ISCA’20 Section 5B

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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    // access instruction
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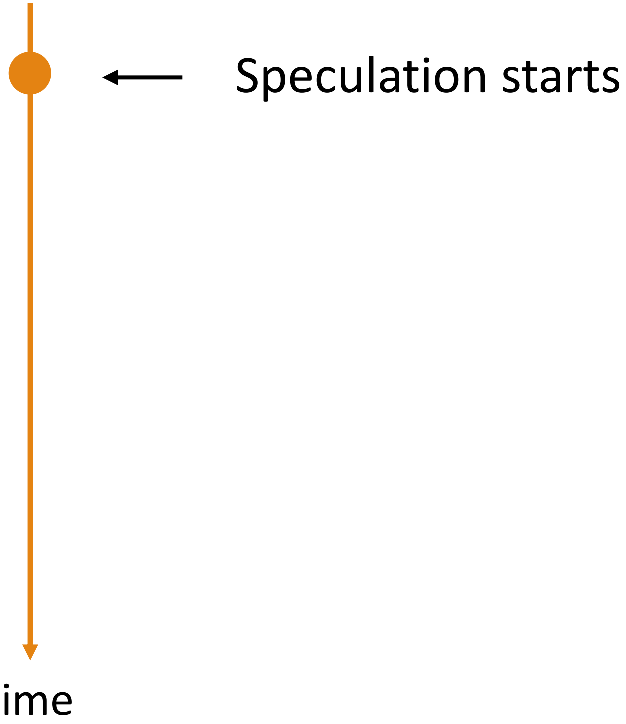

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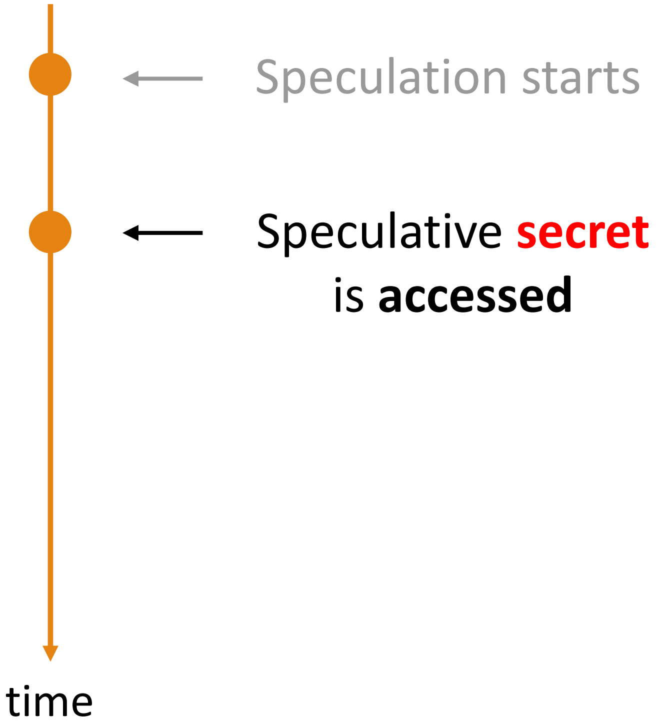

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Speculative secret is **accessed**

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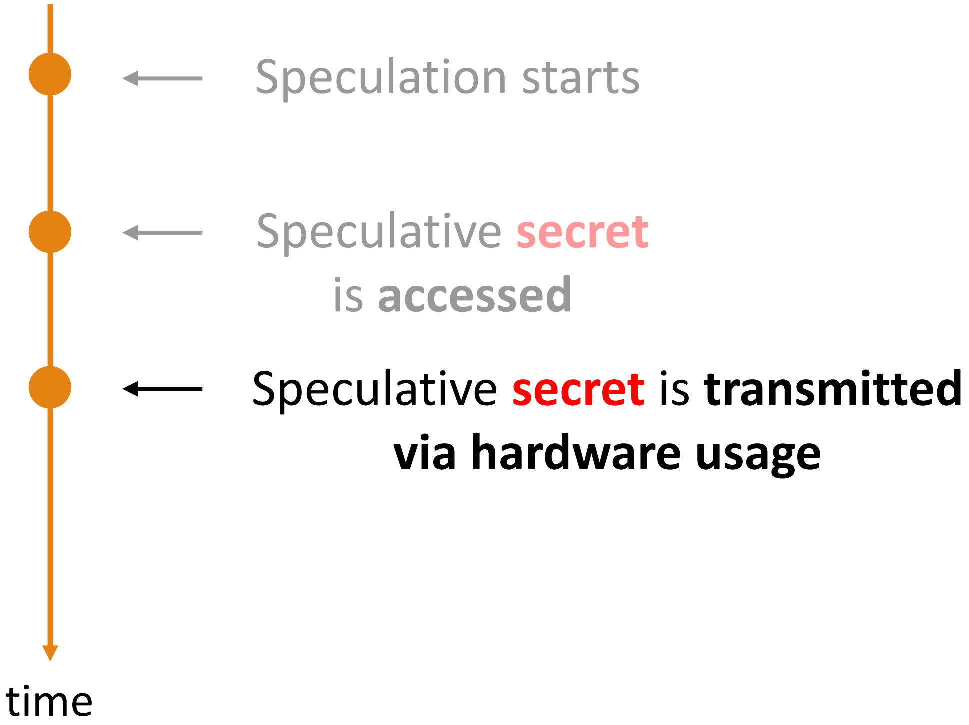

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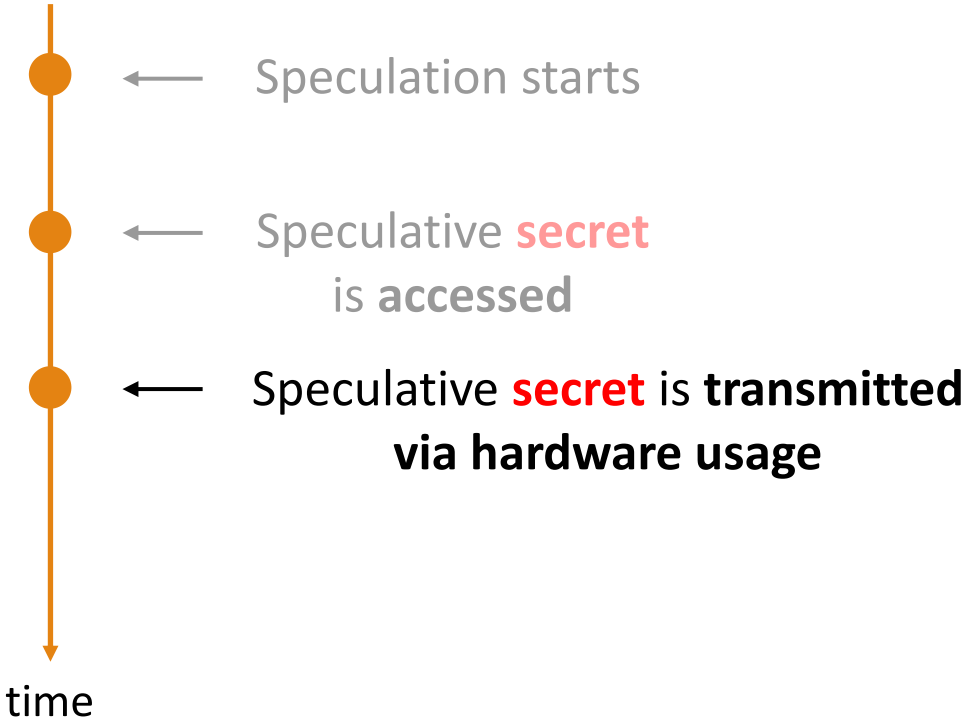
Shared hardware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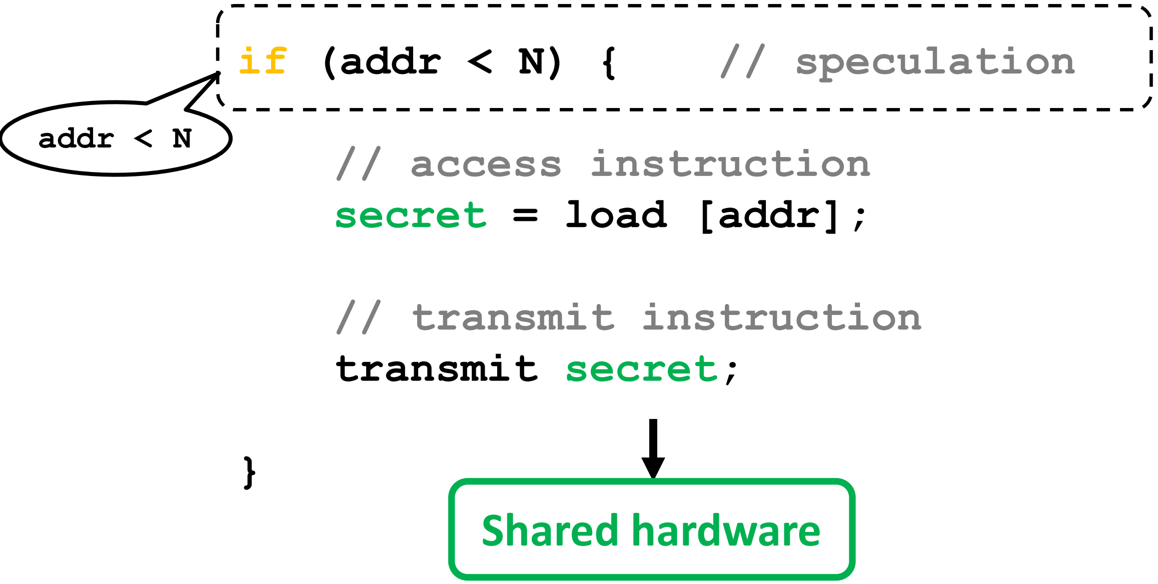

