MicroScope: Enabling Microarchitectural Replay Attacks

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Overview

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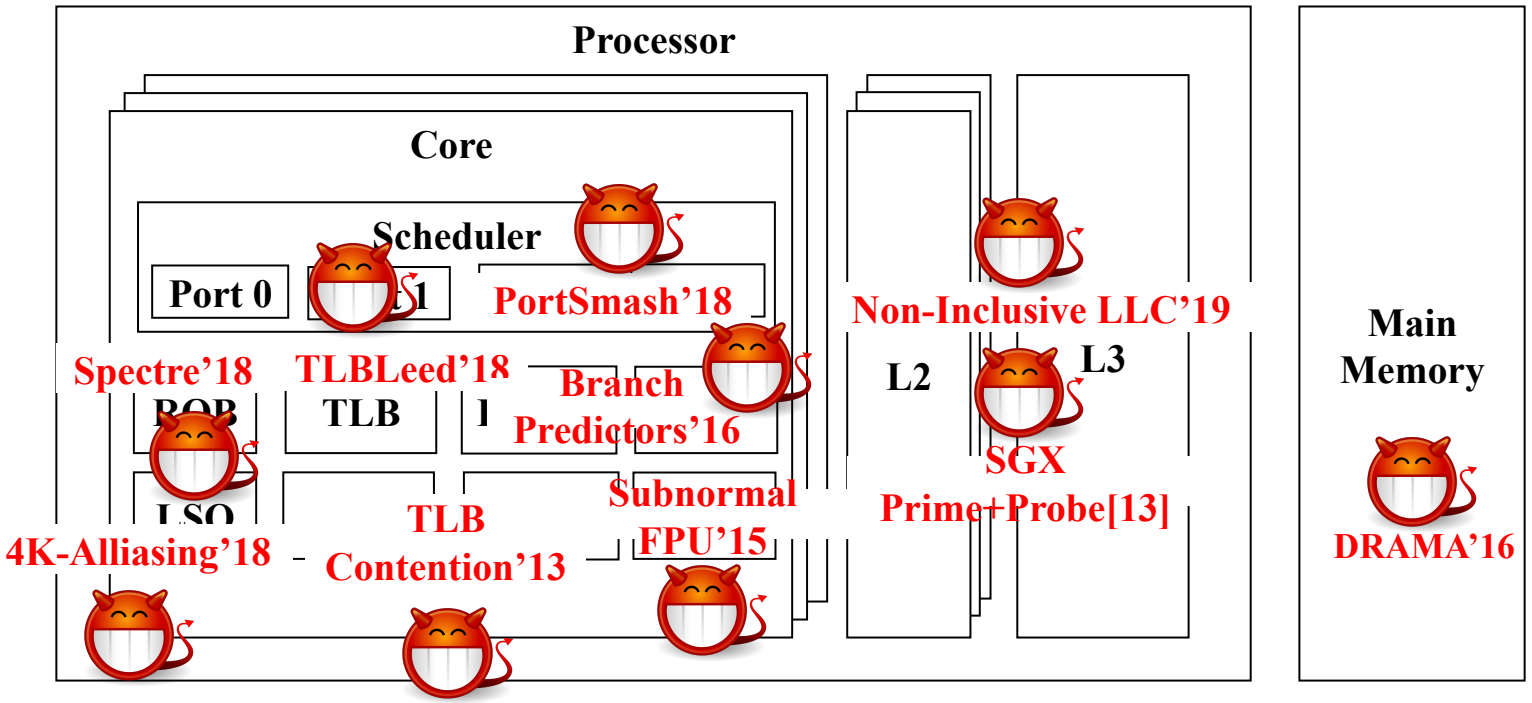
The Era of Side-Channels



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How much can leak over side channels?

Victim:

```
if (secret)
  use resource
else
  don't use resource
```

Attacker:

```
for ..
  t1 = time()
     use resource
  t2 = time()
```

- Need repeated measurements to be confident → Denoise
- However, many applications run only once → Attacker gets 1 measurement
- Can attackers really extract secrets?

