

Speculative Data-Oblivious Execution: Mobilizing Safe Prediction For Safe and Efficient Speculative Execution

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Speculative Execution Attacks

- Attacker exploits **speculative execution** to leak data through hardware usage

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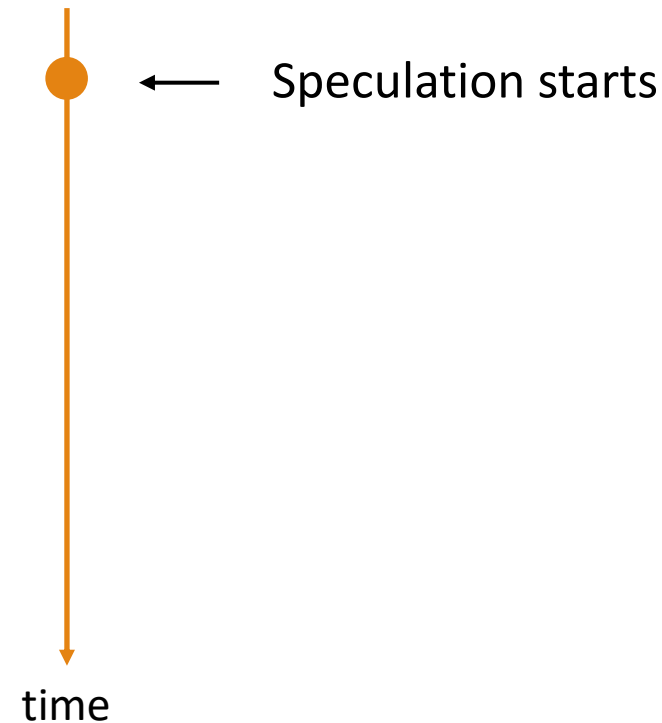
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    // access instruction
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```
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    // transmit instruction
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    transmit secret;
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}
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Speculative Execution Attacks

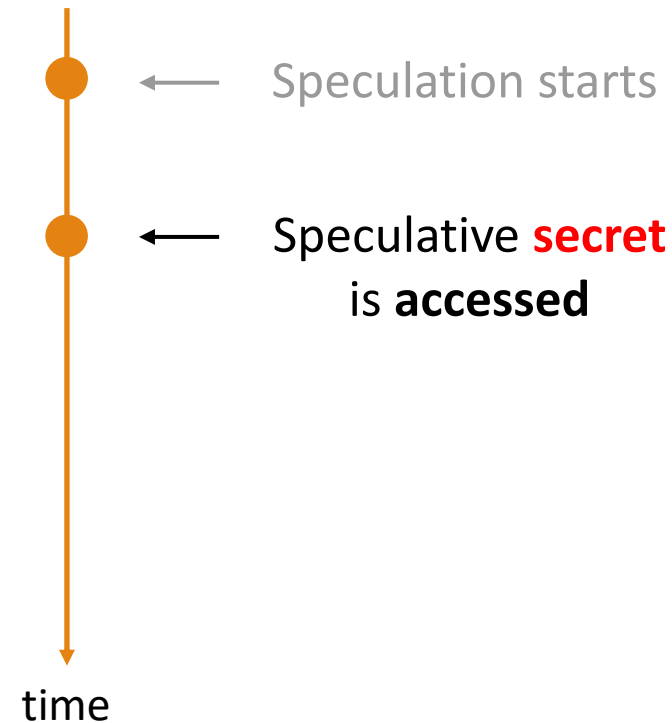
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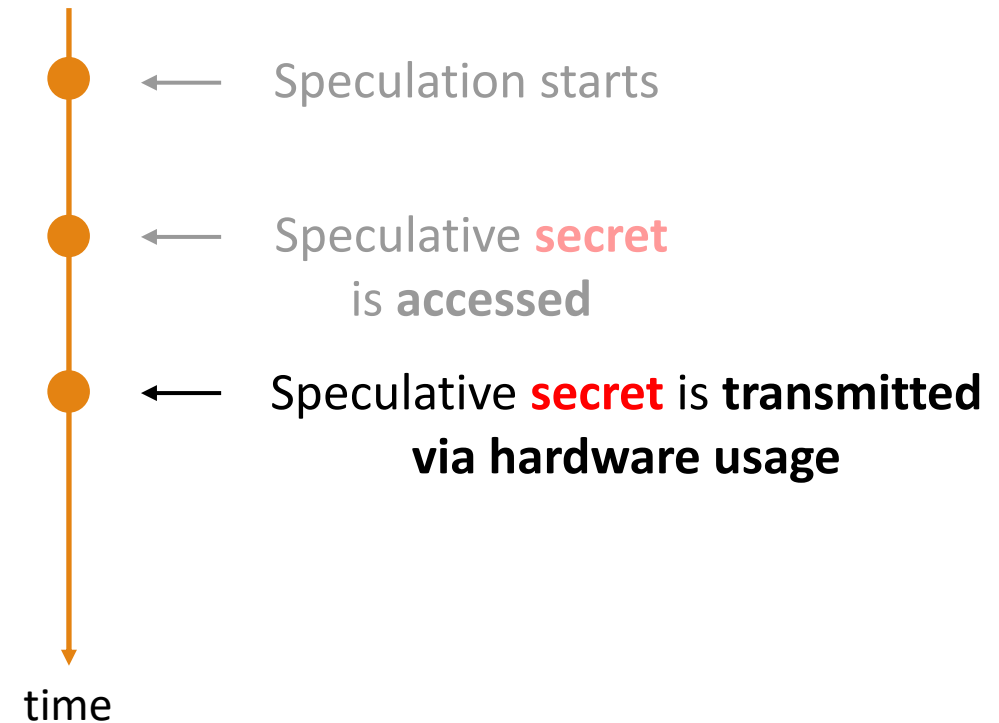
