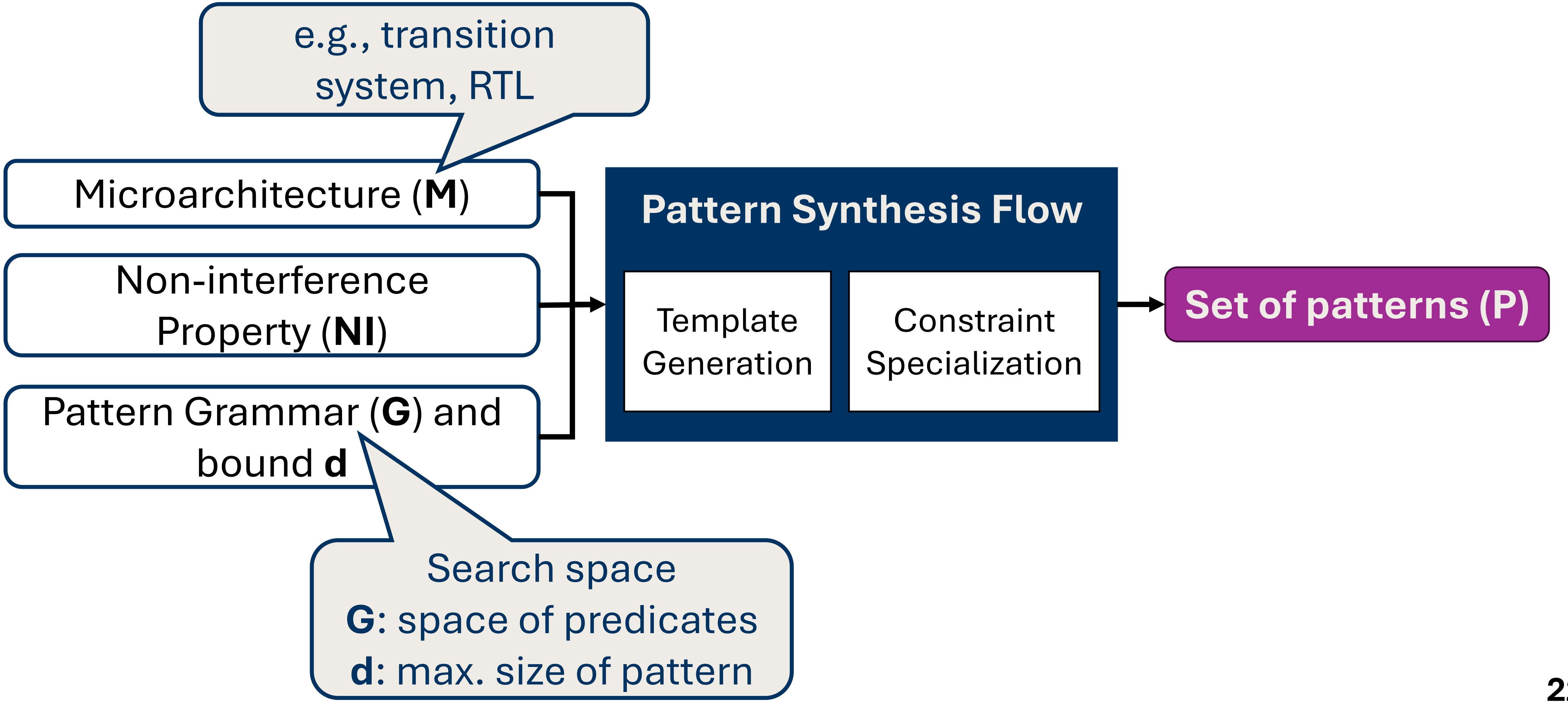

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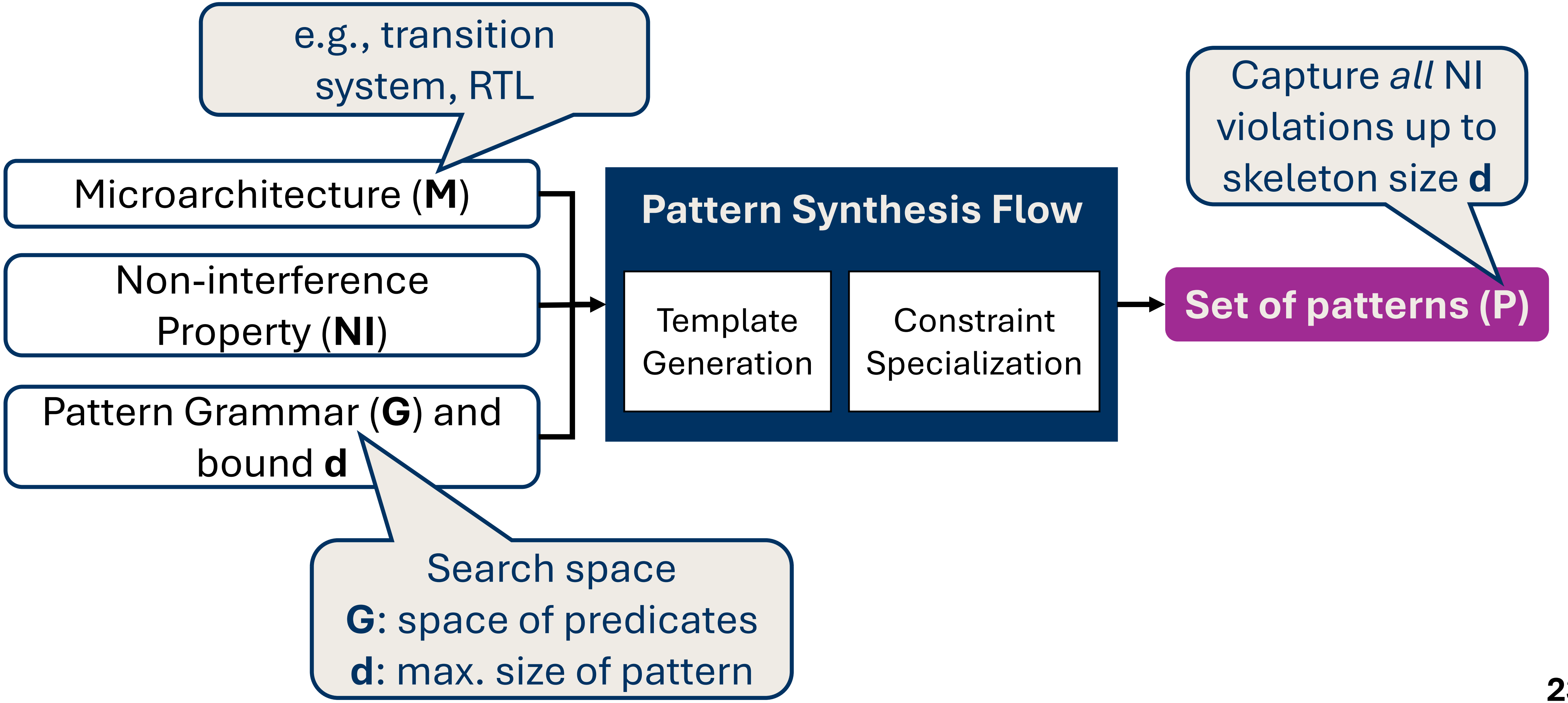

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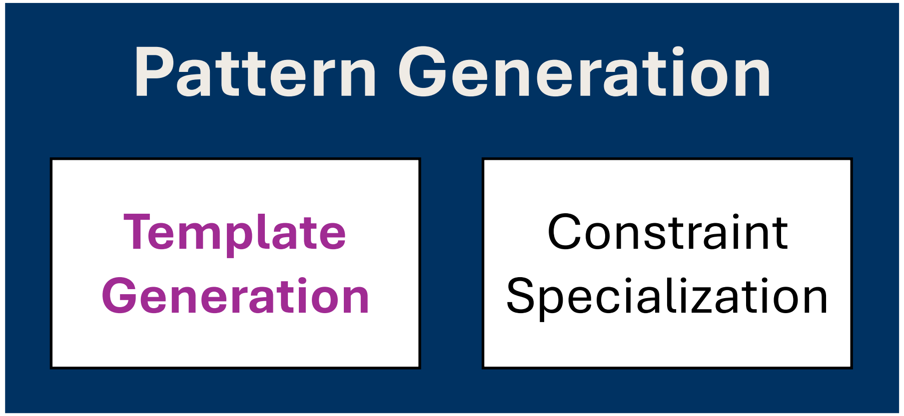
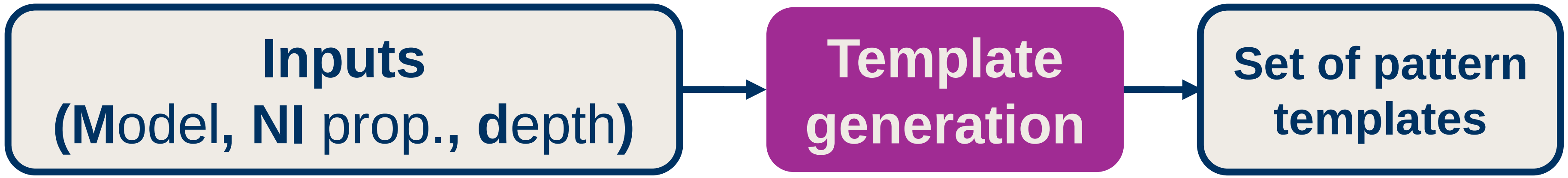
  - **Template Generation**
  - Constraint-based Specialization
- Theoretical Guarantee
- Implementation and Evaluation



1. Template Generation



Collect all depth **d** templates (opcode seq.) which falsify the **NI** property

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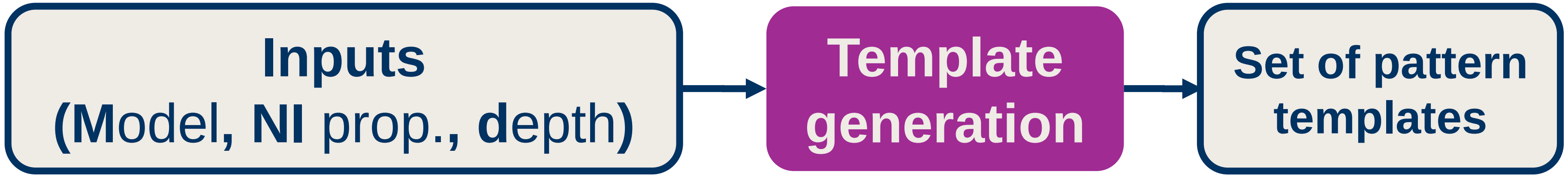

Collect all depth **d** templates (opcode seq.) which falsify the **NI** property

```
add-add-add          : SAFE
add-add-sub          : SAFE
add-add-load         : SAFE
           ...