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Contribution: Microarchitectural Replay Attacks

- Attacker leverages speculative execution
  - To repeatedly replay a snippet of victim code
  - That runs only once

} Primitive to denoise arbitrary side channels

Victim:

```
ld addr // "replay handle"
…
ld secret // secret the attacker tries to leak
```

{ Memory operation that will cause a squash and re-execute }

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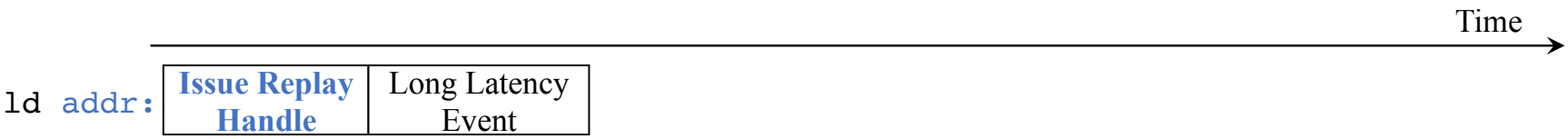
Contribution: Microarchitectural Replay Attacks



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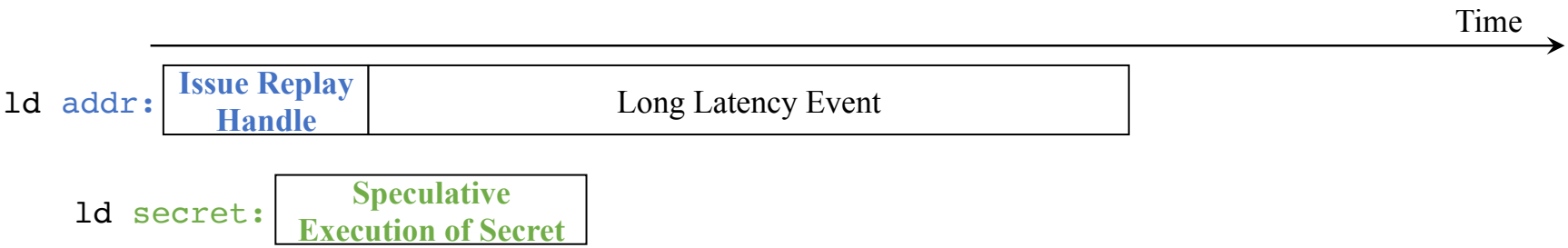
Contribution: Microarchitectural Replay Attacks



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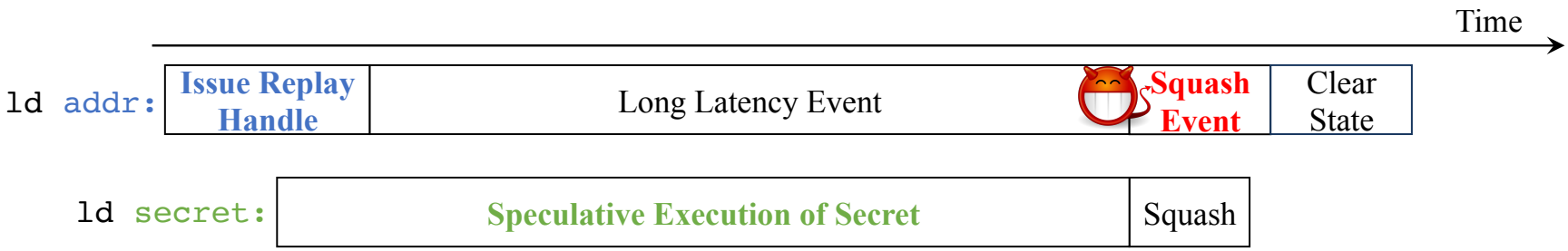
Contribution: Microarchitectural Replay Attacks



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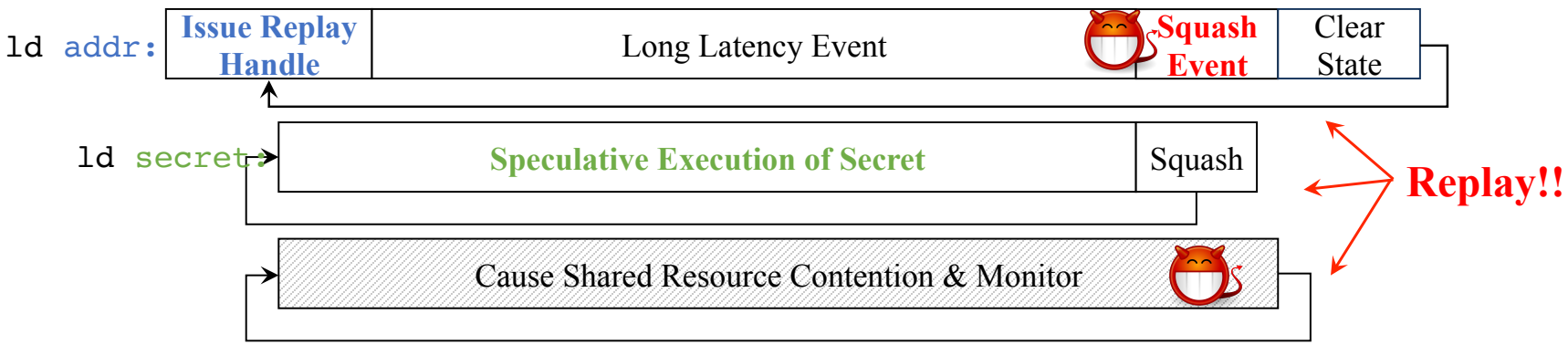