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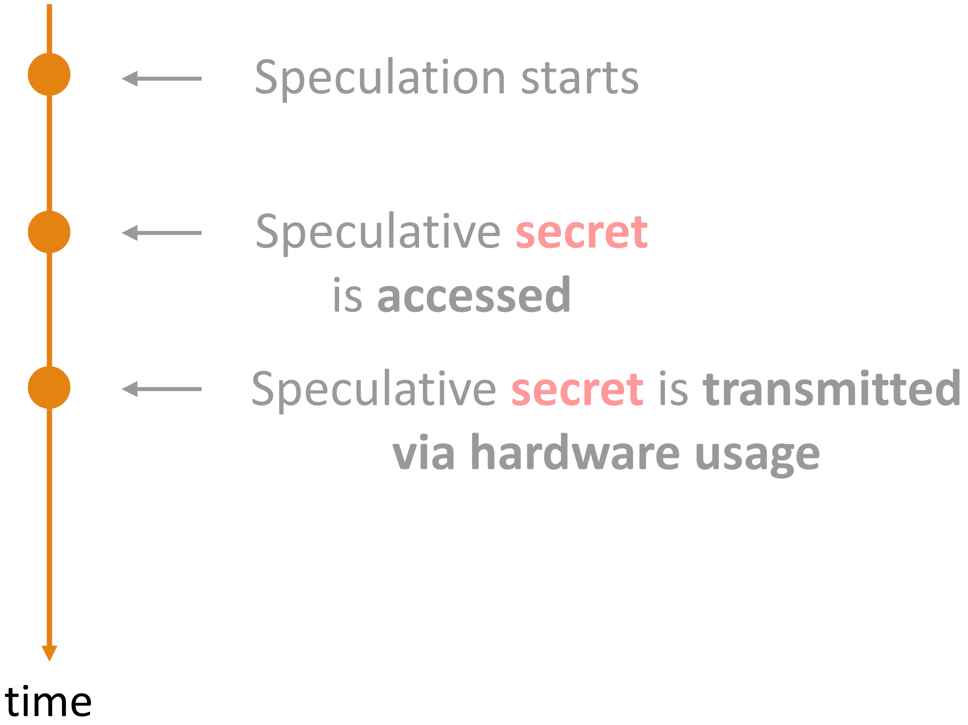

Speculation starts
Speculative secret is accessed
Speculative secret is transmitted via hardware usage
time

Speculative Execution Attacks

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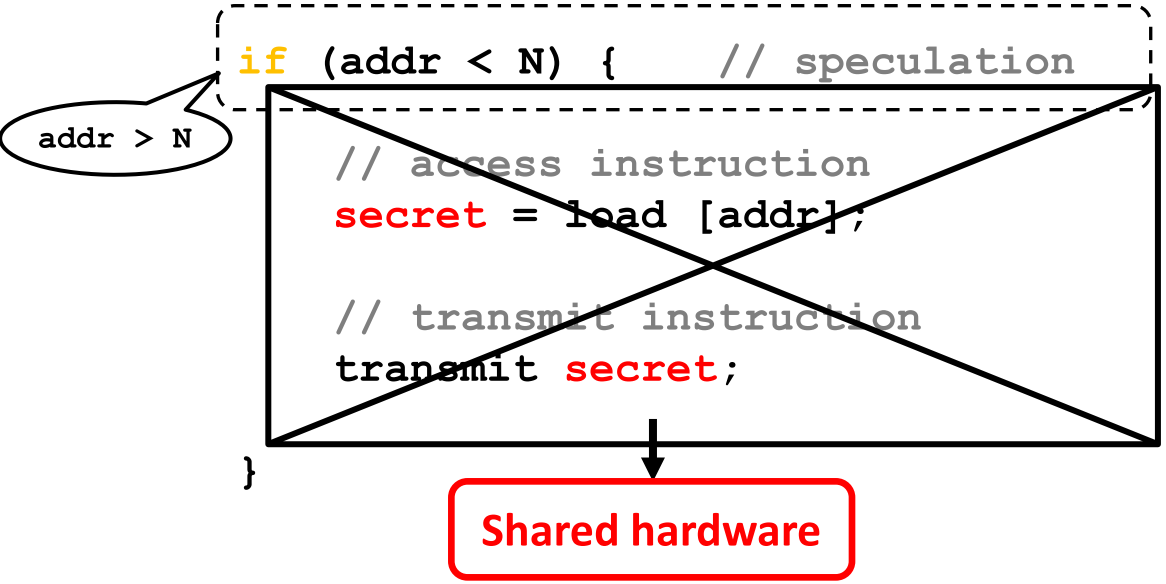

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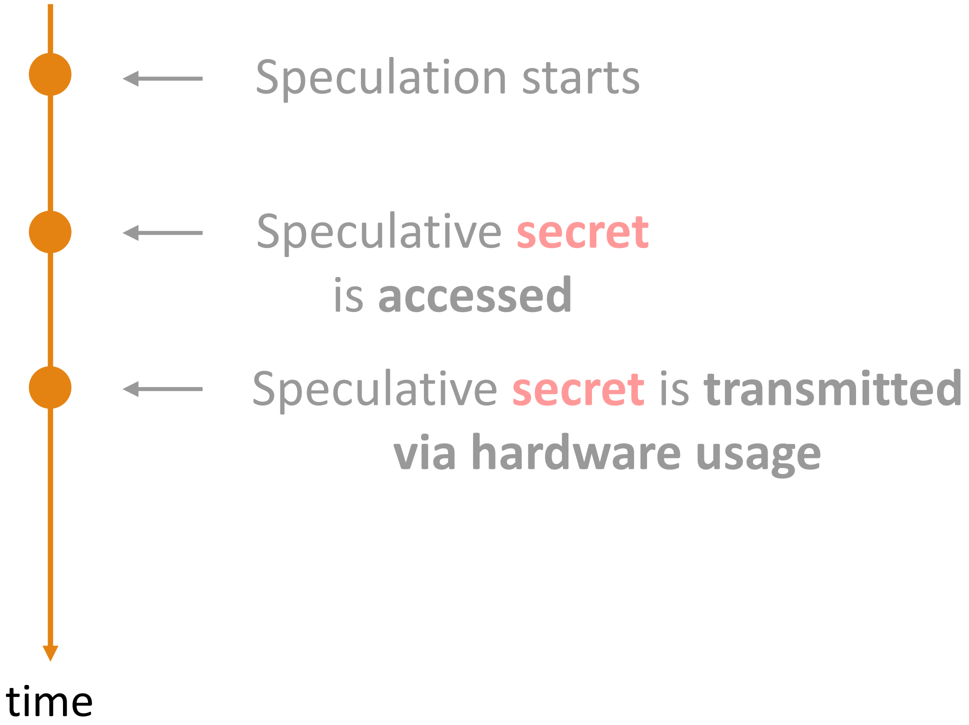

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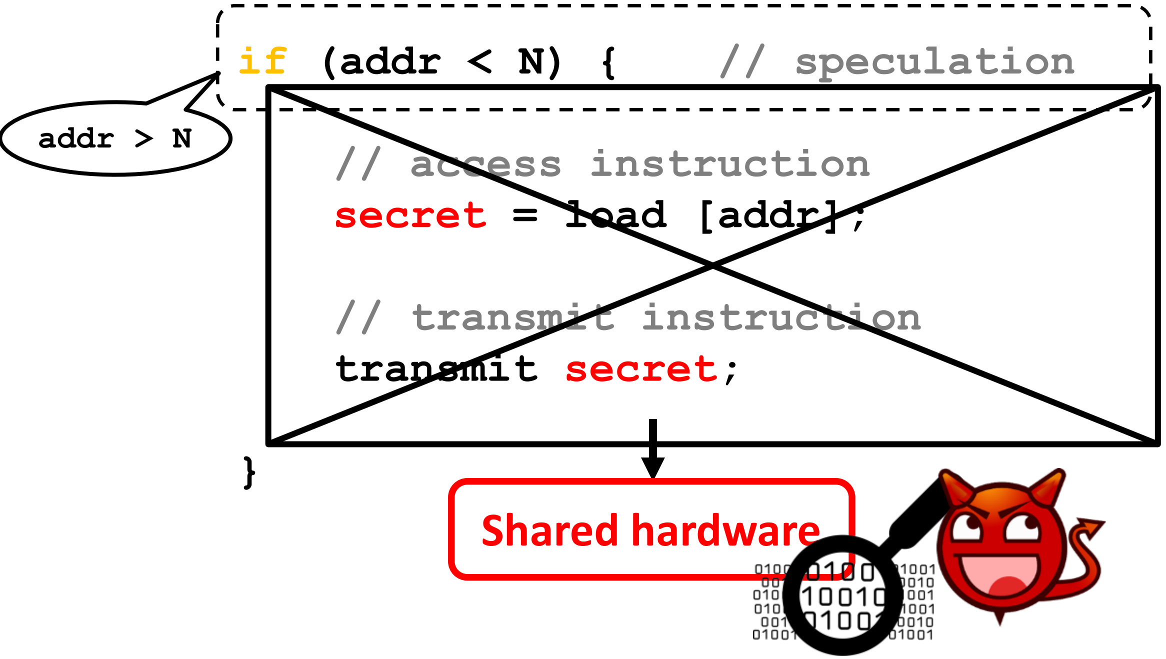