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Speculative Execution Attacks

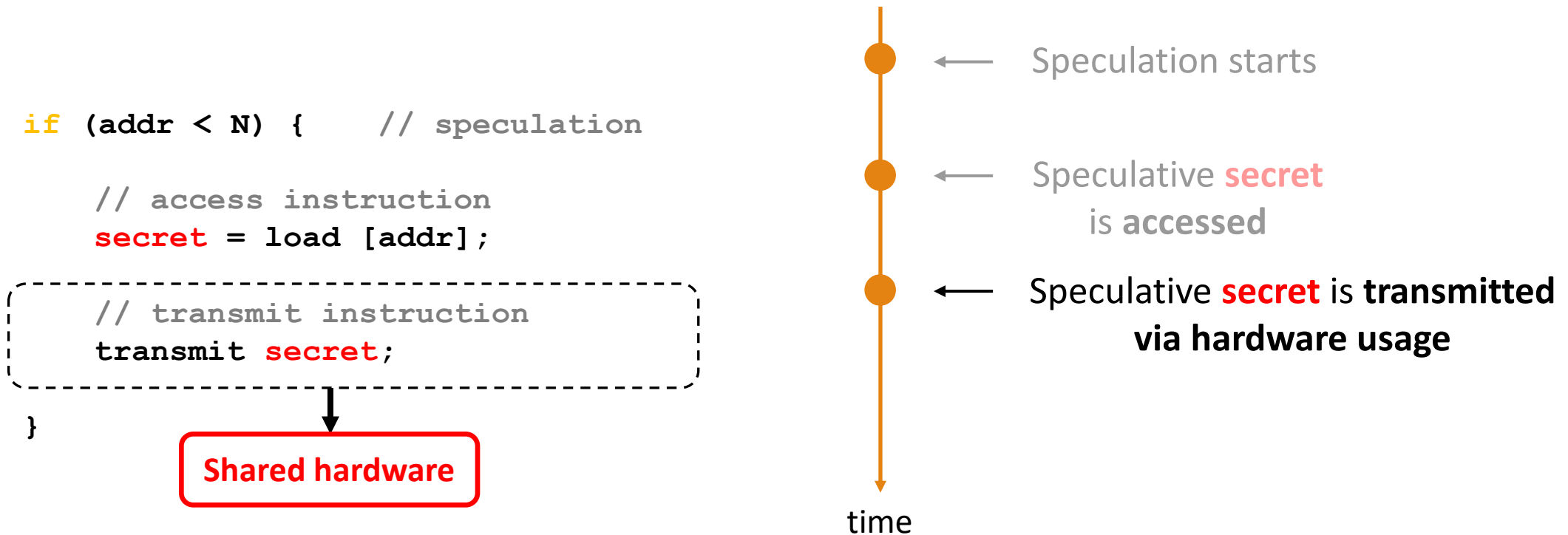
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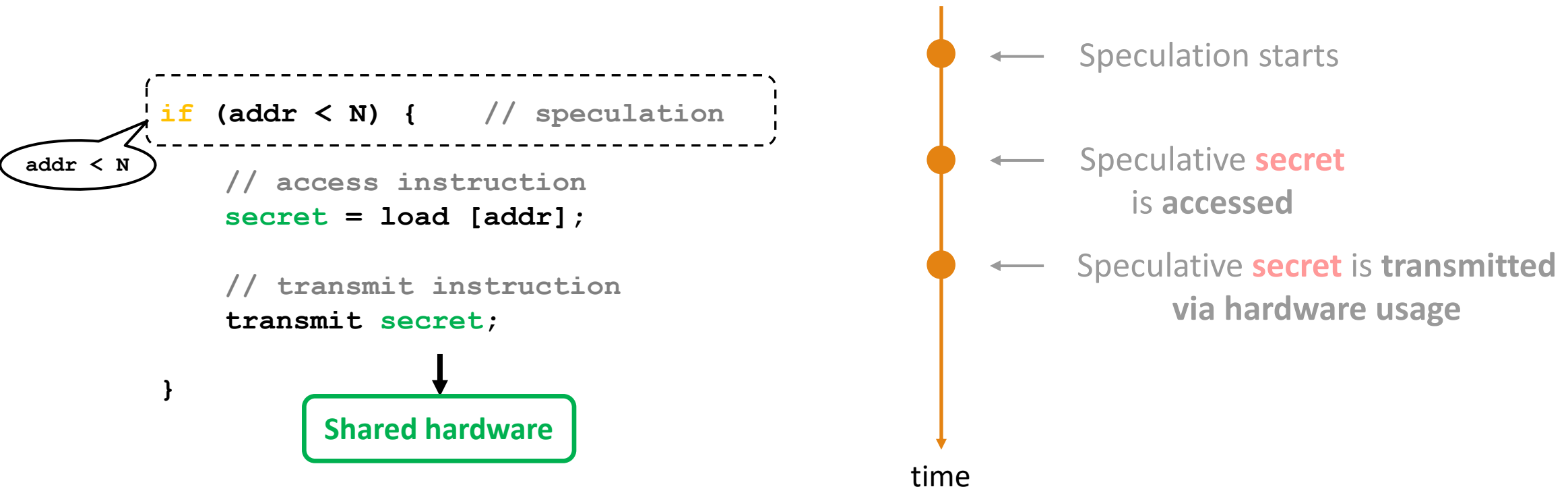
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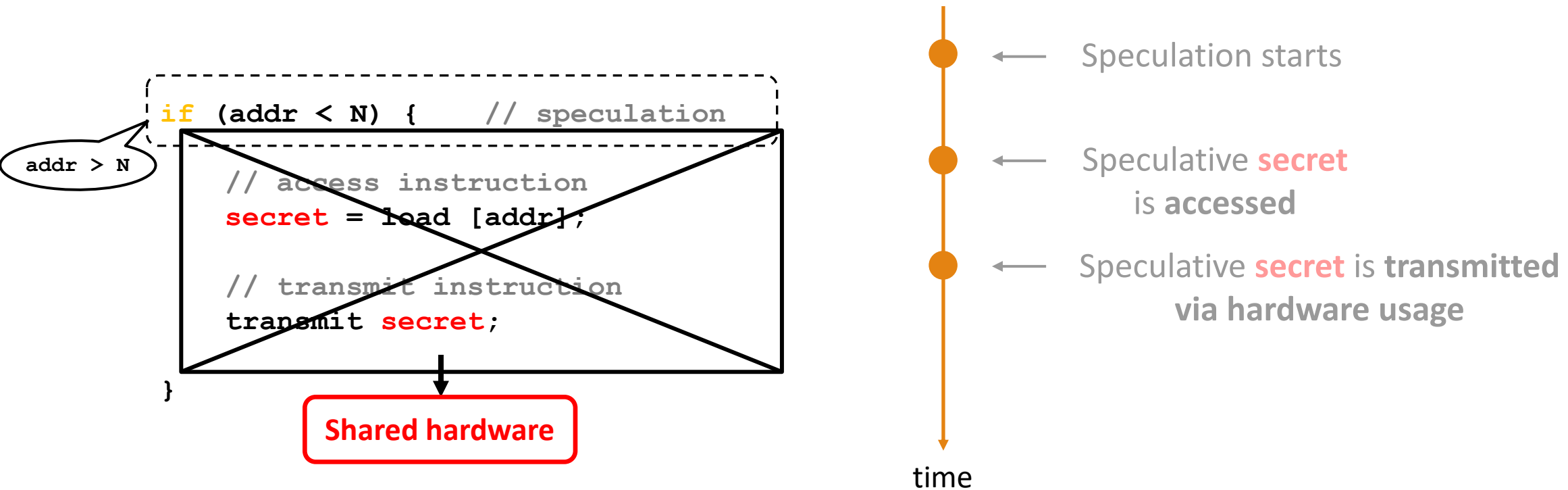
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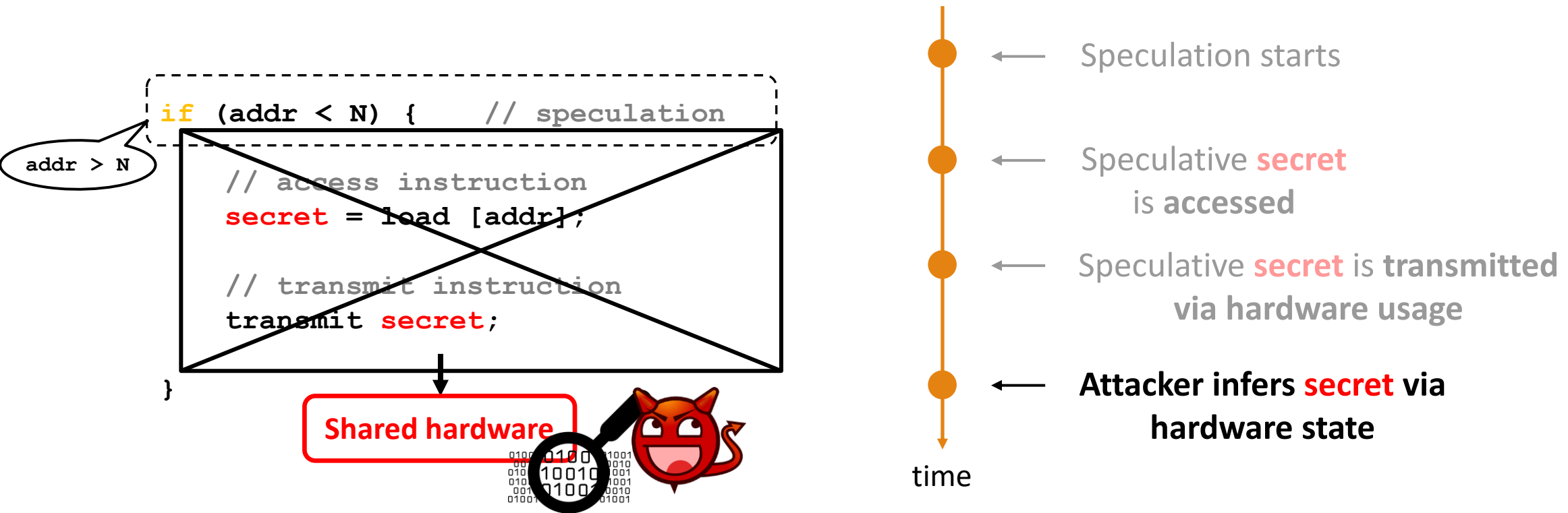
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→ Delaying execution

```
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Existing Mitigations

- How to deal with `transmit secret` ?
- Solution: Delayed Execution
 - Prior works: SpecShield [PACT'19], NDA [MICRO'19], STT [MICRO'19]
- Strong security guarantee
- High performance overhead

Transmit instruction	Hardware vulnerability
load	Cache side channel
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.....



Existing Mitigations

- How to deal with `transmit secret` ?