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Background

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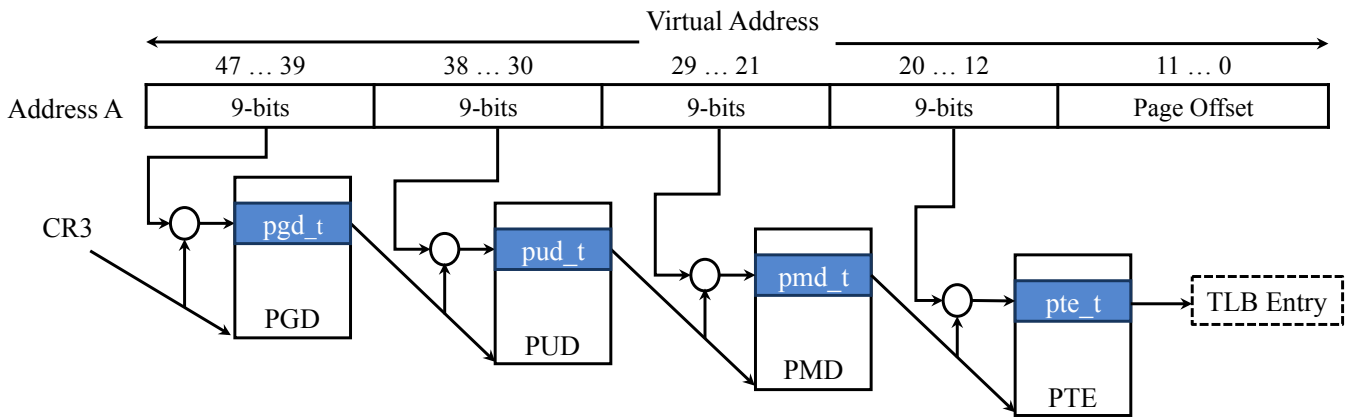
Page Tables Background



- Page tables stored in memory
- On a TLB Miss → "*page walk*" = memory accesses
  - Each step of page walk = cache hit/miss.
  - Page walk cache (PWC): hardware cache of translations
- If Present bit in pte_t is cleared → Page Fault, invoke OS

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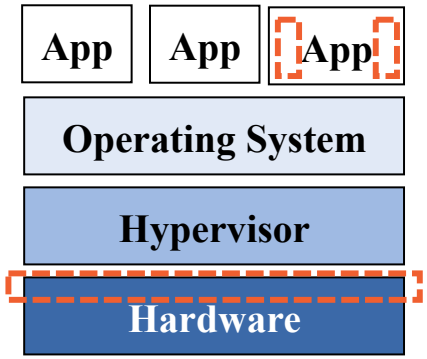
Trusted Computing with SGX

- Designed to run sensitive applications in the cloud
- Do not trust OS/Hypervisor
- OS/Hypervisor cannot introspect/tamper enclave
- Unfortunately, OS/Hypervisor still manages demand paging

Attack Surface With Enclaves



Attack Surface

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Threat Model

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Threat Model

In SGX the OS is responsible

- Demand paging

Attacker (OS) can:

- Evict TLB entries
- Evict page walk cache entries
- Monitor side channels

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MicroScope:

A framework to exploit microarchitectural replay attacks

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Attack Examples

Victim Code

```
1. //public address
2. handle(pub_addr);
3. ...
4. transmit(secret);
5. ...
```

Loop Victim Code:

```
1. for i in ...
2.   handle(pub_addrA);
3.   ...
4.   transmit(secret[i]);
5.   ...
6.   memOp(pub_addrB);
7.   ...
```

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Terminology

Victim Code

```
1. //public address
2. handle(pub_addr);
3. ...
4. transmit(secret);
5. ...
```