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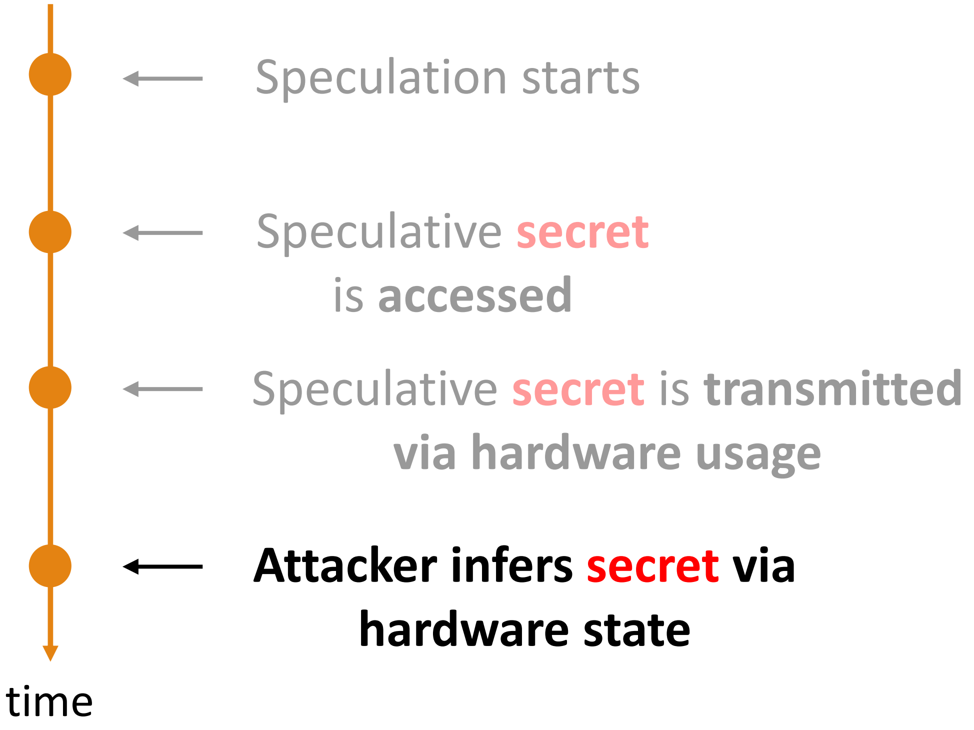

Speculation starts

Speculative secret is **accessed**

Speculative secret is **transmitted via hardware usage**

Attacker infers secret via hardware state

Existing Mitigations

- How to deal with `transmit secret` ?

Existing Mitigations

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- Solution: Delayed Execution
  - Prior works: SpecShield [PACT’19], NDA [MICRO’19], STT [MICRO’19]

Transmit instruction	Hardware vulnerability
load	Cache side channel
Floating point operations	Subnormal floating point
……	……

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```
if (addr < N) {   // speculation

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    transmit secret;

}
```

→ **Delaying execution**

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
Floating point operations	Subnormal floating point
……	……

Existing Mitigations

- How to deal with `transmit secret` ?

Register File

it

Improve the **performance** of *Delayed Execution*

and

Maintain its **security** guarantee

Speculative Data Oblivious (SDO): Executive Summary

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Idea 1. Execute `transmit secret`

😃 **High performance**

Speculative Data Oblivious (SDO): Executive Summary

Idea 1. Execute `transmit secret` by eliminating operand-dependent hardware usage (being data oblivious)

😃 **High performance**

😐 **High security, low performance**

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Idea 2. Predict how the execution should be performed

Speculative Data Oblivious (SDO): Executive Summary

Idea 1. Execute `transmit secret` by eliminating operand-dependent hardware usage (being data oblivious)

😃 **High performance**

😐 **High security, low performance**

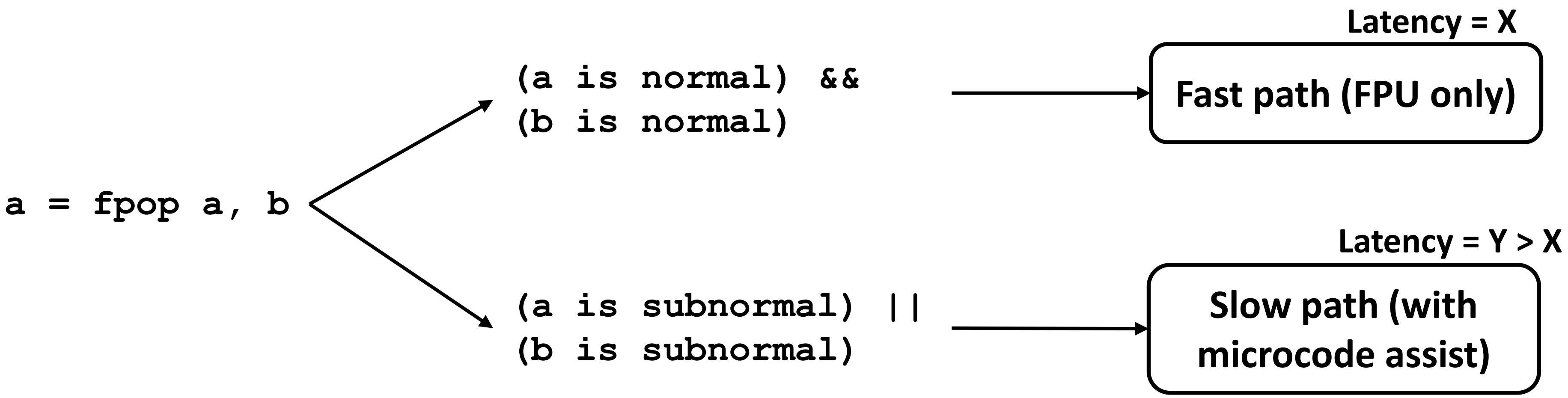
Idea 2. Predict how the execution should be performed

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



```
a = fpop a, b
```

```
(a is normal) &&
(b is normal)
```

Latency = X

Fast path (FPU only)

```
(a is subnormal) ||
(b is subnormal)
```

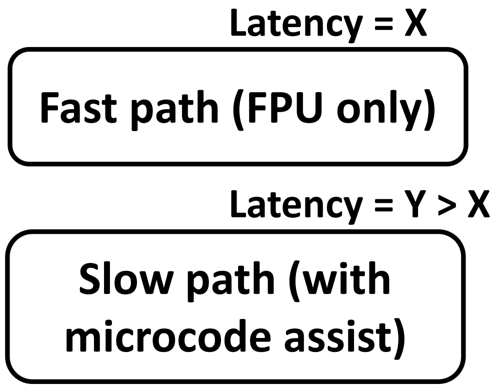
Latency = Y > X

Slow path (with microcode assist)

Problem: Leaking Whether Input is Normal/Subnormal

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

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



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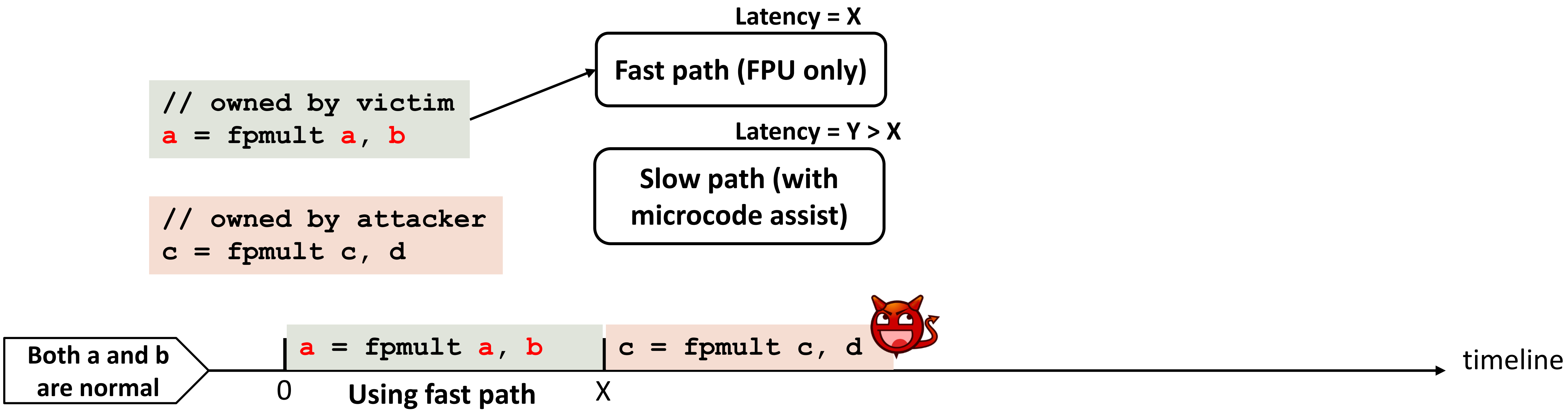