Register File

Improve the **performance** of *Delayed Execution*
and
Maintain its **security** guarantee

it

3

Speculative Data Oblivious (SDO): Executive Summary

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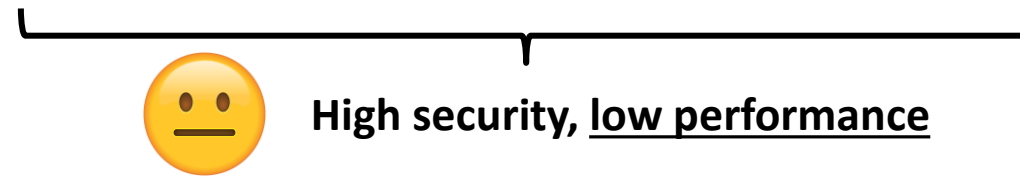
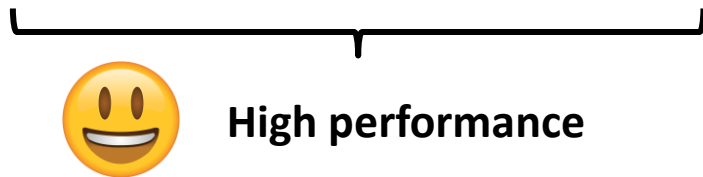
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Speculative Data Oblivious (SDO): Executive Summary

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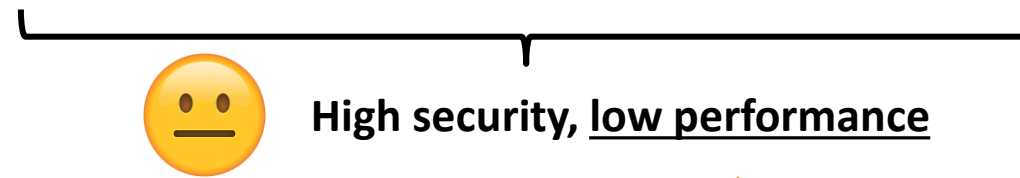
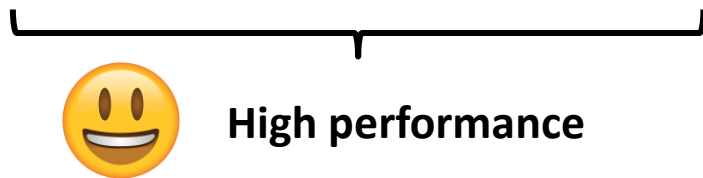
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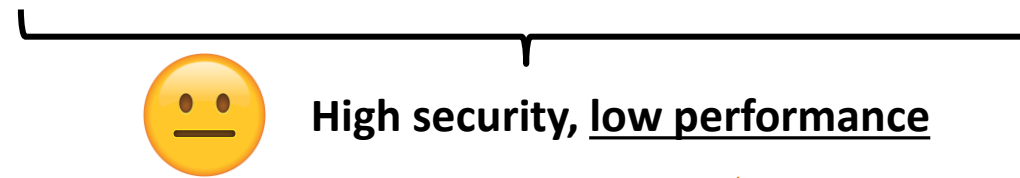
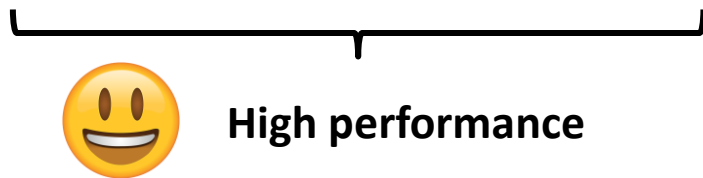
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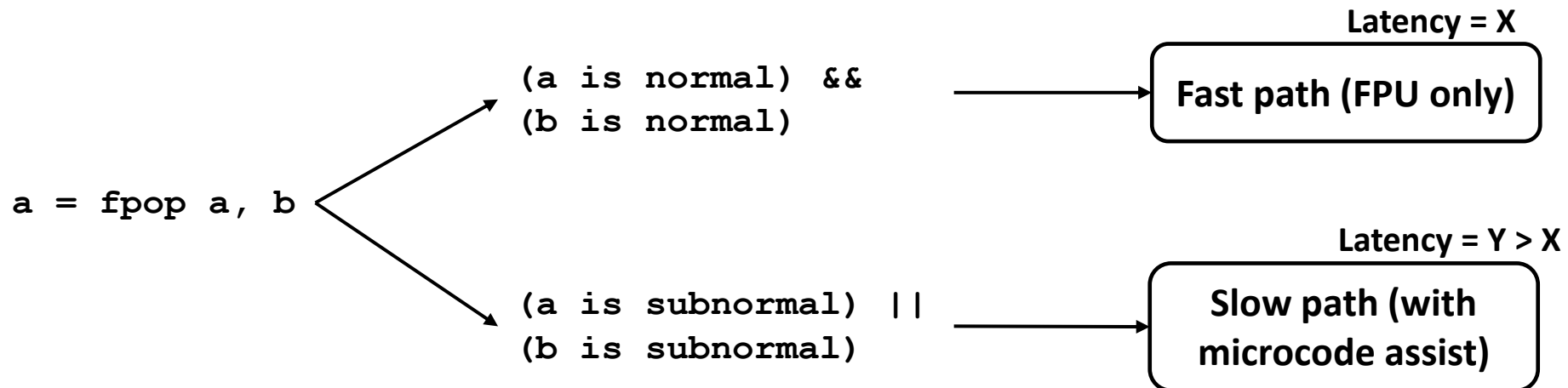


Problem: combining idea 1 & 2 creates security problems

Solution: build on top of Speculative Taint Tracking (STT)

Example: Subnormal Floating-point Operation

- Double-precision floating point
 - Normal input: (2.23e-308, 1.79e308), processed by Floating-Point Unit (FPU)
 - Subnormal input: (4.9e-324, 2.23e-308), requiring microcode assist



Problem: Leaking Whether Input is Normal/Subnormal

```
// owned by victim  
a = fpmult a, b
```

```
// owned by attacker  
c = fpmult c, d
```

Latency = X

Fast path (FPU only)

Latency = Y > X

Slow path (with
microcode assist)