branch-load-load     : UNSAFE
```

1. Template Generation

Inputs (Model, NI prop., depth) → **Template generation** → **Set of pattern templates**

Collect all depth **d** templates (opcode seq.) which falsify the **NI** property

```
add-add-add        : SAFE
add-add-sub        : SAFE
add-add-load       : SAFE
              ...
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```

Too overapproximate: add constraints to reduce false positives

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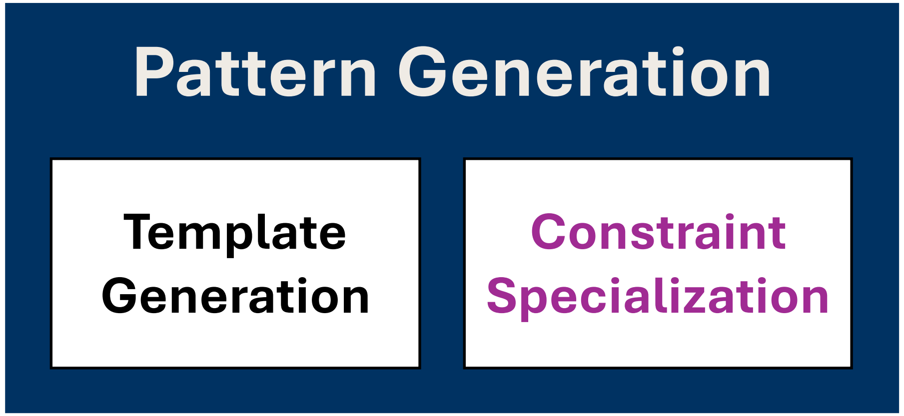

2. Constraint Specialization

Add constraints to make the template precise (reduce false positives)

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Constraints are sourced from a predicate grammar

Predicate Atom	Meaning
datadep(inst1, inst2)	Data dependency between inst1 and inst2
addrdep(inst1, inst2)	Address dependency
…	…
speculative(inst)	Instruction inst executes speculatively
highoperand(inst)	Instruction operand is secret dependent
…	…

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Add constraints to make the template precise (reduce false positives)

```
1.br-2.load-3.load :: true
```

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2. Constraint Specialization

Add constraints to make the template precise (reduce false positives)

`1.br-2.load-3.load :: true`

`1.br-2.load-3.load :: addrdep(`*`2.load, 3.load`*`)`

`1.br-2.load-3.load ::` **addrdep(*2.load*,*3.load*) && *spec(1.br)***

2. Constraint Specialization

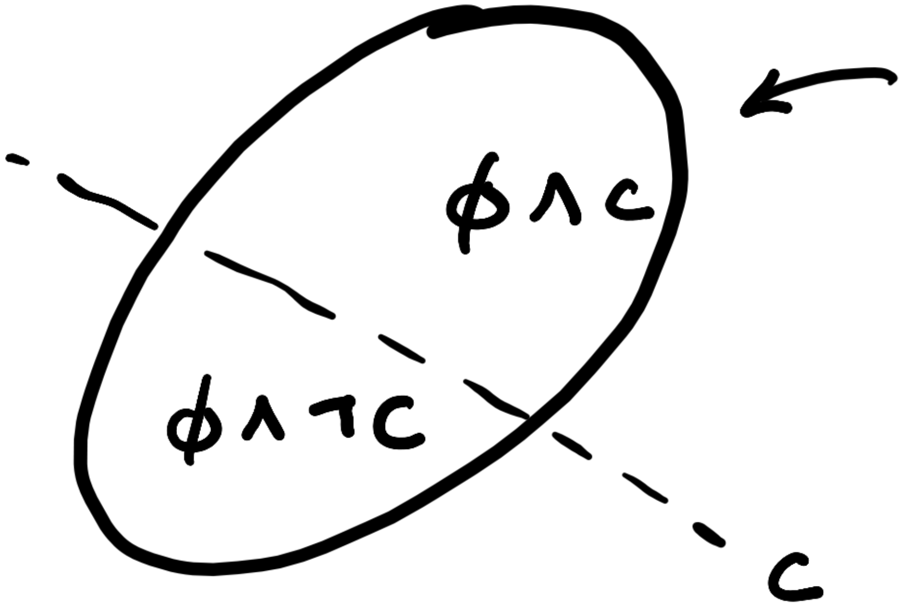
Add constraints to make the template precise (reduce false positives)

How do we add constraints without missing non-interference violations?

Counterfactual atom addition

(Adding constraints without missing non-interference violations)

Should we specialize a pattern (w, ϕ) further by adding constraint *c*?