```
// owned by victim
a = fpmult a, b
```

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

Latency = X

Fast path (FPU only)

Latency = Y > X

Slow path (with microcode assist)

Both a and b are normal

`a = fpmult a, b` `c = fpmult c, d`

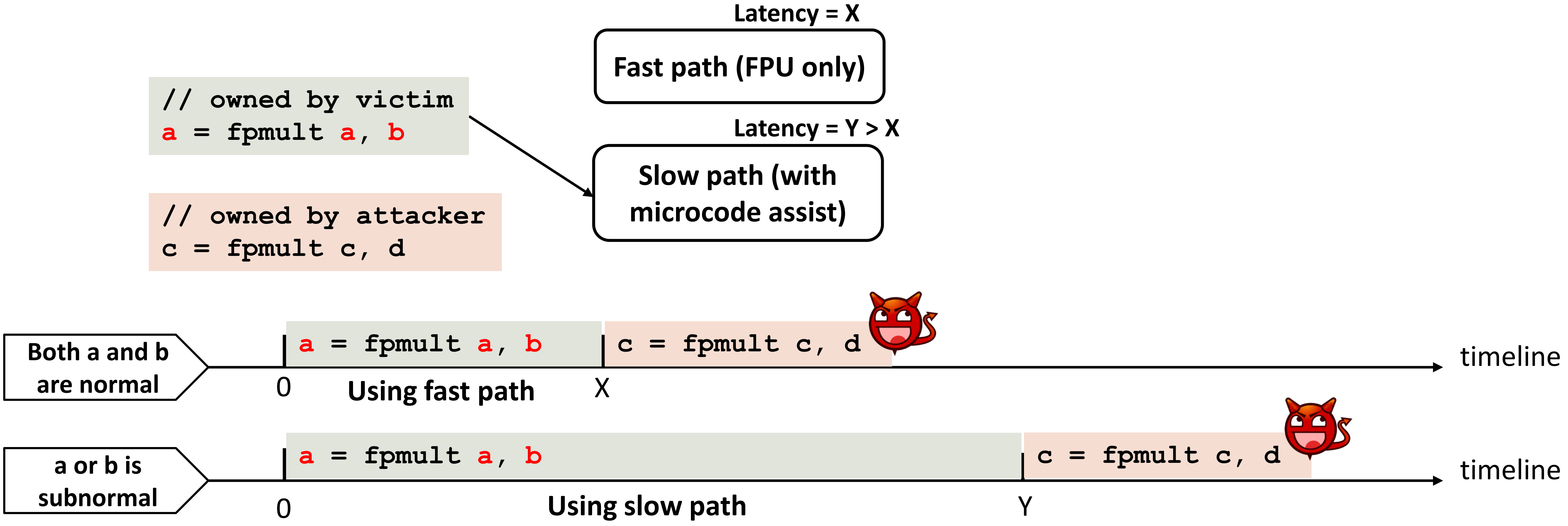
0

Using fast path

X

timeline

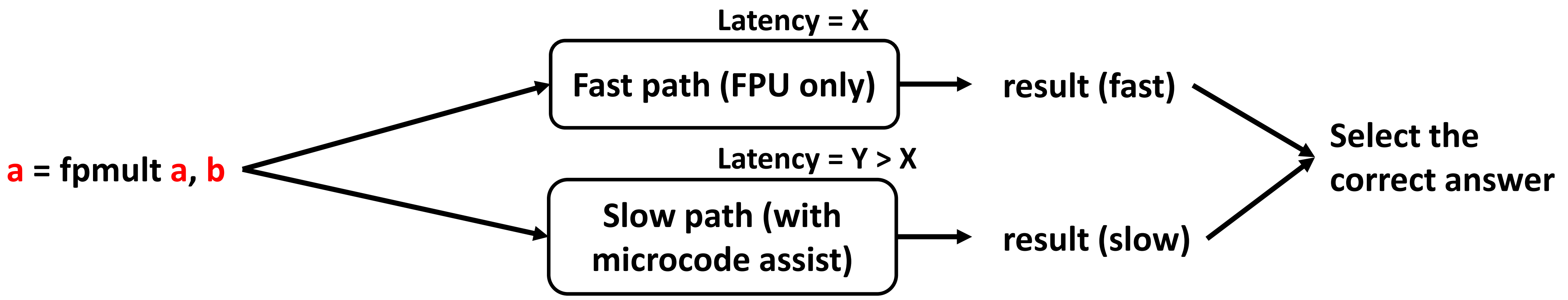
Problem: Leaking Whether Input is Normal/Subnormal



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

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

Idea 1: Being Data Oblivious



a = fpmult a, b

Latency = X

Fast path (FPU only)