Replay handle:

- Load to a public address (known to OS)

Transmitter:

- Any instruction(s) whose execution reveals secret through some side channel
- Occurs < ROB length from Replay Handle

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Timeline of a MicroScope Attack - Setup

Attacker Victim

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Timeline of a MicroScope Attack - Setup

Attacker Victim

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Attacker Victim

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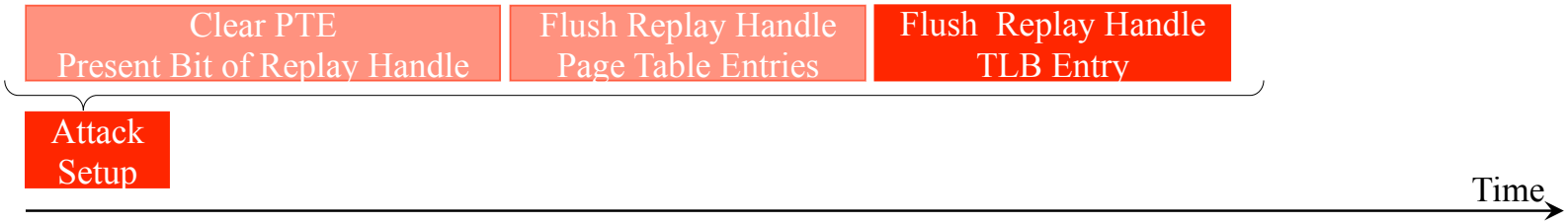
Timeline of a MicroScope Attack - Setup



Attacker Victim

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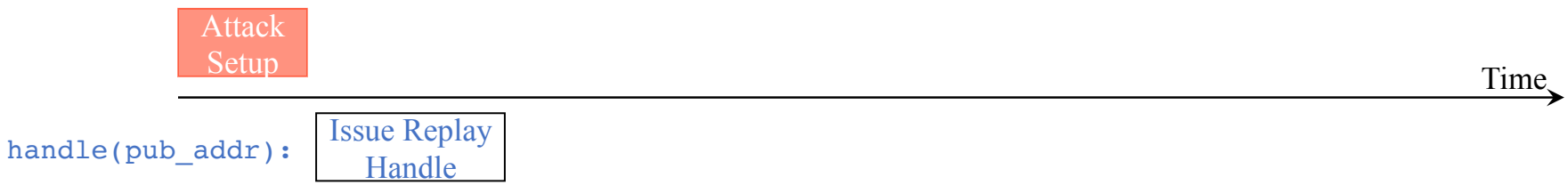
Timeline of a MicroScope Attack



Attacker Victim

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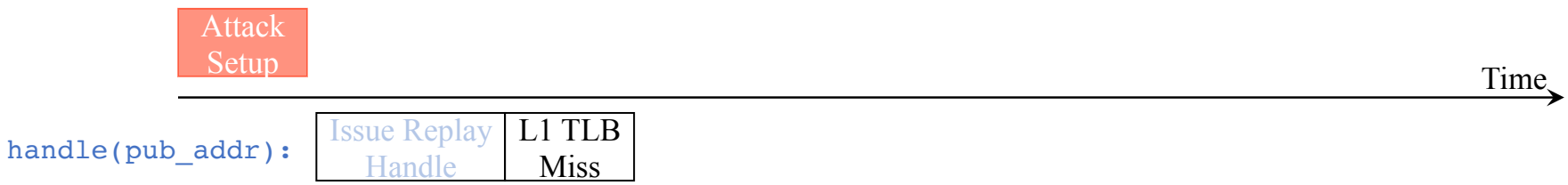
Timeline of a MicroScope Attack