Executions matching pattern (w, ϕ)

Counterfactual atom addition

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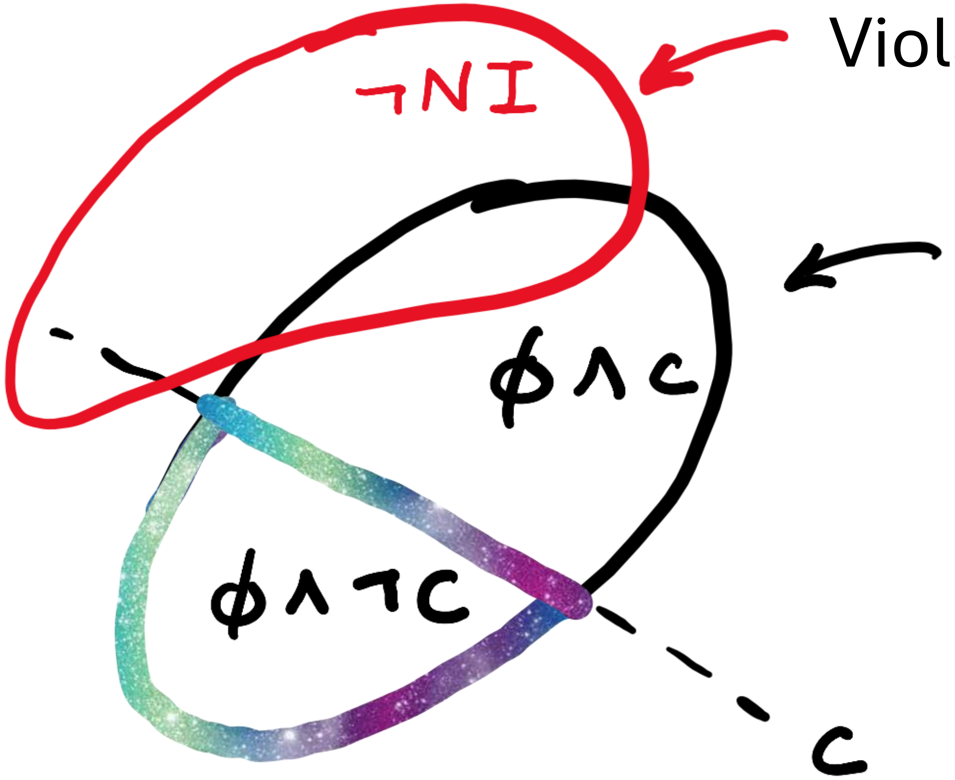

Violations of non-interference

Executions matching pattern (w, ϕ)

Safe to add *c*, when  and  do not overlap.

Can be cast as a SAT/SMT problem!

2. Constraint Specialization

Constraint-based specialization: high level procedure

For (atom in candidates):

If (adding counterfactual(atom) is SAFE)

Add atom

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- Problem Formulation
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- **Theoretical Guarantee**
- Implementation and Evaluation

Theoretical Guarantee

Program C has a violation of **skeleton size *k* if**
C has a dependency-closed sub-sequence of *size* <= *k* that violates NI

$$C \not\models_k \mathrm{NI}(\Sigma_{\mathrm{init}}, \mathrm{V}_{\mathrm{pub}}, \mathrm{V}_{\mathrm{obs}})$$

Theoretical Guarantee

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Generated patterns

$$\forall C.\ C \not\models_k \mathrm{NI}(\Sigma_{\mathrm{init}}, \mathrm{V}_{\mathrm{pub}}, \mathrm{V}_{\mathrm{obs}}) \implies \exists \mathrm{p} \in \mathrm{P}.\ C \models \mathrm{p}$$

"If C has a small skeleton, some pattern in P will catch violation"

Outline

- Problem Formulation
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- **Implementation and Evaluation**

Evaluation

- Implementation: prototype tool SECANT (with UCLID5 [1] backend)
  - Scala-embedded model specification DSL
  - Pattern generation and verification engines

[1] Polgreen, et. al. UCLID5: Multi-modal Formal Modeling, Verification, and Synthesis. CAV 2022.