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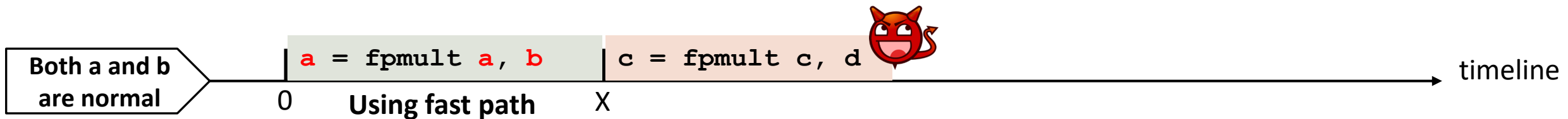
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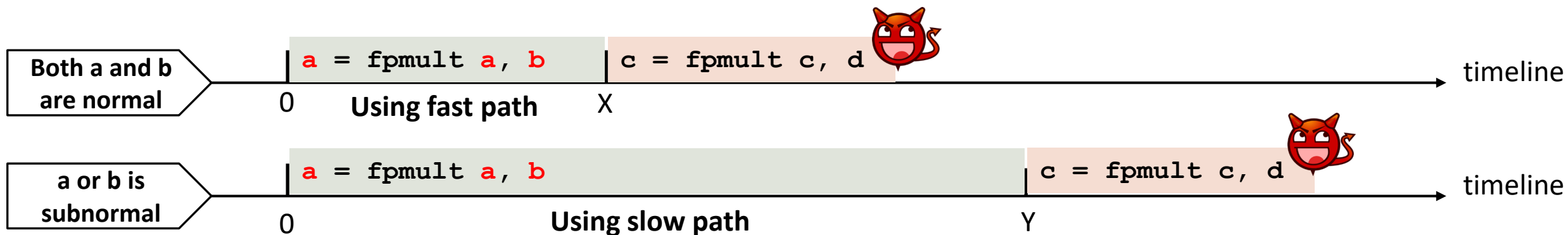
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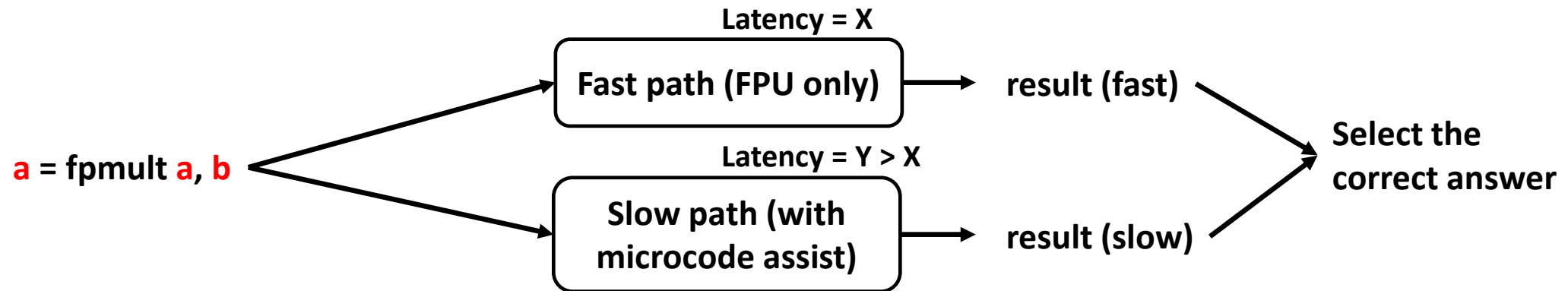
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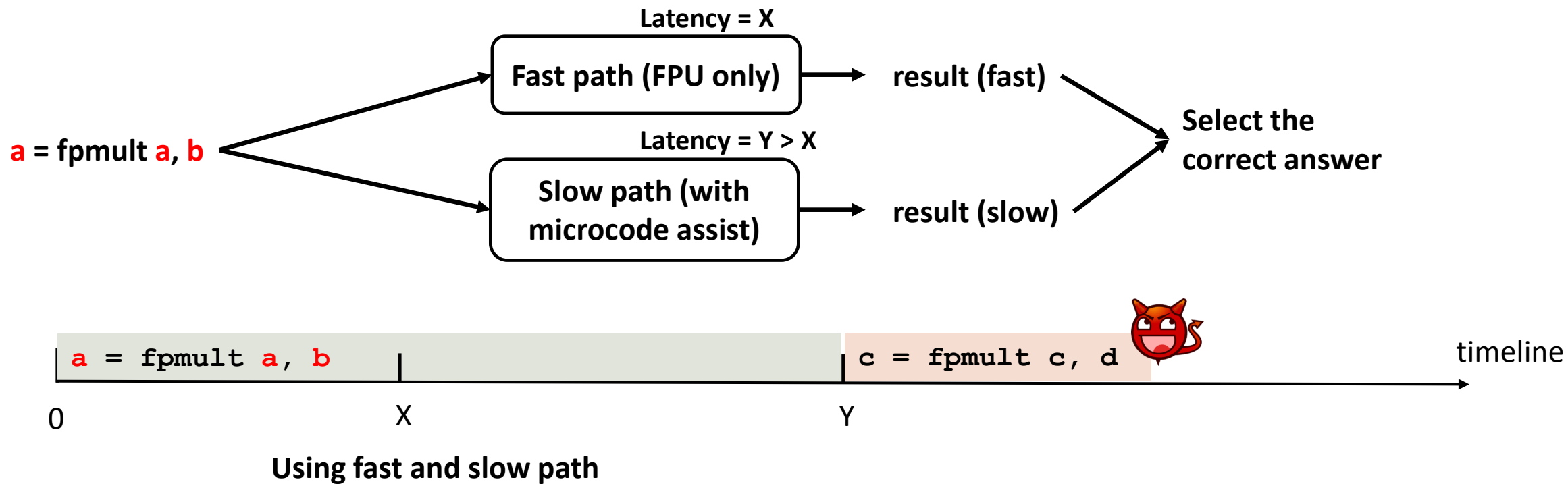
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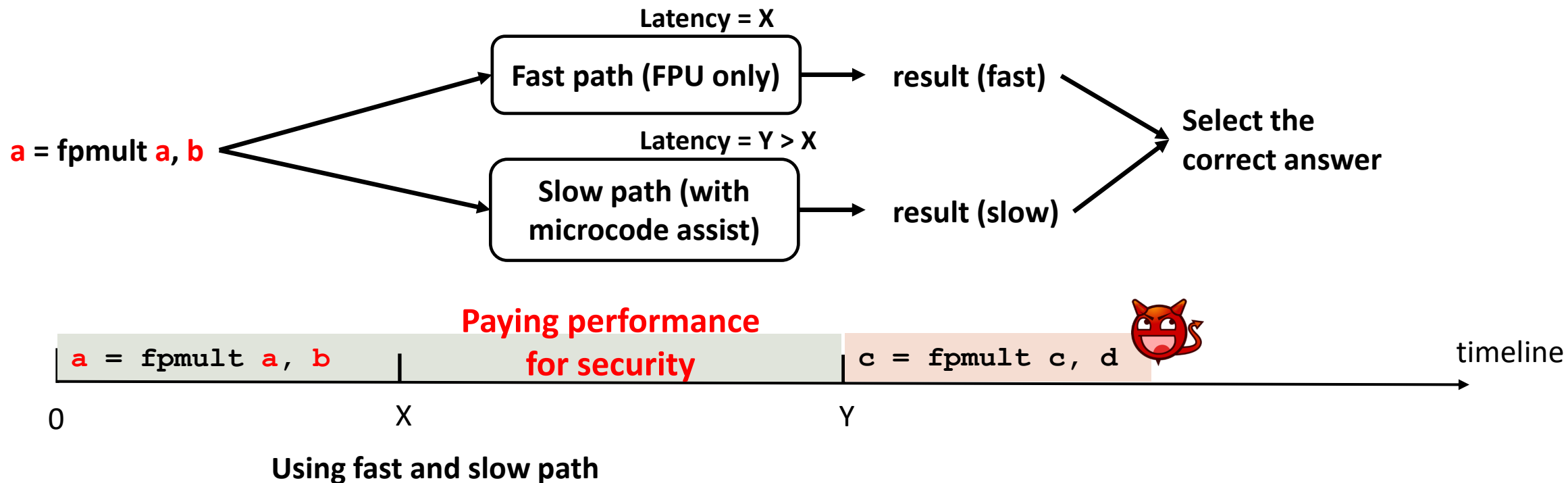
Idea 1: Being Data Oblivious



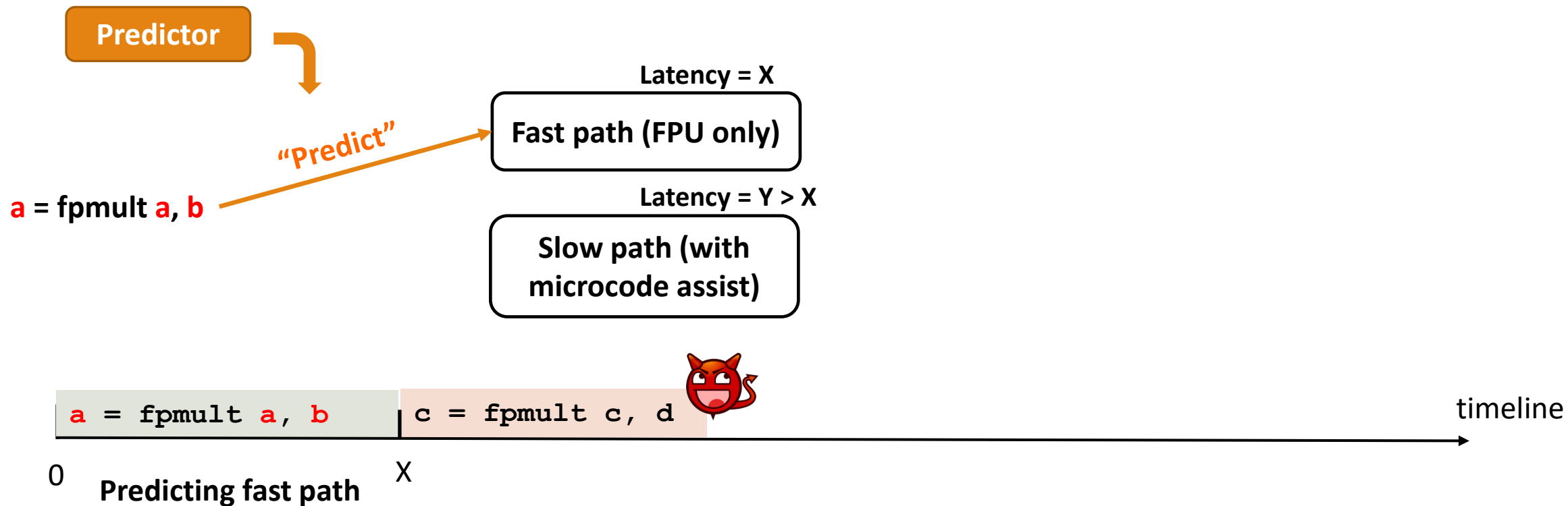
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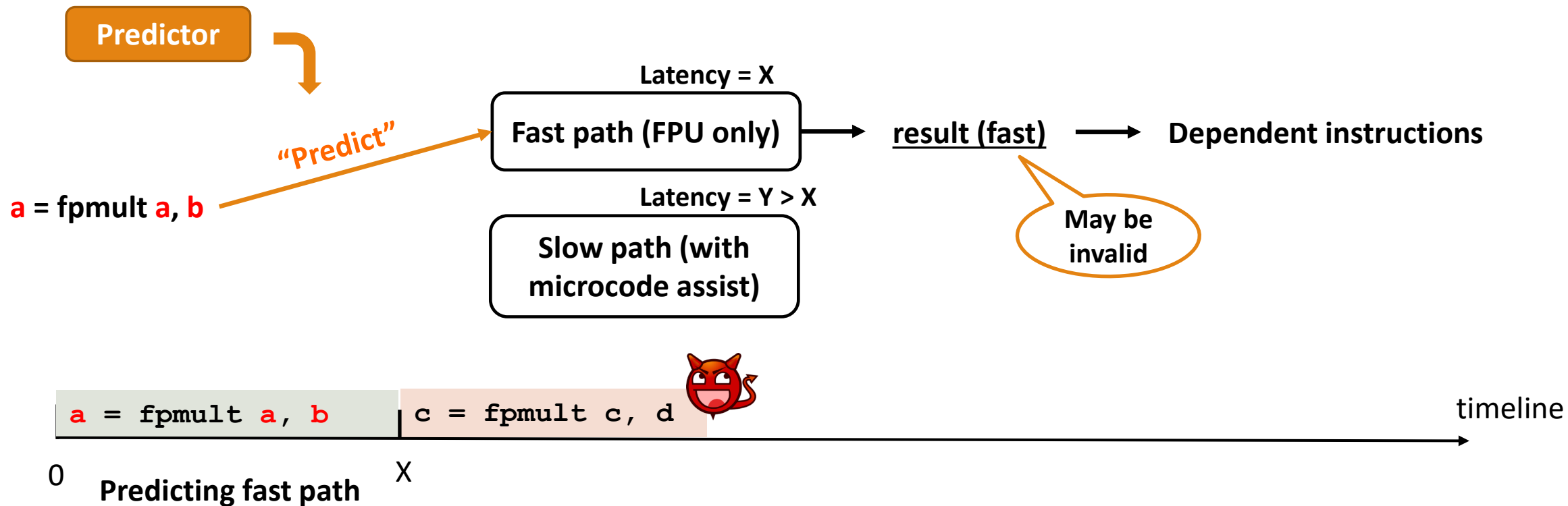
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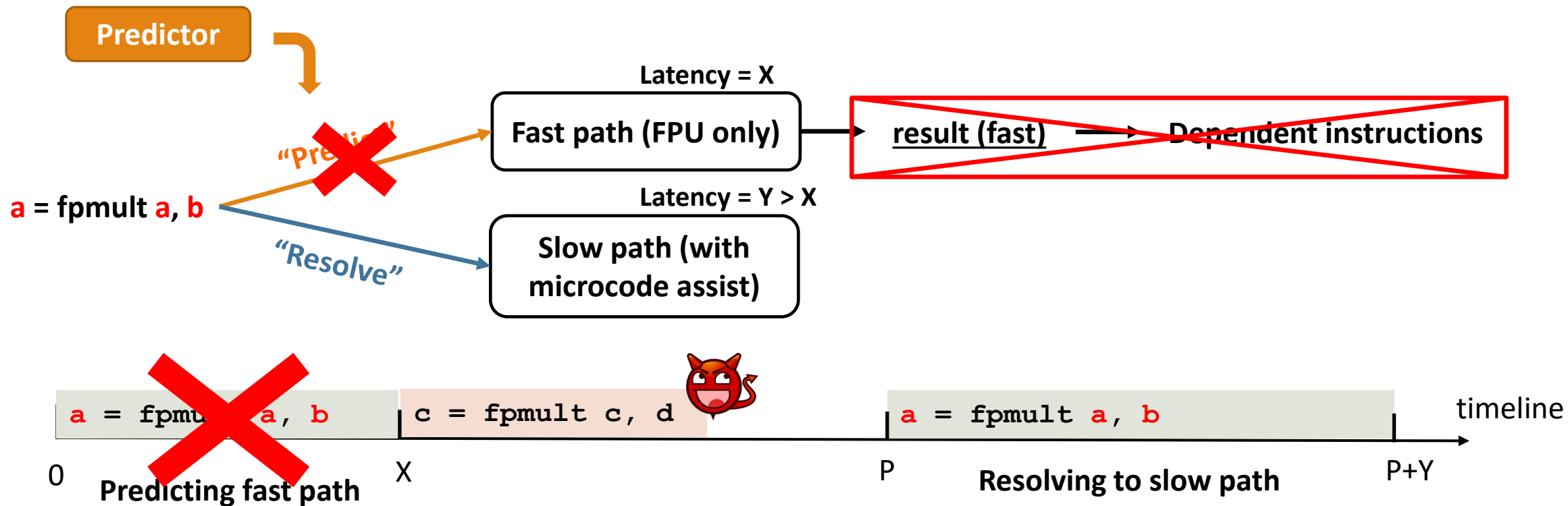
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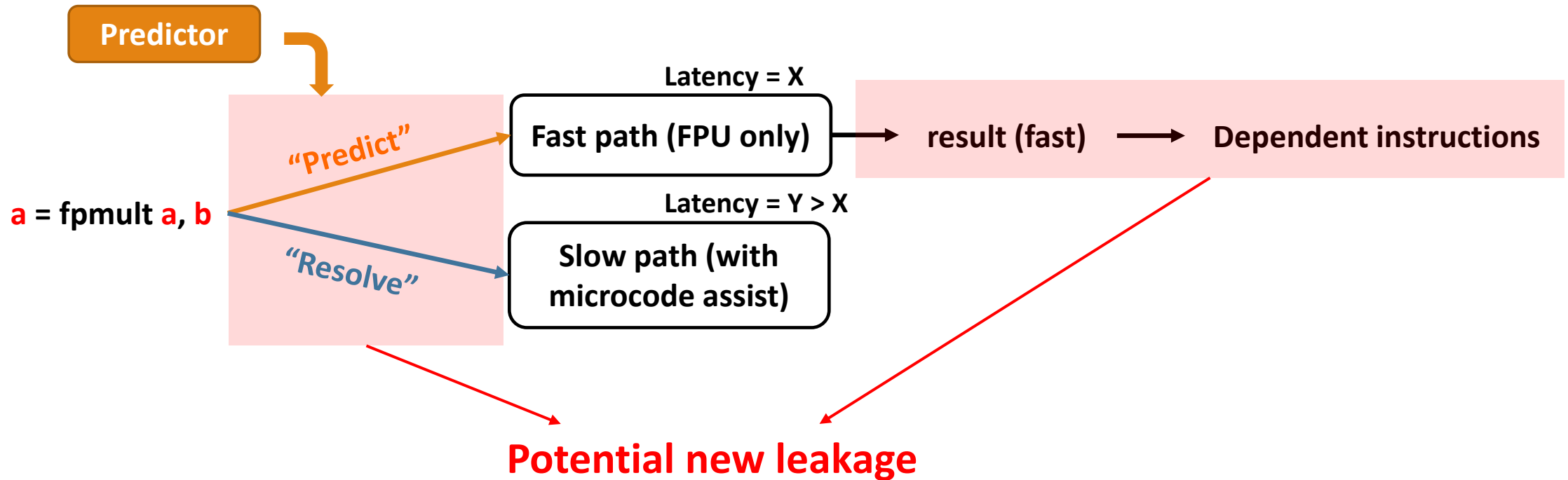
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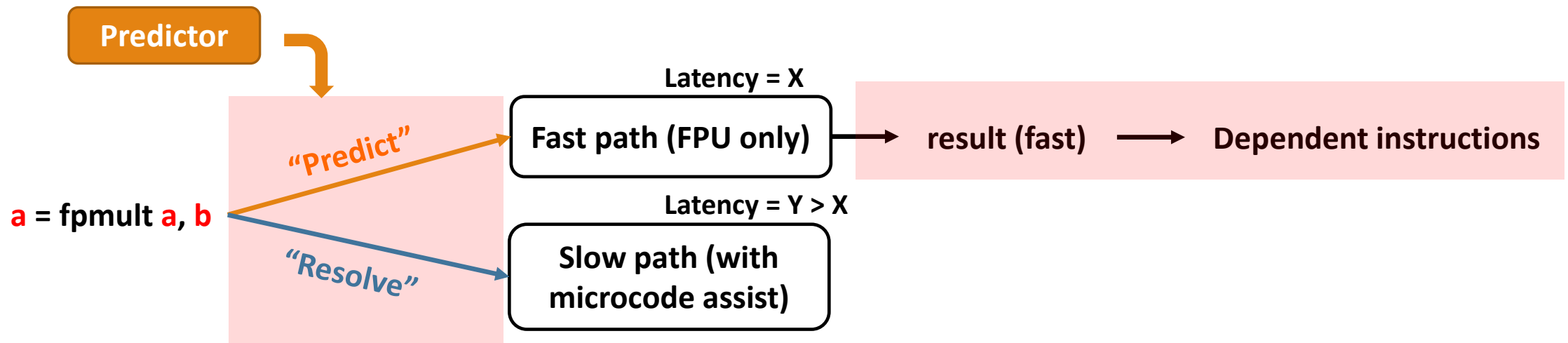
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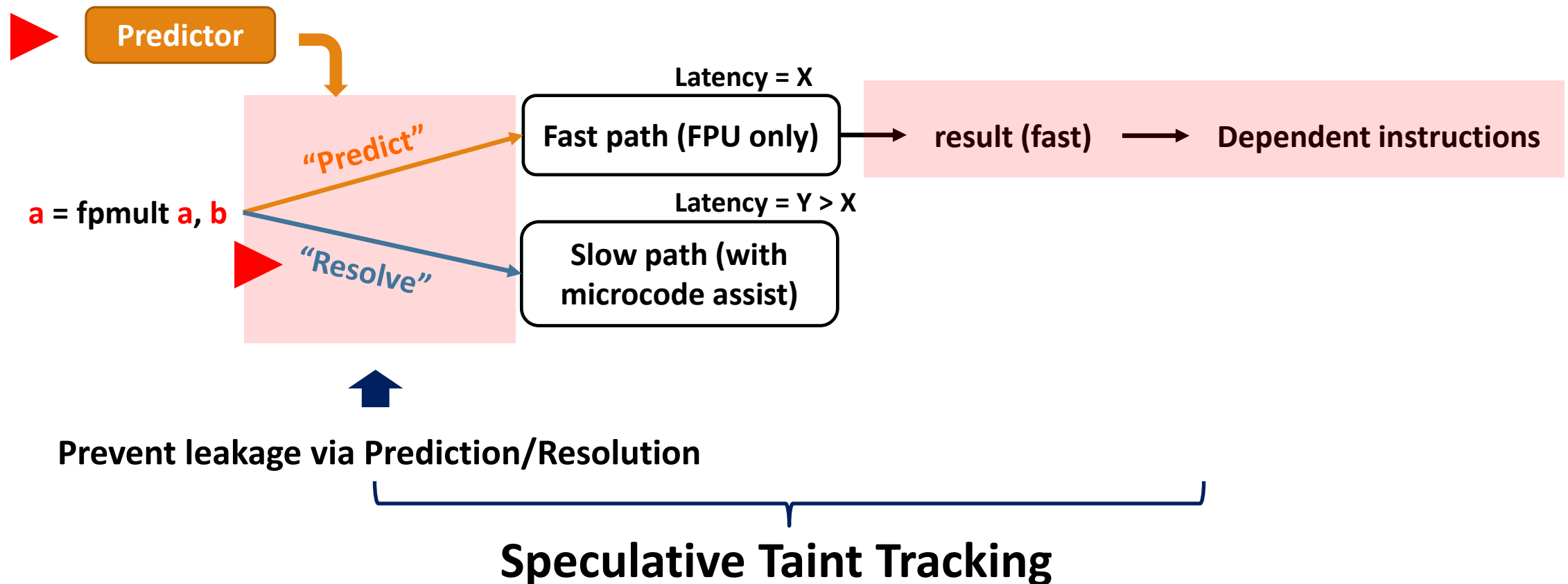


Applying STT for Security

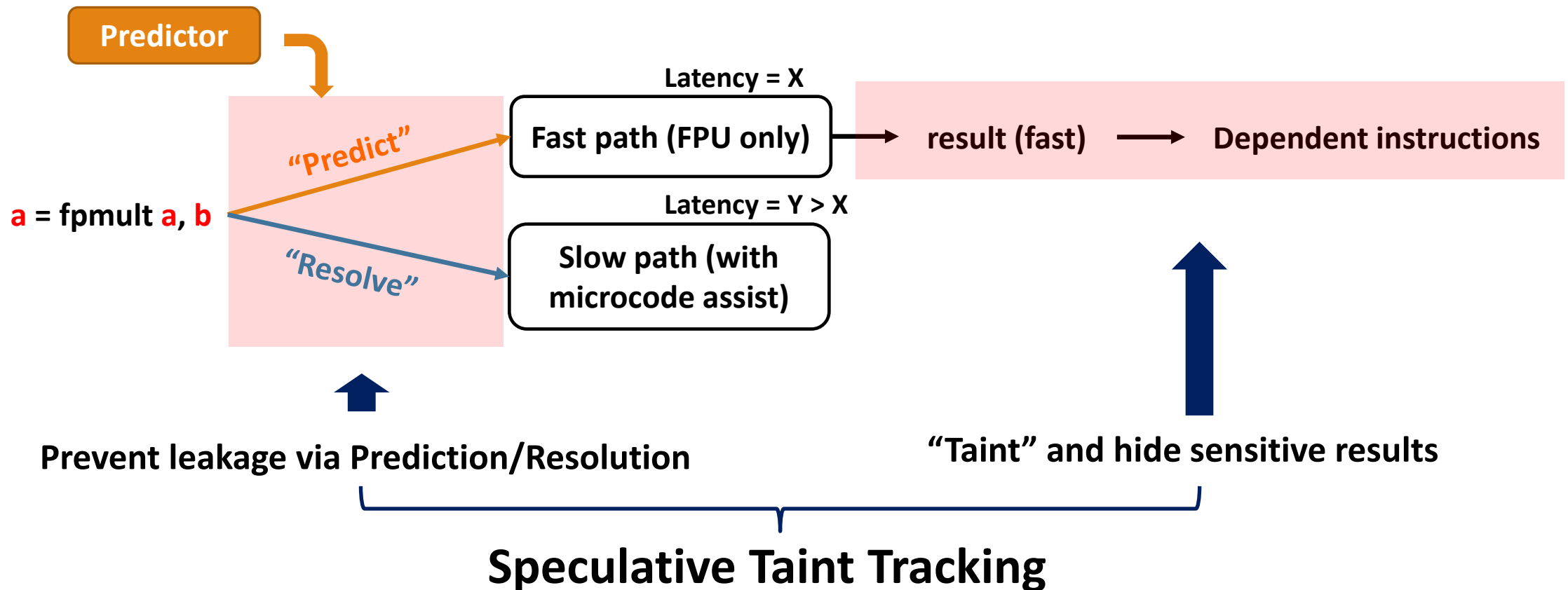


Speculative Taint Tracking

Applying STT for Security



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How STT “**taints and hides sensitive results**”:

- Sensitive data is marked tainted
- Taint propagates through program dataflow