result (fast)

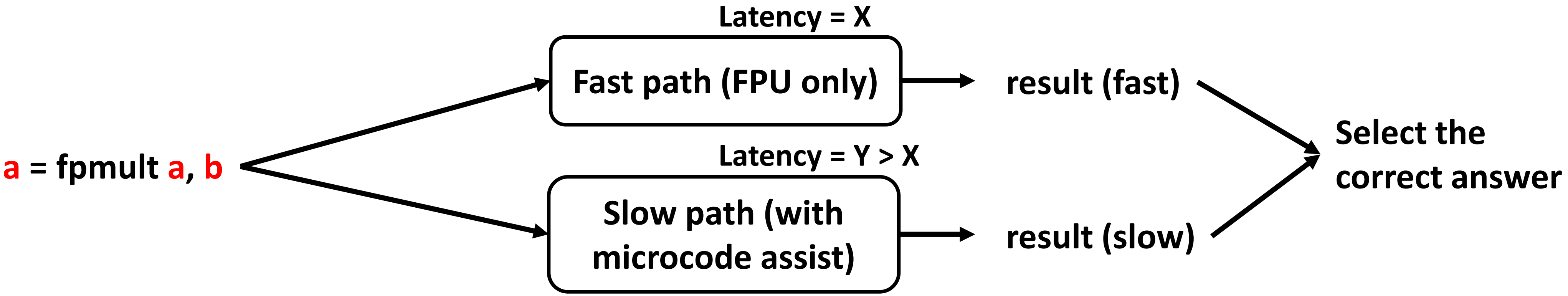
Latency = Y > X

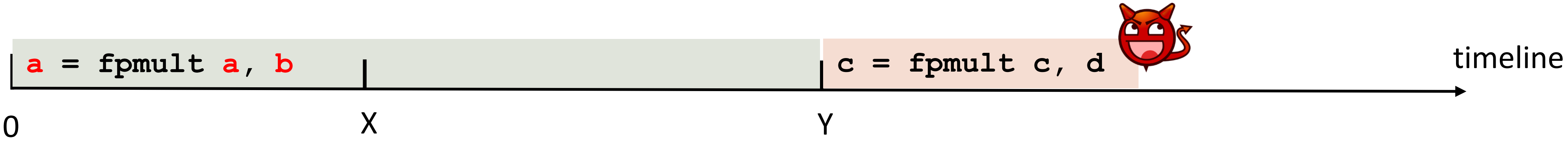
Slow path (with microcode assist)

result (slow)

Select the correct answer

Idea 1: Being Data Oblivious





Using fast and slow path

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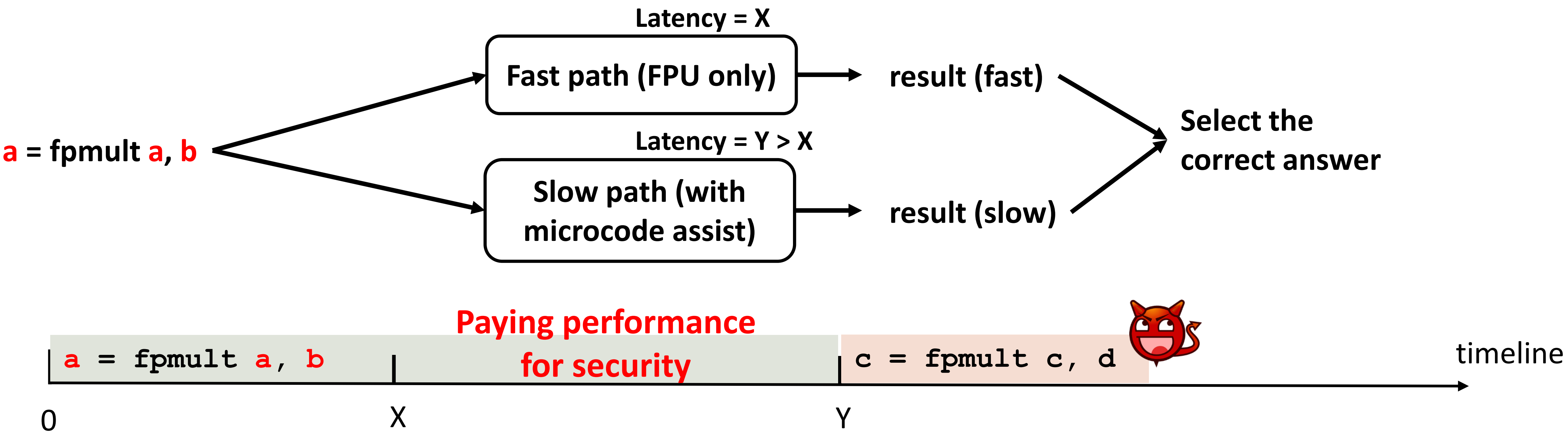
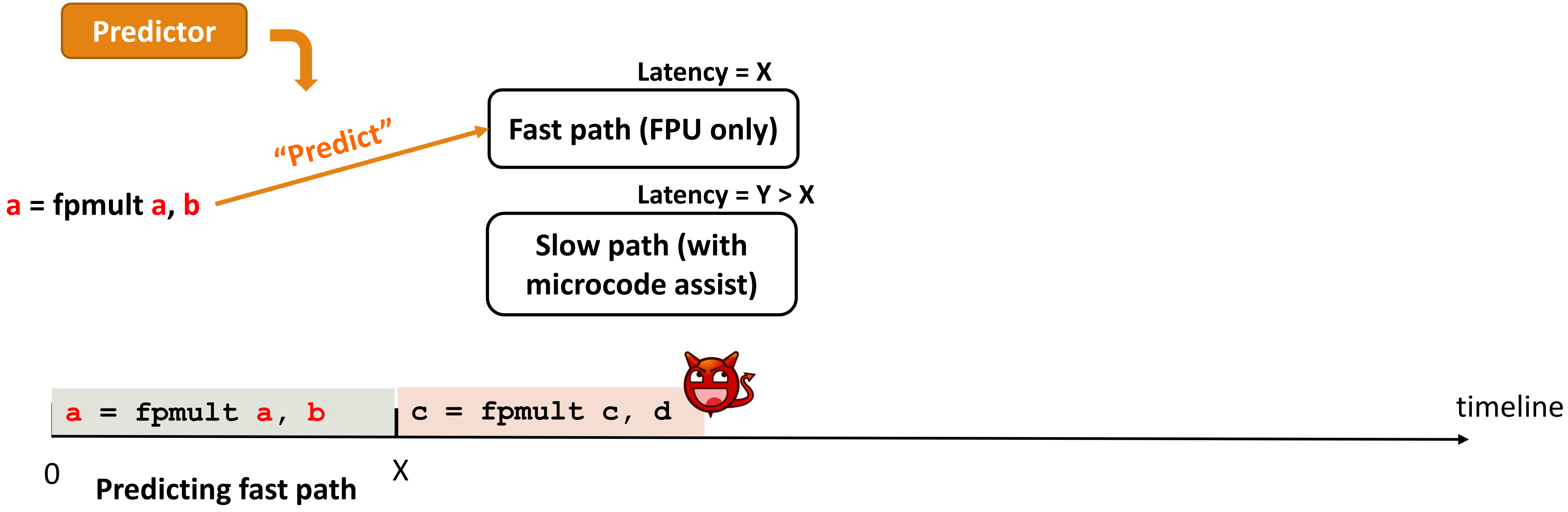


Using fast and slow path

Idea 2: “Predicting” Execution to Perform



Predictor

“Predict”

a = fpmult a, b

Latency = X

Fast path (FPU only)

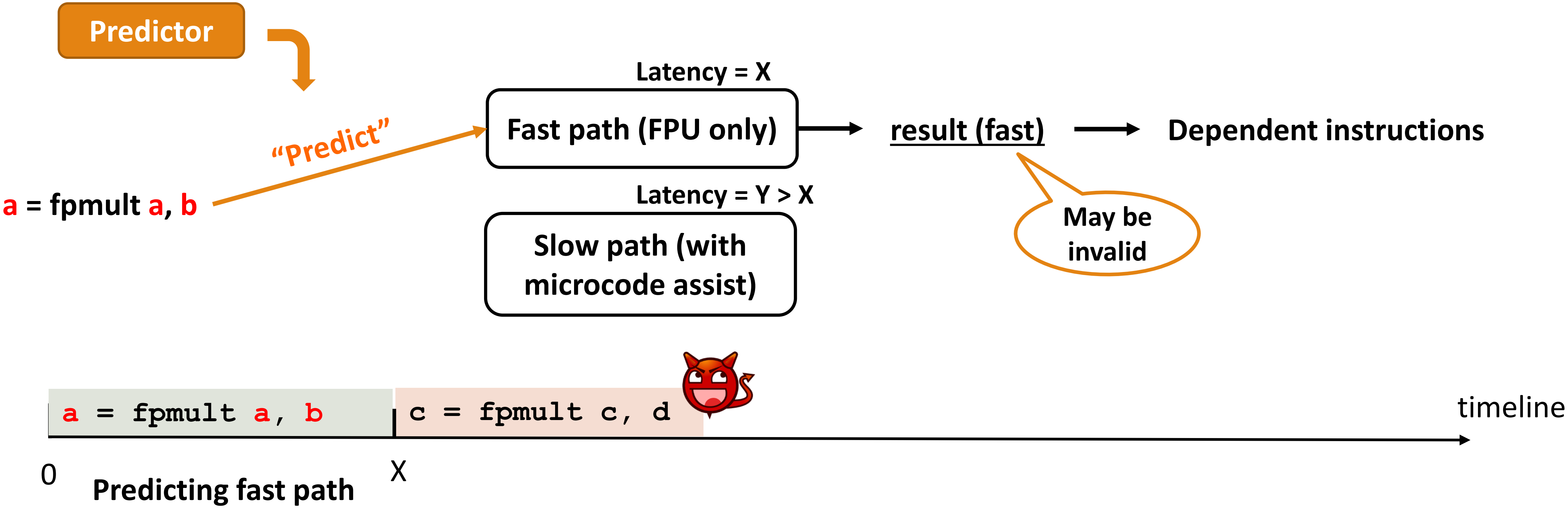
Latency = Y > X

Slow path (with microcode assist)