Evaluation

- Implementation: prototype tool SECANT (with UCLID5 [1] backend)
  - Scala-embedded model specification DSL
  - Pattern generation and verification engines

- Evaluation on 3 abstract microarchitecture models:
  - Silent Stores
  - Dynamic Instruction Reuse
  - Branch/STL Speculation

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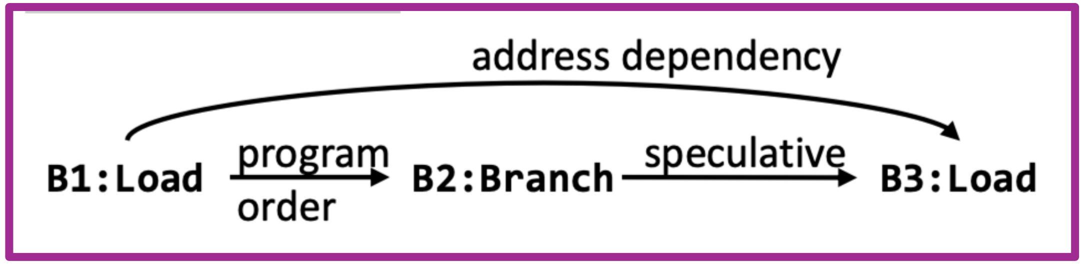
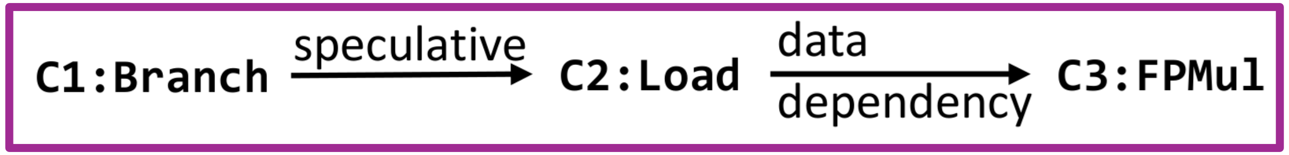
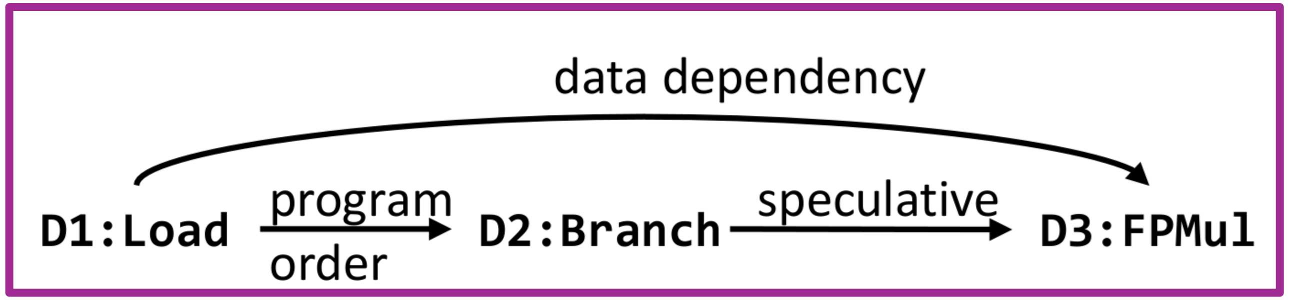
Results: New Patterns

Spectre BCB+Cache:

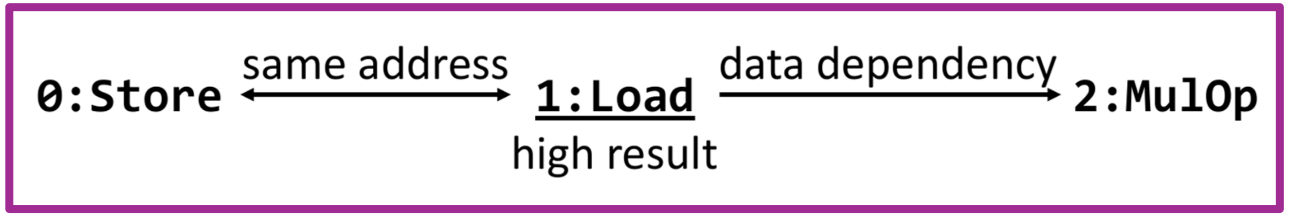


Spectre BCB+CR:





Spectre STL+CR:



Results: Improved Verification Performance

Modified Kocher's BCB/STL tests:

Replaced cache-based side channel with a computation-based side channel.

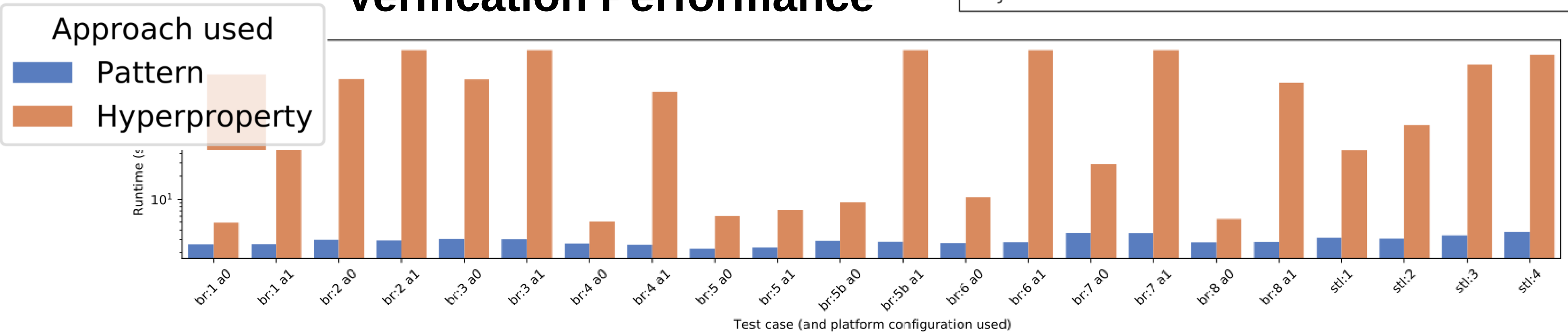
Spectre BCB

```
  void test1 (uint64_t idx) { // INSECURE
    // Bounds-check-bypass
    if (idx < publicarray_size)