- Transmitters with tainted arguments are handled safely

Applying STT for Security

How STT prevents leakage via prediction/resolution

STT Makes Prediction Great (SAFE**) Again!**



We build predictors to reduce defense overhead

- Taint propagates through program dataflow
- Transmitters with tainted arguments are handled safely

Speculative Data Oblivious Execution (SDO)

**Idea 1. Safely execute transmitters
in a data-oblivious (DO) manner**

**Idea 2. Predict how the
execution should be performed**

 Data Oblivious variants + Predicting which variant

+ Safe Prediction with STT

=

SDO

 Net result: execute unsafe transmitters **early** and **safely**

Speculative Data Oblivious Execution (SDO)

What's Next:

- **Generic SDO Framework**
- **Implementing SDO for load instructions**
- **Evaluation**
- **Conclusion**

SDO Framework

- Step 1: Define data-oblivious (DO) variants for unsafe transmitters

SDO Framework: Step 1: Define Data-oblivious (DO) Variants

Transmit instruction	<code>dest ← op args</code>
DO variants	<code>DO-op₁</code> ... <code>DO-op_N</code>
Execution of DO variants	<code>(dest₁, success₁) ← DO-op₁ args</code> ... <code>(dest_N, success_N) ← DO-op_N args</code>

SDO Framework: Step 1: Define Data-oblivious (DO) Variants

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`dest = fpmult args`

Fast path (FPU only)