```
a = fpmult a, b
c = fpmult c, d
```

Predicting fast path

Idea 2: “Predicting” Execution to Perform



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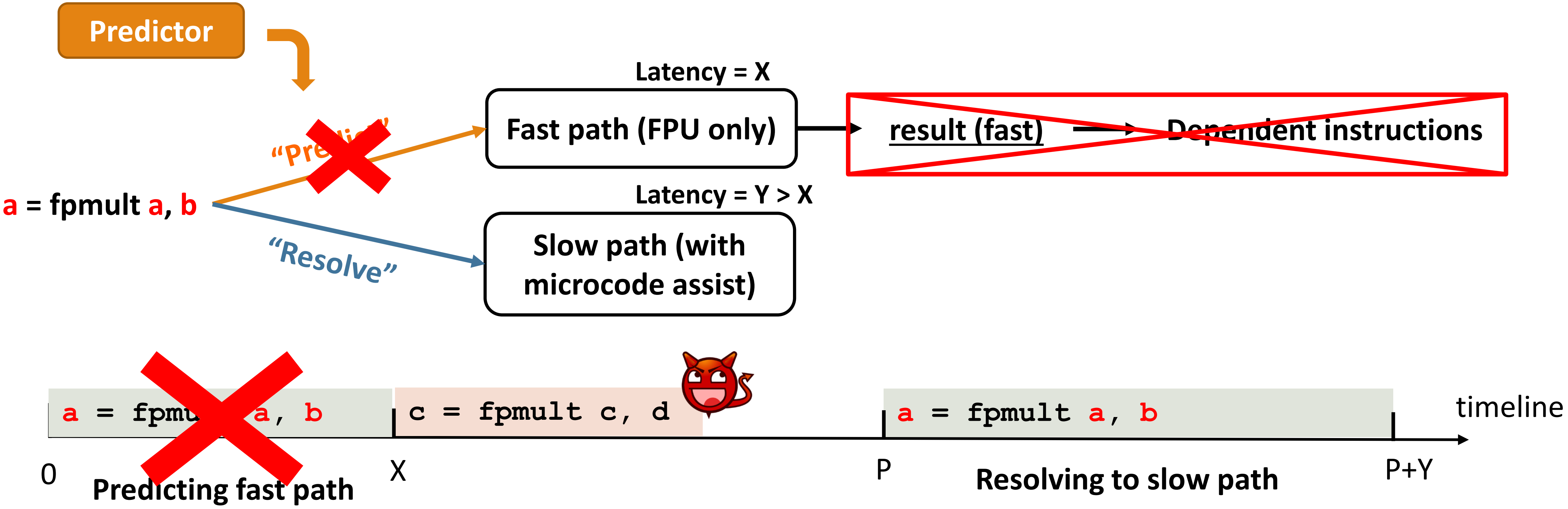

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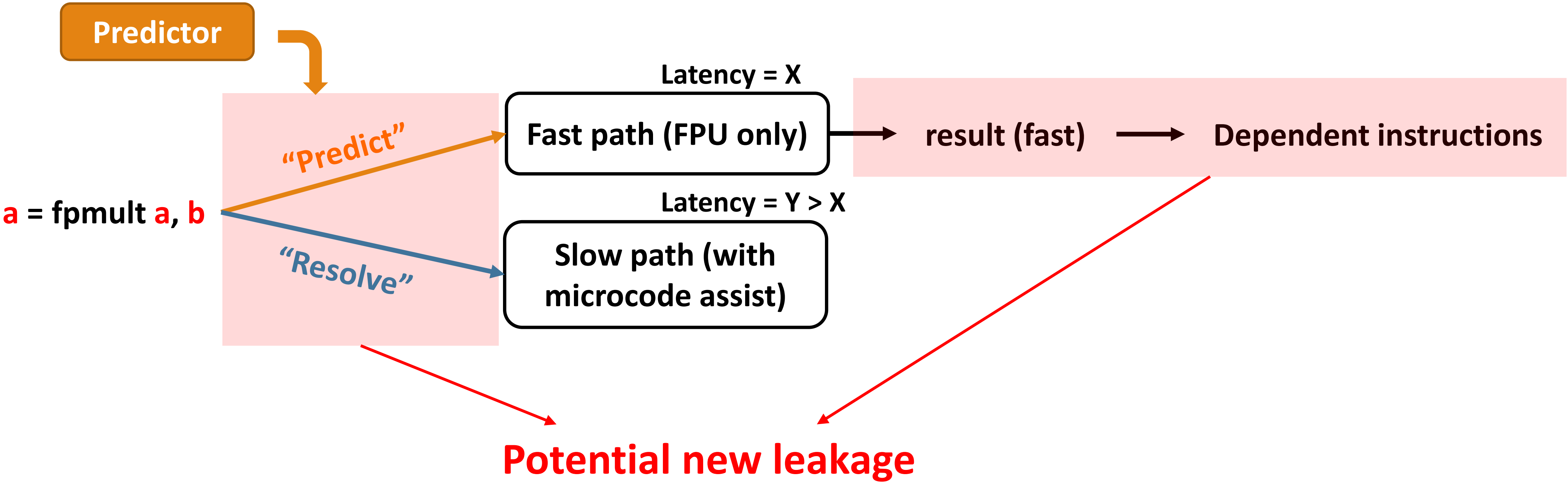
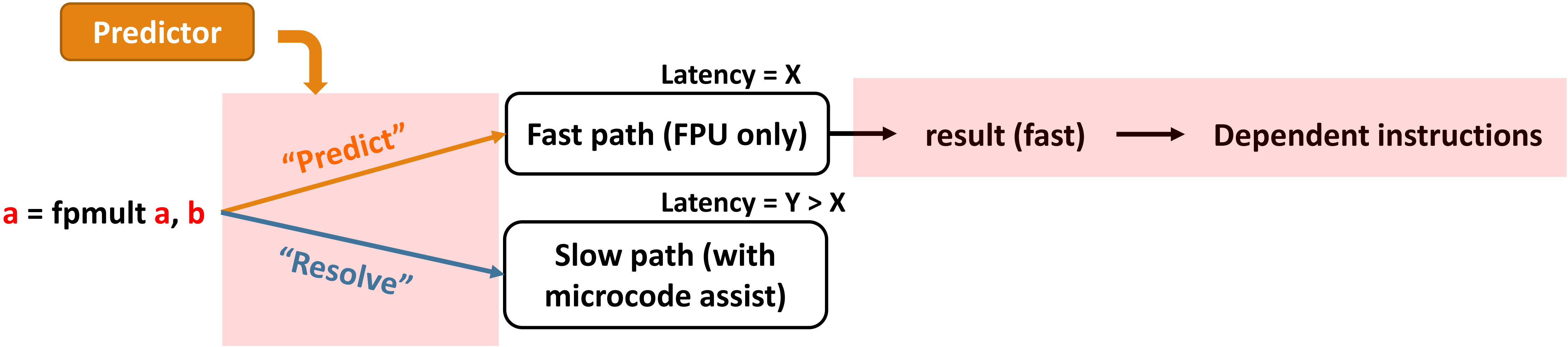
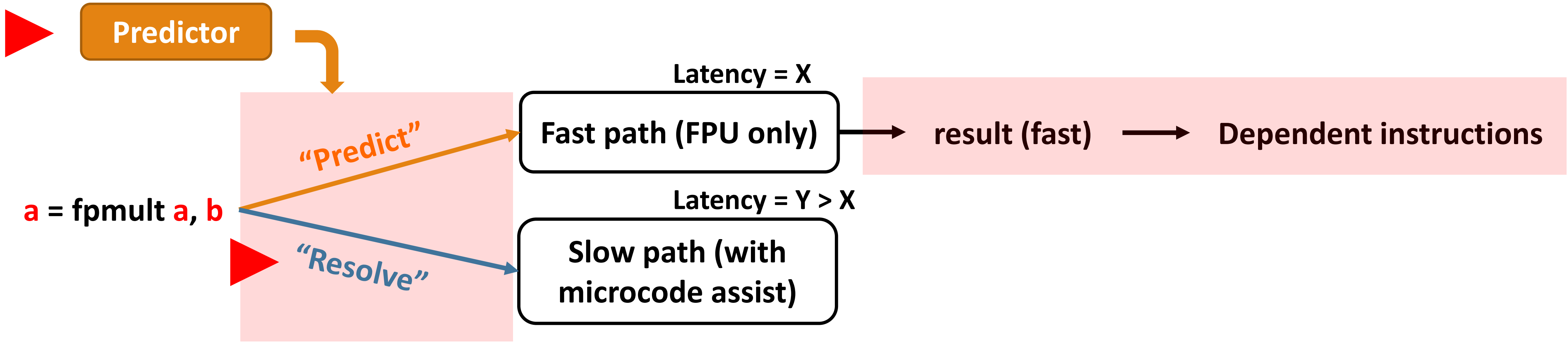


Applying STT for Security



Speculative Taint Tracking

Applying STT for Security



Prevent leakage via Prediction/Resolution

Speculative Taint Tracking

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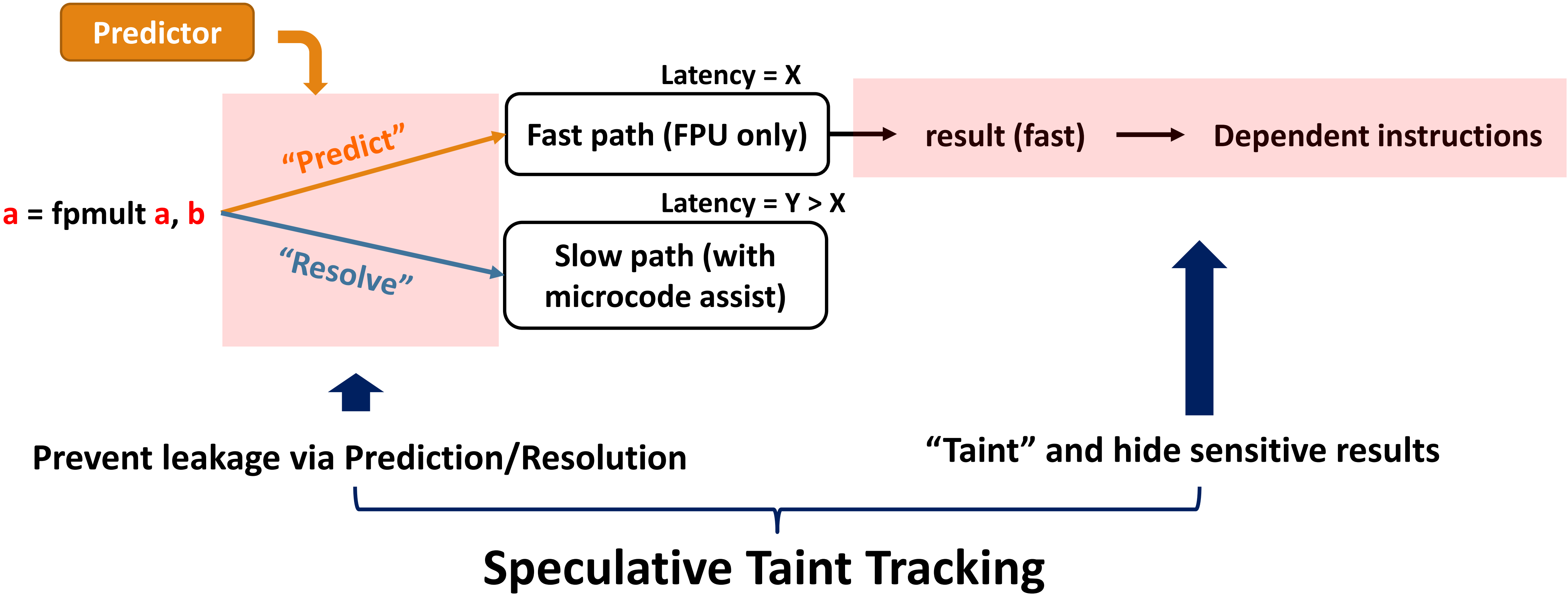

Predictor

Latency = X

Fast path (FPU only)

result (fast)

Dependent instructions

a = fpmult a, b

"Predict"

"Resolve"

Latency = Y > X

Slow path (with microcode assist)

Prevent leakage via Prediction/Resolution

"Taint" and hide sensitive results

Speculative Taint Tracking

Applying STT for Security

How STT “**prevents leakage via prediction/resolution”:**

- Never update predictors with any secret information
- Delay resolution until safe

Applying STT for Security

How STT “**prevents leakage via prediction/resolution”:**

- Never update predictors with any secret information
- Delay resolution until safe

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	dest <- op args
DO variants	DO-op$_1$ … DO-op$_N$
Execution of DO variants	(dest$_1$, success$_1$) <- DO-op$_1$ args … (dest$_N$, success$_N$) <- DO-op$_N$ args

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

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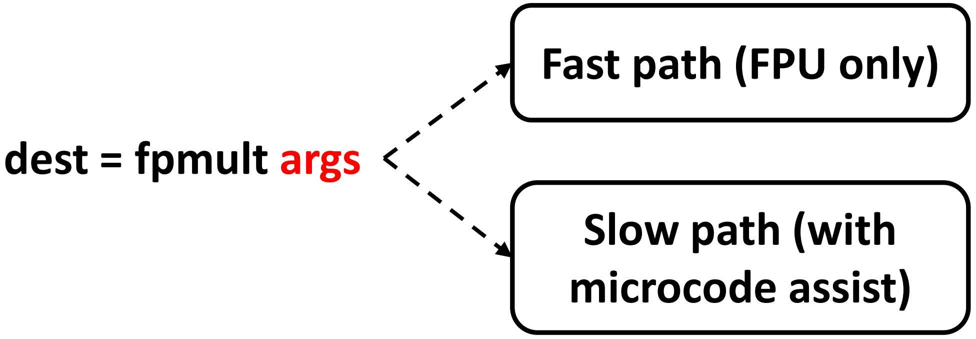


dest = fpmult args

Fast path (FPU only)

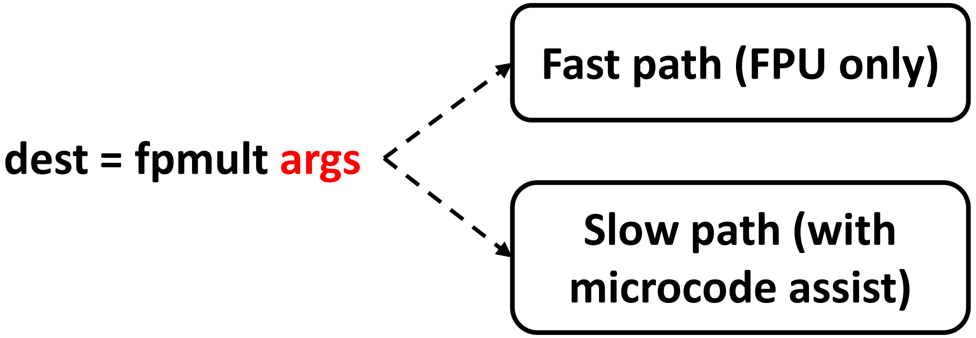
Slow path (with microcode assist)

fast_path

slow_path

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

Transmit instruction	dest <- op args
DO variants	DO-op_1 … DO-op_N
Execution of DO variants	$(\text{dest}_1, \text{success}_1) \leftarrow \text{DO-op}_1$ args … $(\text{dest}_N, \text{success}_N) \leftarrow \text{DO-op}_N$ args



dest = fpmult args

Fast path (FPU only)

Slow path (with microcode assist)

$\text{dest}_{\text{fast}}, \text{success}_{\text{fast}} \leftarrow$ fast_path args

($\text{success}_{\text{fast}}$ = TRUE if args is normal)

$\text{dest}_{\text{slow}}, \text{success}_{\text{slow}} \leftarrow$ slow_path args