-     temp &= publicarray2[publicarray[idx]*512];
+     temp &= publicarray[idx] * SCALAR;
  }
```

Spectre STL

```
  void test2 (uint32_t idx) { // INSECURE
    idx = idx & (publicarray_size - 1);
    /* Access overwritten secret */
-   temp &= publicarray2[publicarray[idx] * 512];
+   temp &= publicarray[idx] * SCALAR;
  }
```

Verification Performance



Results: Improved Verification Performance

Modified Kocher's BCB/ST

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with a computation-based

- **~100x improvement, increases with test size**

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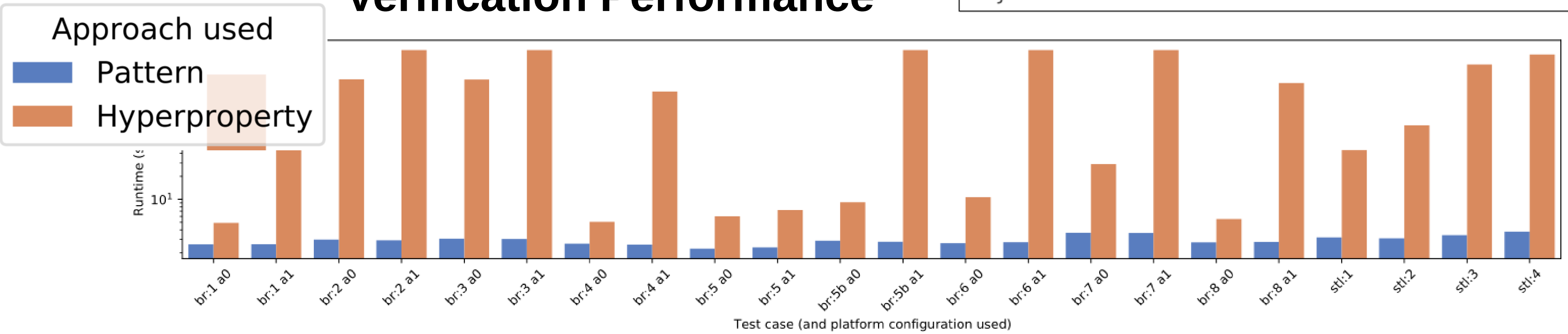

Results: Improved Verification Performance

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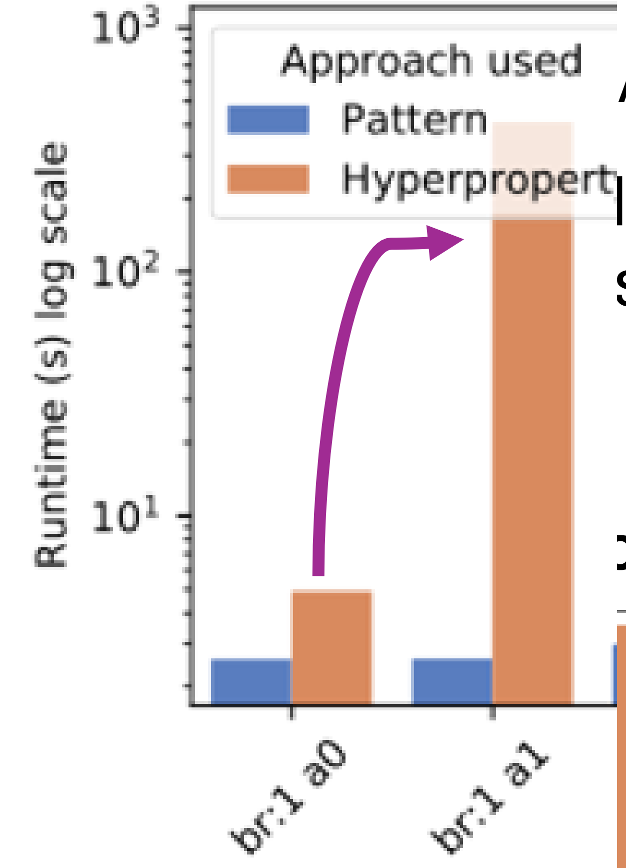
- ~100x improvement, increases with test size
- Microarchitectural complexity affects hyperproperty but not pattern runtime



on Performance