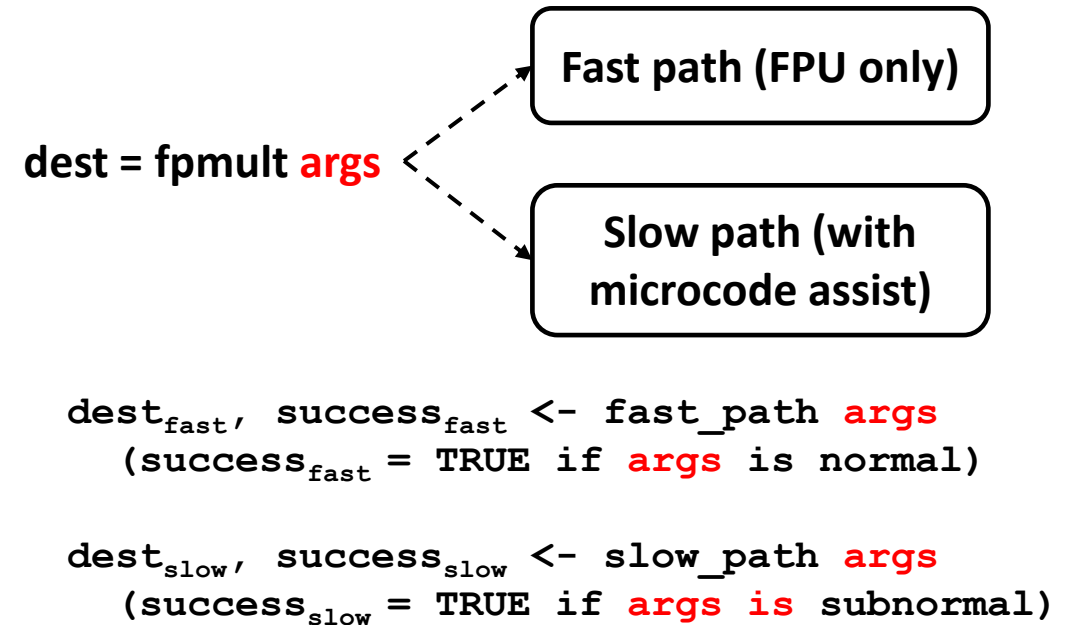
Slow path (with
microcode assist)

`fast_path`

`slow_path`

SDO Framework: Step 1: Define Data-oblivious (DO) Variants

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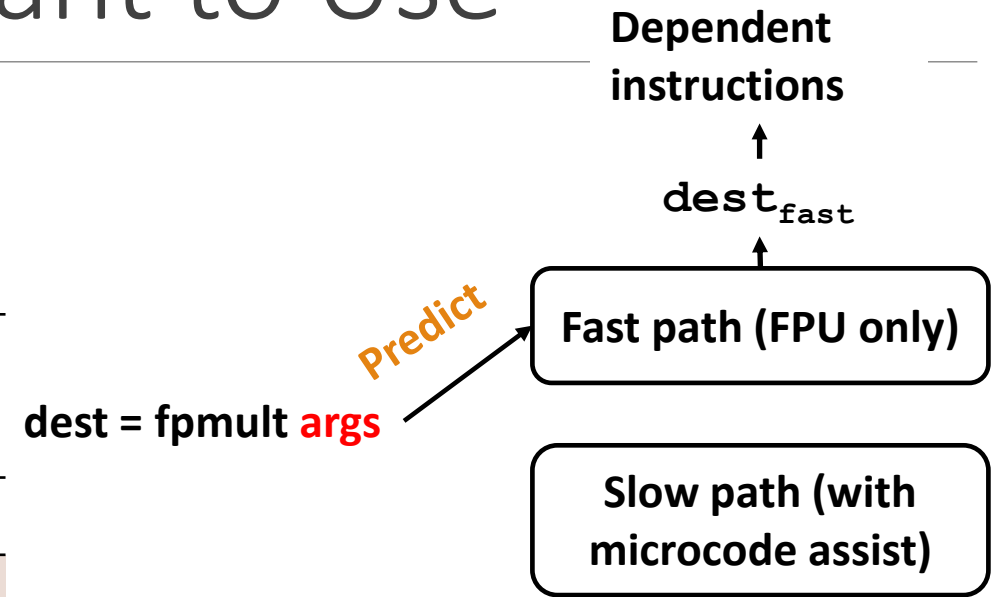


SDO Framework: Step 2: Predict Which DO Variant to Use

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Predicting DO variant	<code>i <- Pred.predict (public_input)</code> <code>(dest_i, success_i) <- DO-op_i args</code>

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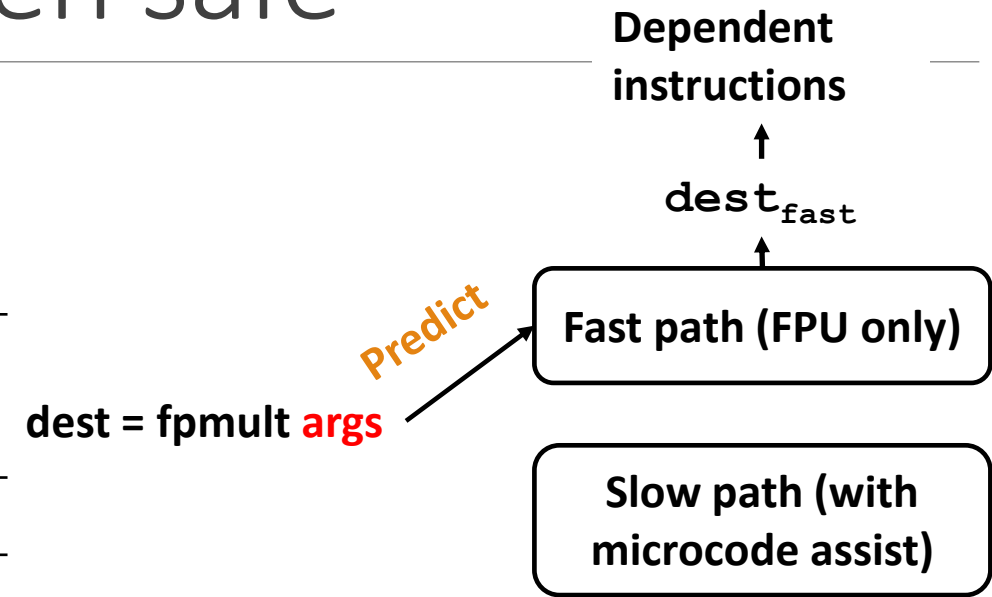


Static Predictor: always predicting “Fast path”

```
destfast, successfast <- fast_path args
(successfast = TRUE if args is normal
 successfast = FALSE if args is subnormal)
```

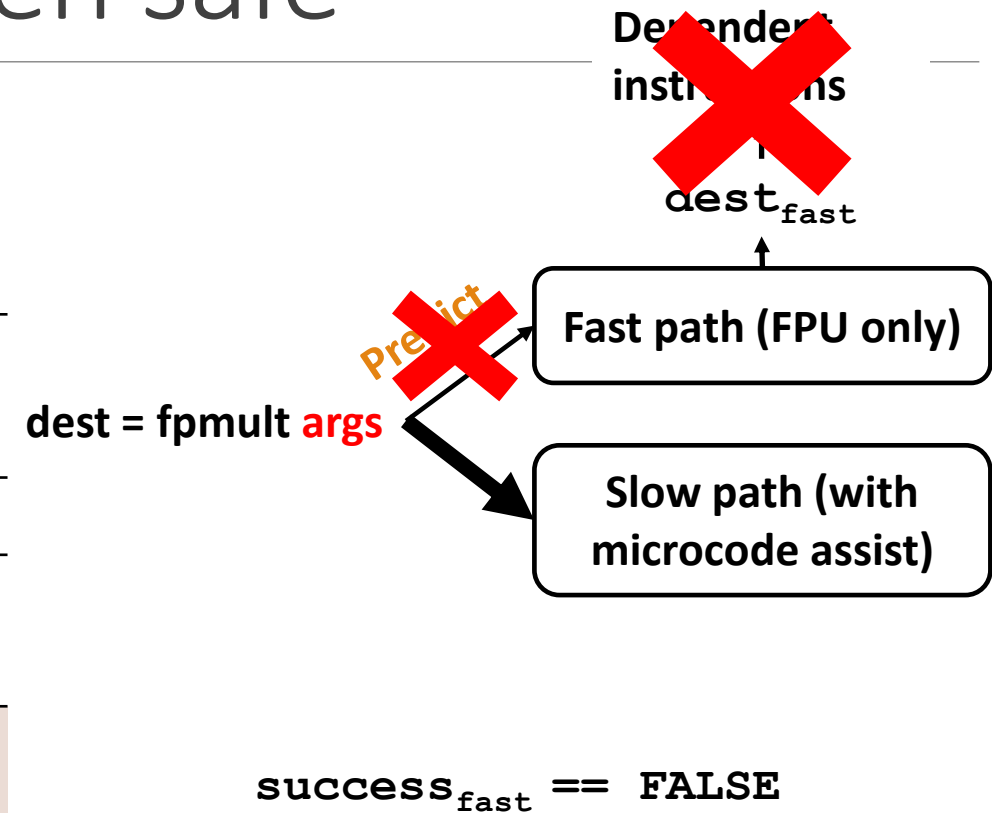
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Designing SDO for Loads

- Load is the vital motivation and challenge for SDO
 - The execution of loads is complicated, susceptible to various attacks
 - Most performance overhead comes from loads

Step 1: Define DO Variants for Loads

- DO variants
 - DO-ld_{L1} : only accessing L1
 - DO-ld_{L2} : only accessing L1 and L2 sequentially
 - DO-ld_{L3} : only accessing L1, L2 and L3 sequentially
 - $\text{DO-ld}_{\text{Mem}}$: accessing L1, L2, L3 and DRAM sequentially