($\text{success}_{\text{slow}}$ = TRUE if args is subnormal)

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

Transmit instruction	`dest <- op args`
DO variants	DO-op$_1$ … DO-op$_N$
Predictor	`Pred`
Predicting DO variant	`i <- Pred.predict (public_input)` (dest$_i$, success$_i$) <- DO-op$_i$ args

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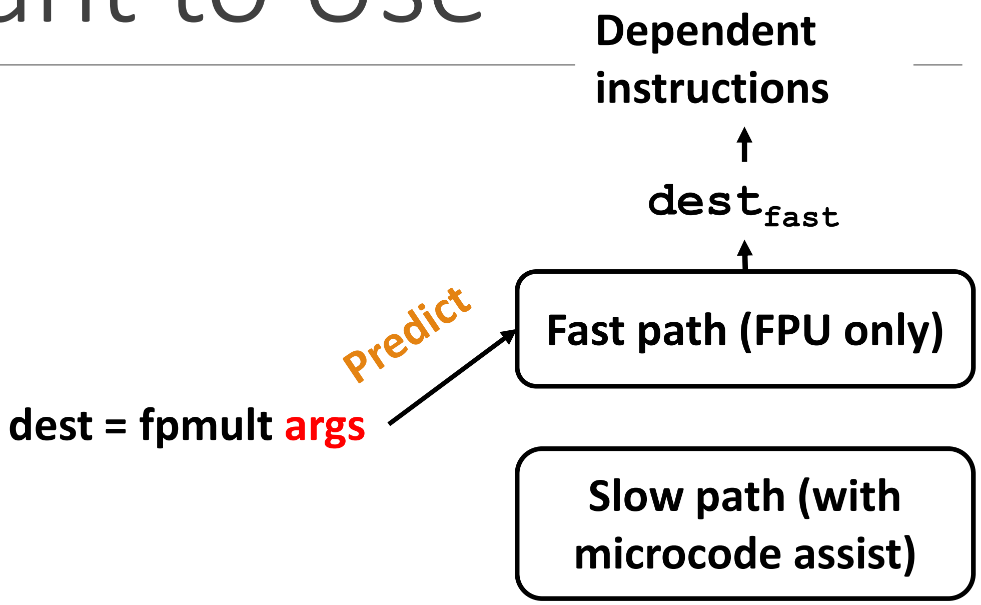


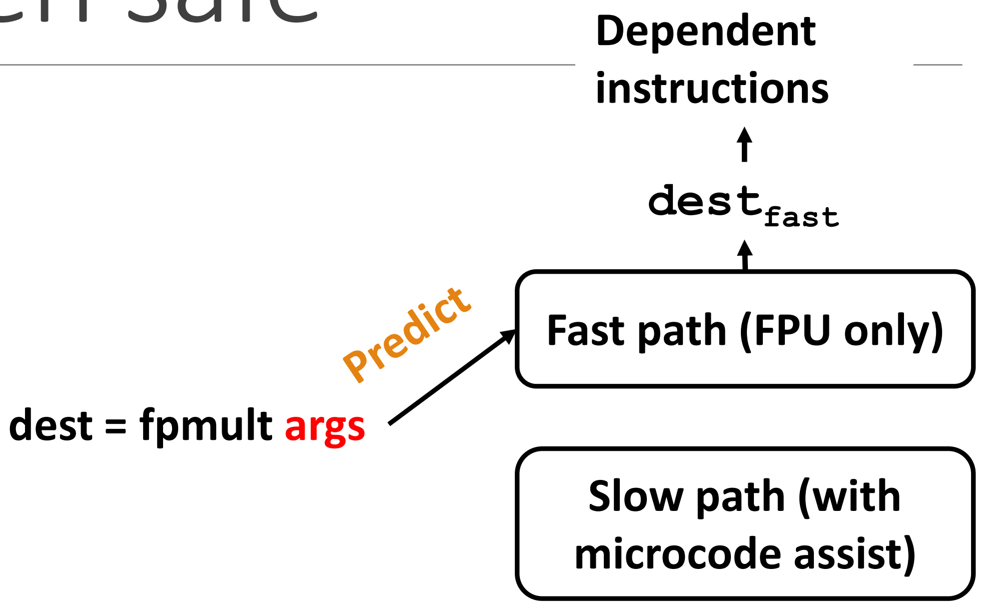
Static Predictor: always predicting “Fast path”

dest_{fast}, success_{fast} <- fast_path args
  (success_{fast} = TRUE if args is normal
   success_{fast} = FALSE if args is subnormal)

SDO Framework: Step 3: Resolve Prediction when safe

Transmit instruction	dest <- op args
DO variants	DO-op$_1$ … DO-op$_N$
Predictor	Pred
Predicting DO variant	i <- Pred.predict (public_input) (dest$_i$, success$_i$) <- DO-op$_i$ args

Resolving when safe	Pred.update(…)
	if (!success$_i$)
	squash from “dest <- op args”



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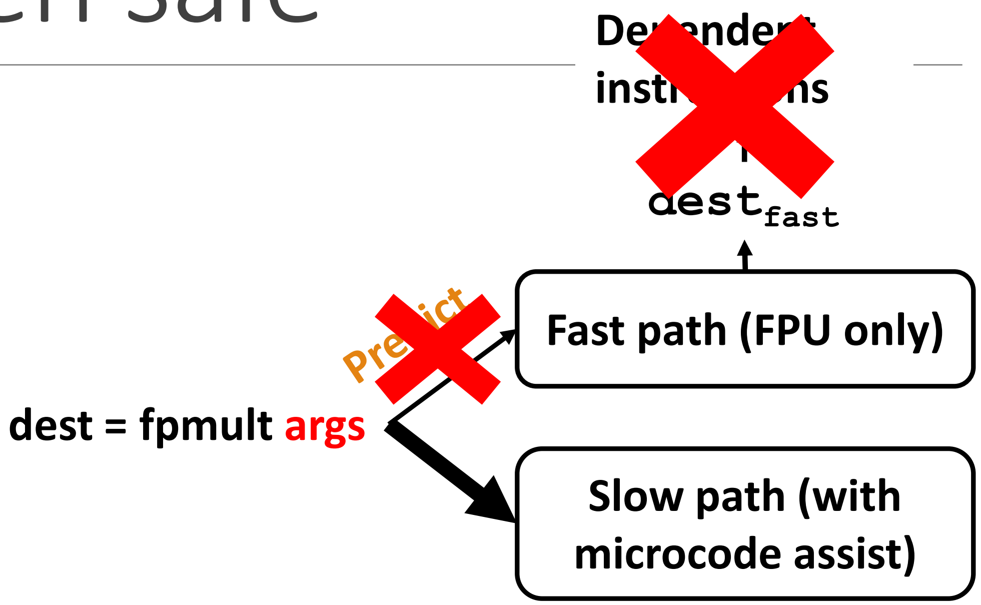

success$_{fast}$ == FALSE

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
  - `DO-ld`$_{Mem}$: accessing L1, L2, L3 and DRAM sequentially
- (`dest`$_{xx}$, `success`$_{xx}$) `<- DO-ld`$_{xx}$ `addr` `// dest`$_{xx}$ `=` $\perp$ `if success`$_{xx}$ `== FALSE`

Step 1: Define DO Variants for Loads

- DO variants
  - **$\texttt{DO-ld}_{\texttt{L1}}$** : only accessing L1
  - **$\texttt{DO-ld}_{\texttt{L2}}$** : only accessing L1 and L2 sequentially
  - **$\texttt{DO-ld}_{\texttt{L3}}$** : only accessing L1, L2 and L3 sequentially
  - **$\texttt{DO-ld}_{\texttt{Mem}}$** : accessing L1, L2, L3 and DRAM sequentially
- $(\texttt{dest}_{\texttt{XX}},\ \texttt{success}_{\texttt{XX}})\ \texttt{<-}\ \texttt{DO-ld}_{\texttt{XX}}\ \texttt{addr}$ $\quad$ $\texttt{//}\ \texttt{dest}_{\texttt{XX}} = \perp\ \texttt{if}\ \texttt{success}_{\texttt{XX}}\ \texttt{==}\ \texttt{FALSE}$
- DO variants (**$\texttt{DO-ld}_{\texttt{Li}}$**) must be free of adversary-observable hardware resource usage
  - Cannot modify cache state (tag, data, LRU bits, etc.)
  - Cannot incur address-dependent latency (e.g., free of bank conflict, port contention)
  - ……

Step 1: Define DO Variants for Loads

- DO variants
  - $\mathtt{DO\text{-}ld}_{\mathtt{L1}}$: only accessing L1