Attacker Victim

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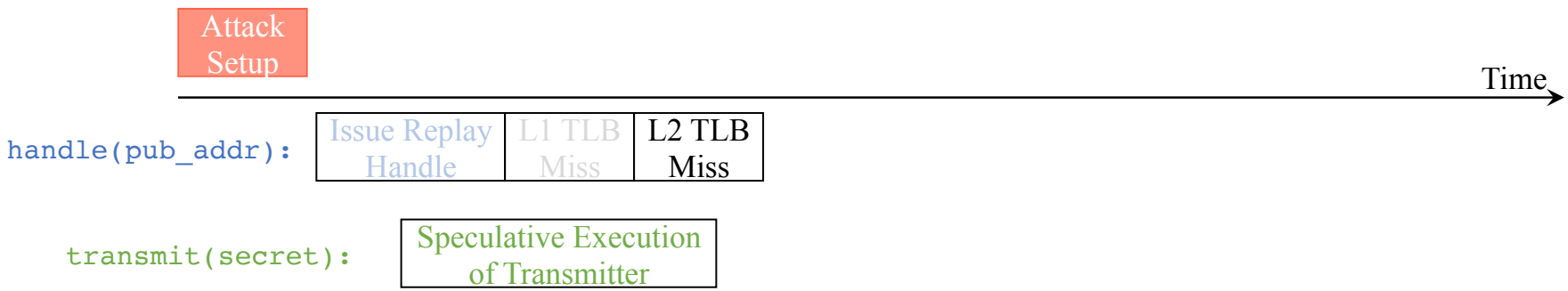
Timeline of a MicroScope Attack



Attacker Victim

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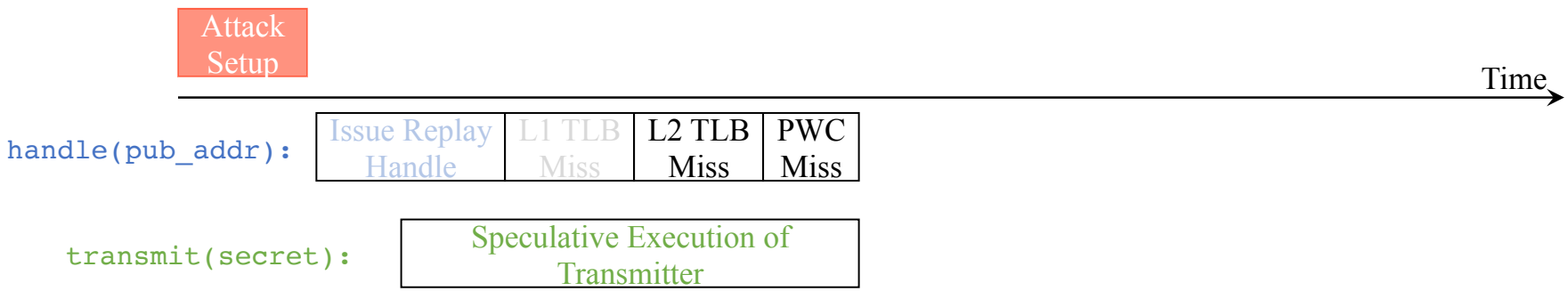
Timeline of a MicroScope Attack



Attacker Victim

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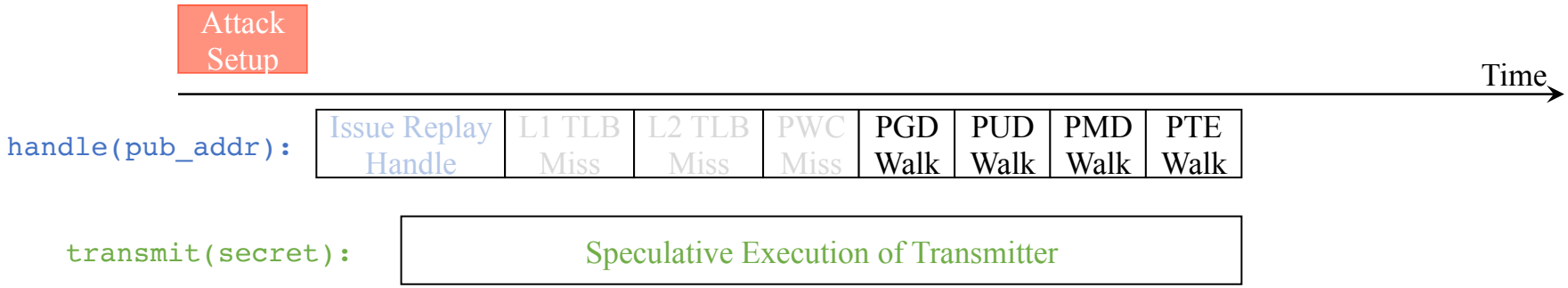
Timeline of a MicroScope Attack