- $(\text{dest}_{xx}, \text{success}_{xx}) \leftarrow \text{DO-ld}_{xx} \text{ addr} \quad // \text{dest}_{xx} = \perp \text{ if } \text{success}_{xx} == \text{FALSE}$

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- DO variants (DO-ld_{L_i}) must be free of adversary-observable hardware resource usage
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- For more details (e.g., load re-ordering, performance optimizations) about DO variants, please see the paper

Step 2: Predict Which DO Variant to Use

- Goal: **accurate** and **precise** cache level prediction
 - Suppose a load requires data from cache level i and the predictor predicts level j
 - “accurate and precise”: $i == j$
 - “accurate but imprecise”: $i < j$ -> redundant cache access -> unnecessary load latency
 - “inaccurate”: $i > j$ -> cache miss -> writeback \perp to dependents -> squash

Predicted level	DO Variant
1 (L1)	DO-1d _{L1}
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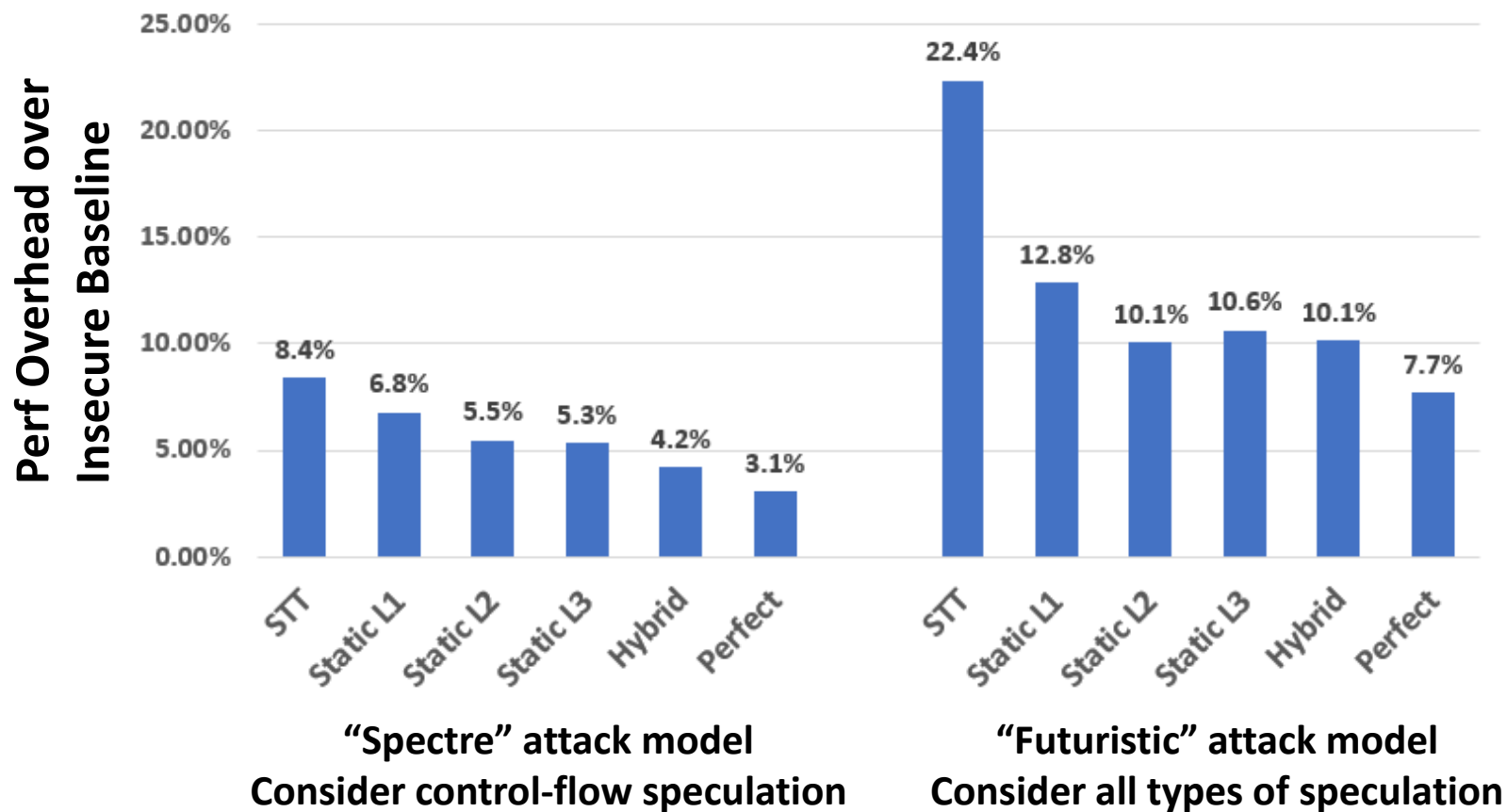
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- Hybrid predictor:
 - “Greedy” (for loads with irregular access pattern):
 - Maintain a history, and pick the lowest level among history
 - “Loop” (for loads with regular access pattern)
 - Learn the recurring pattern, and predict based on the pattern

Predicted level	DO Variant
1 (L1)	DO-1d _{L1}
2 (L2)	DO-1d _{L2}