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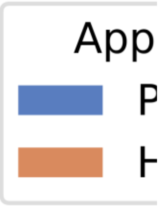
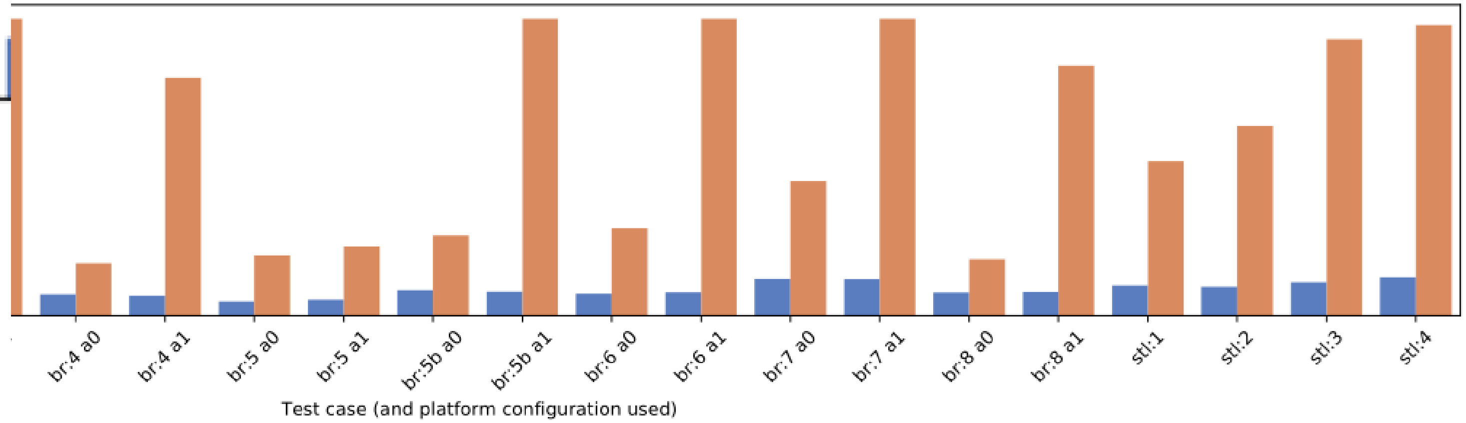
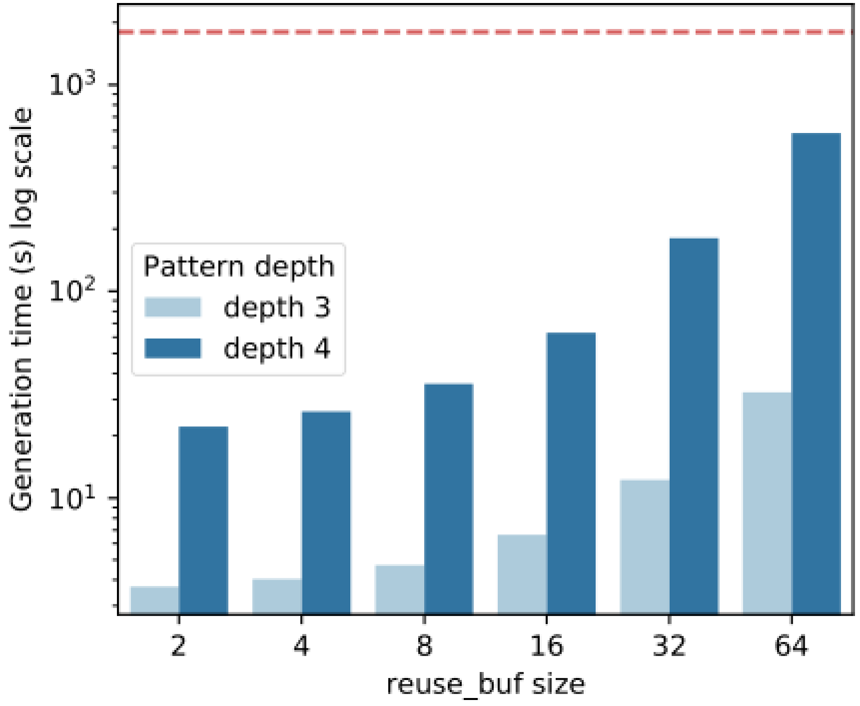
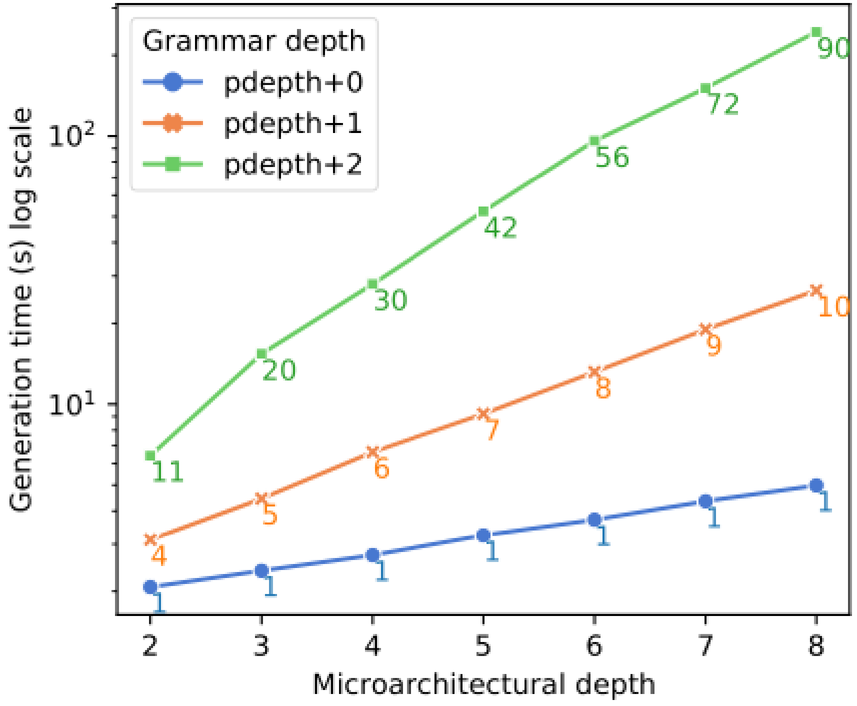




Results: Scalability of Generation

With microarchitectural complexity and grammar depth





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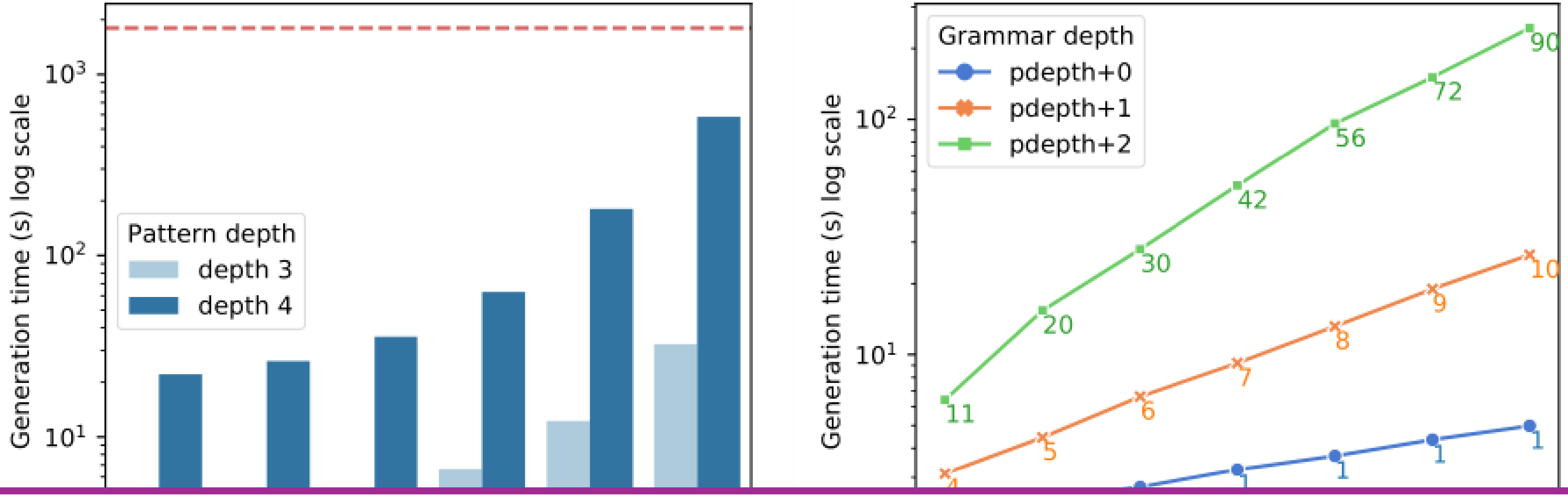
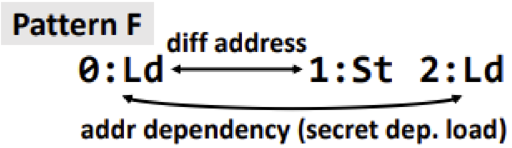


- Exponential scaling in microarch. parameters and depth
- Reasonable for abstract models
- Future work: Evaluate performance with RTL designs

Results: False positives

Patterns are prone to false positives




```
void test_K (uint32_t idx) {
  // Address (A) = (arr1+idx)
  _temp = arr1[idx];     // Ld0: LSQC Index = A[SET_W+1:2]
  arr1[idx+(1<<K)] = 0; // St0: LSQC Index = (A+(1<<K))[SET_W+1:2]
  _temp1 = arr2[_temp]; // Ld1
}
```

Check	Result with test_K (Fig. 14) and SET_W set index	