  - $\mathtt{DO\text{-}ld}_{\mathtt{L2}}$: only accessing L1 and L2 sequentially
  - $\mathtt{DO\text{-}ld}_{\mathtt{L3}}$: only accessing L1, L2 and L3 sequentially
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- $(\mathtt{dest}_{\mathtt{XX}},\ \mathtt{success}_{\mathtt{XX}})\ \texttt{<-}\ \mathtt{DO\text{-}ld}_{\mathtt{XX}}\ \mathtt{addr}$ $\quad$ `//` $\mathtt{dest}_{\mathtt{XX}} = \perp$ `if` $\mathtt{success}_{\mathtt{XX}}$ `== FALSE`
- DO variants ($\mathtt{DO\text{-}ld}_{\mathtt{Li}}$) must be free of adversary-observable hardware resource usage
  - Cannot modify cache state (tag, data, LRU bits, etc.)
  - Cannot incur address-dependent latency (e.g., free of bank conflict, port contention)
  - ……
- 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 ⊥ to dependents -> squash

Predicted level	DO Variant
1 (L1)	$\texttt{DO-ld}_{\texttt{L1}}$
2 (L2)	$\texttt{DO-ld}_{\texttt{L2}}$
3 (L3)	$\texttt{DO-ld}_{\texttt{L3}}$
4 (Memory)	$\texttt{DO-ld}_{\texttt{Mem}}$

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  - "inaccurate": `i > j` -> cache miss -> writeback $\perp$ to dependents -> squash
- 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-ld$_{L1}$
2 (L2)	DO-ld$_{L2}$
3 (L3)	DO-ld$_{L3}$
4 (Memory)	DO-ld$_{Mem}$

Step 3: Resolve When Load is Safe

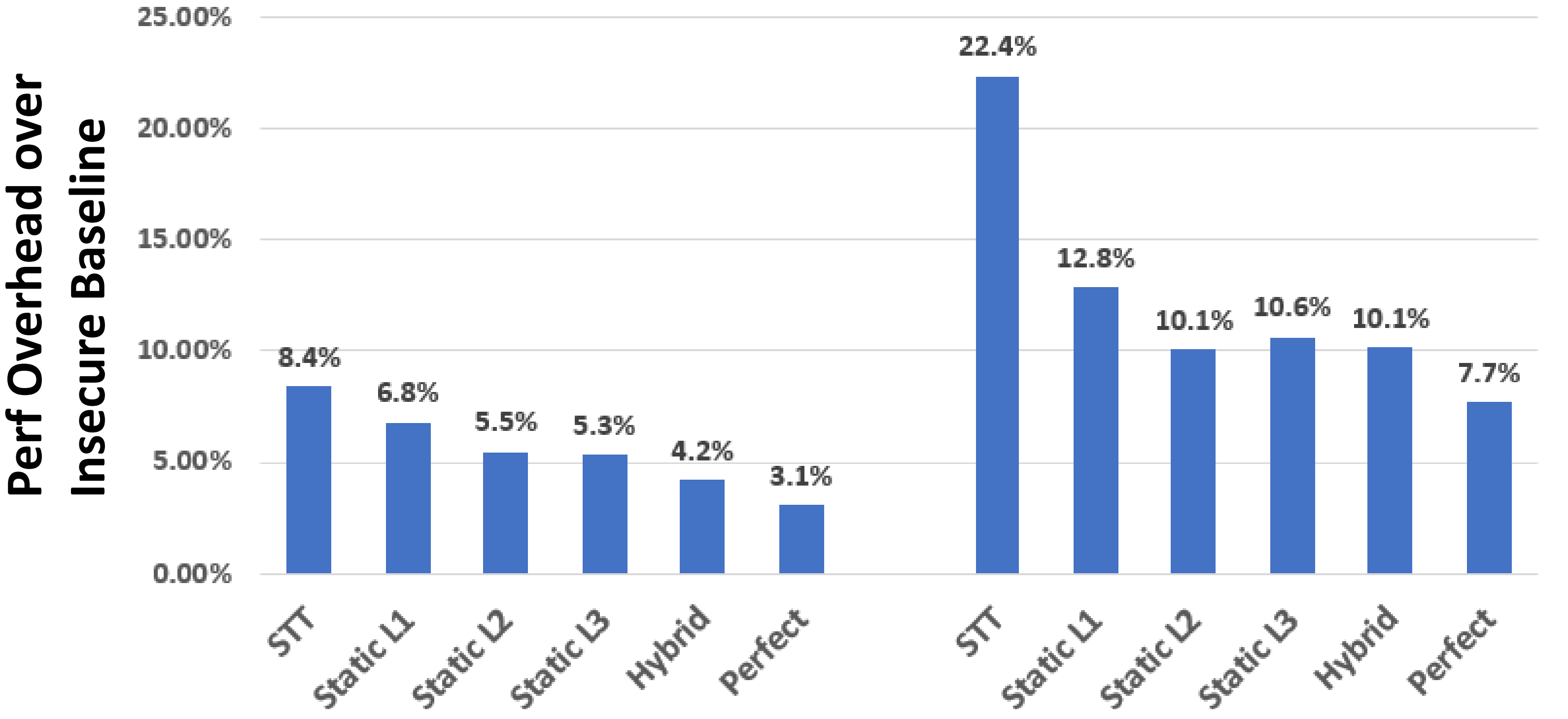
- Update the predictor
- Squash if **`success == FALSE`**
- In a multi-processor:

  `DO-ld`$_{LX}$ cannot modify cache state

  → Data fetched by **`DO-ld`**$_{LX}$ may not be cached in L1

  → May missing 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



“Spectre” attack model
Consider control-flow speculation

“Futuristic” attack model
Consider all types of speculation

Transmitters:

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

Static L1: always predicting $\texttt{DO-ld}_{\texttt{L1}}$
Static L2: always predicting $\texttt{DO-ld}_{\texttt{L2}}$
Static L3: always predicting $\texttt{DO-ld}_{\texttt{L3}}$
Hybrid: using the hybrid predictor
Perfect: prediction is accurate and precise

Conclusion

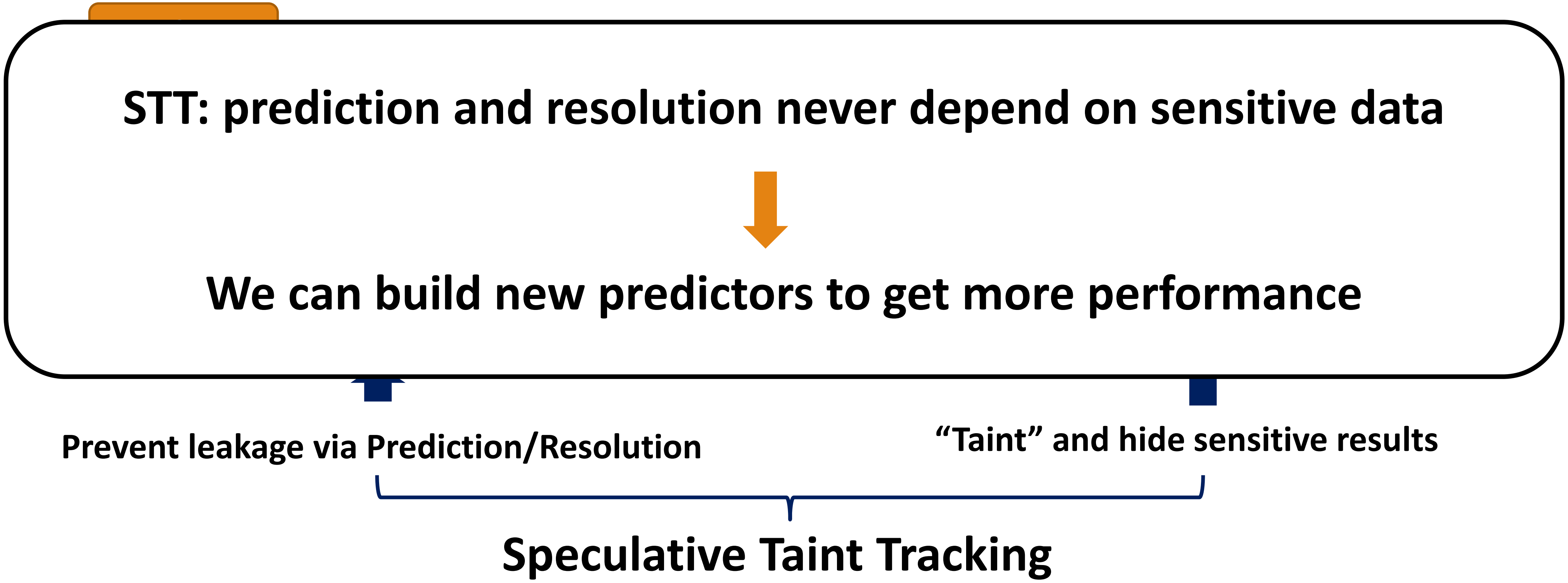
- SDO serves as a new speculative execution attack mitigation with high-performance and high-security
- The proposed SDO framework augments STT with significant speedup without compromising security

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