3 (L3)	DO-1d _{L3}
4 (Memory)	DO-1d _{Mem}

Step 3: Resolve When Load is Safe

- Update the predictor
- Squash if **success == FALSE**
- In a multi-processor:
 - DO-1d_{LX} cannot modify cache state
 - Data fetched by DO-1d_{LX} may not be cached in L1
 - May miss cache invalidation
- Solution: send a second load request to validate if a cache invalidation was missed
 - We adopt the validation infrastructure proposed in InvisiSpec [MICRO'18]

Performance Evaluation on SPEC2017



Transmitters:

- Load
- Floating-point multiplication
- Floating-point division

Static L1: always predicting $DO-1d_{L1}$

Static L2: always predicting $DO-1d_{L2}$

Static L3: always predicting $DO-1d_{L3}$

Hybrid: using the hybrid predictor

Perfect: prediction is accurate and precise

Conclusion

- SDO serves as a new speculative execution attack mitigation with high-performance and high-security
- The proposed SDO framework augments STT with significant speedup without compromising security

Data Oblivious variants + Predicting which variant + Safe Prediction with STT

=

Safe, early execution of transmitters



Applying STT for Security

STT: prediction and resolution never depend on sensitive data



We can build new predictors to get more performance

Prevent leakage via Prediction/Resolution

“Taint” and hide sensitive results

Speculative Taint Tracking