	$K > SET\_W + 2$	$K \leq SET\_W + 2$
Hyperproperty	SAFE	UNSAFE
Pat. F	UNSAFE	UNSAFE

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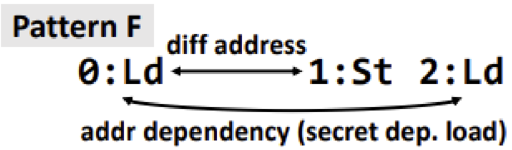

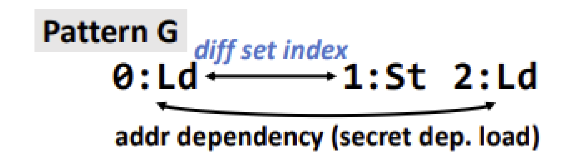


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Hyperproperty	SAFE	UNSAFE
Pat. F	UNSAFE	UNSAFE
Pat. G	SAFE	UNSAFE

Grammar exposes a precision-complexity tradeoff

Takeaways

Motivation: extend formal guarantees from hyperproperties to patterns

Generation Approach: template exploration + grammar-based counterfactual constraint addition

Results: new patterns, order of magnitude verification runtime improvement, pattern-grammar tradeoff

SemPat: From Hyperproperties to Attack Patterns for Scalable Analysis of Microarchitectural Security. Adwait Godbole, Yatin A. Manerkar, Sanjit A. Seshia. ACM CCS 2024. Salt Lake City, UT.

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Questions?