Attacker Victim

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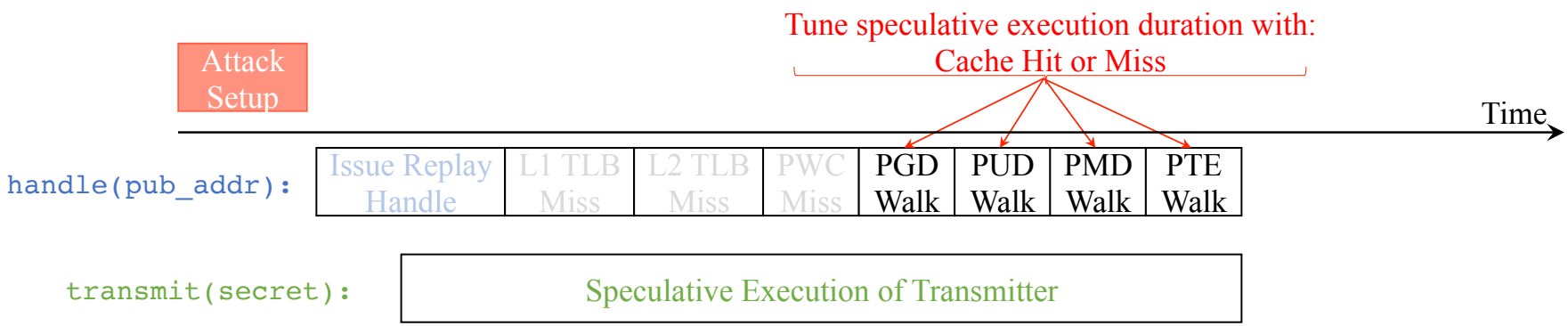
Timeline of a MicroScope Attack



Attacker Victim

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Timeline of a MicroScope Attack

Attacker Victim

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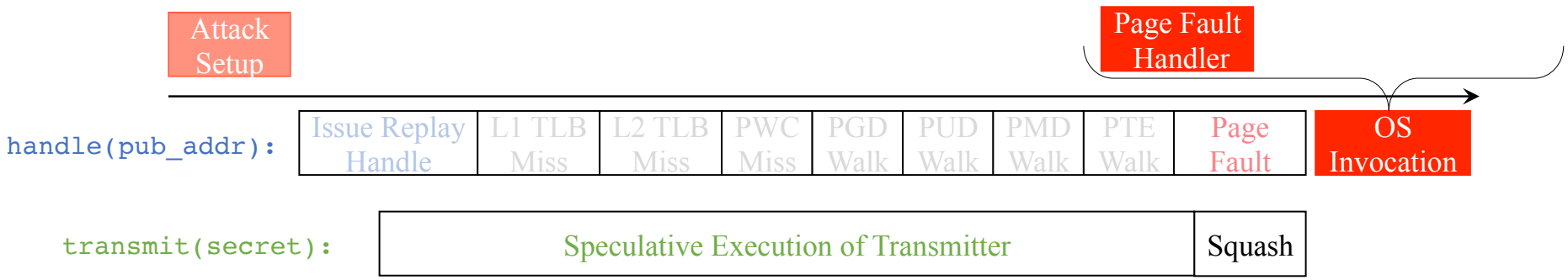

Attacker Victim

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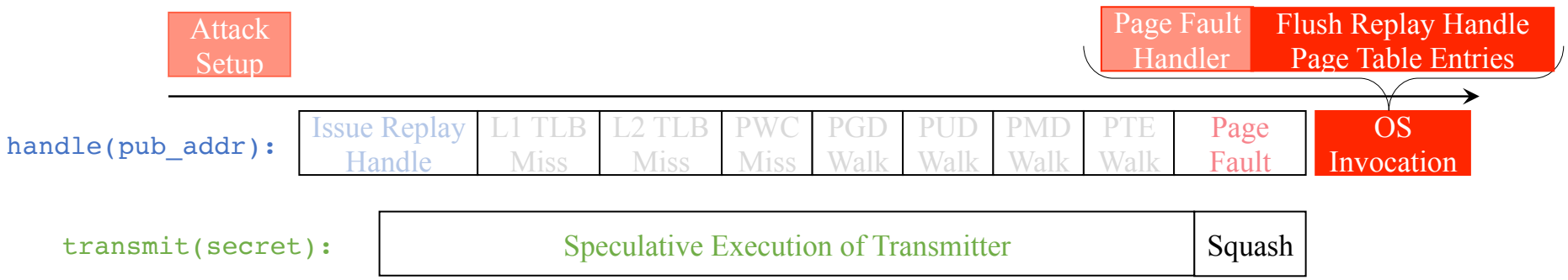
Timeline of a MicroScope Attack



Attacker Victim

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Timeline of a MicroScope Attack

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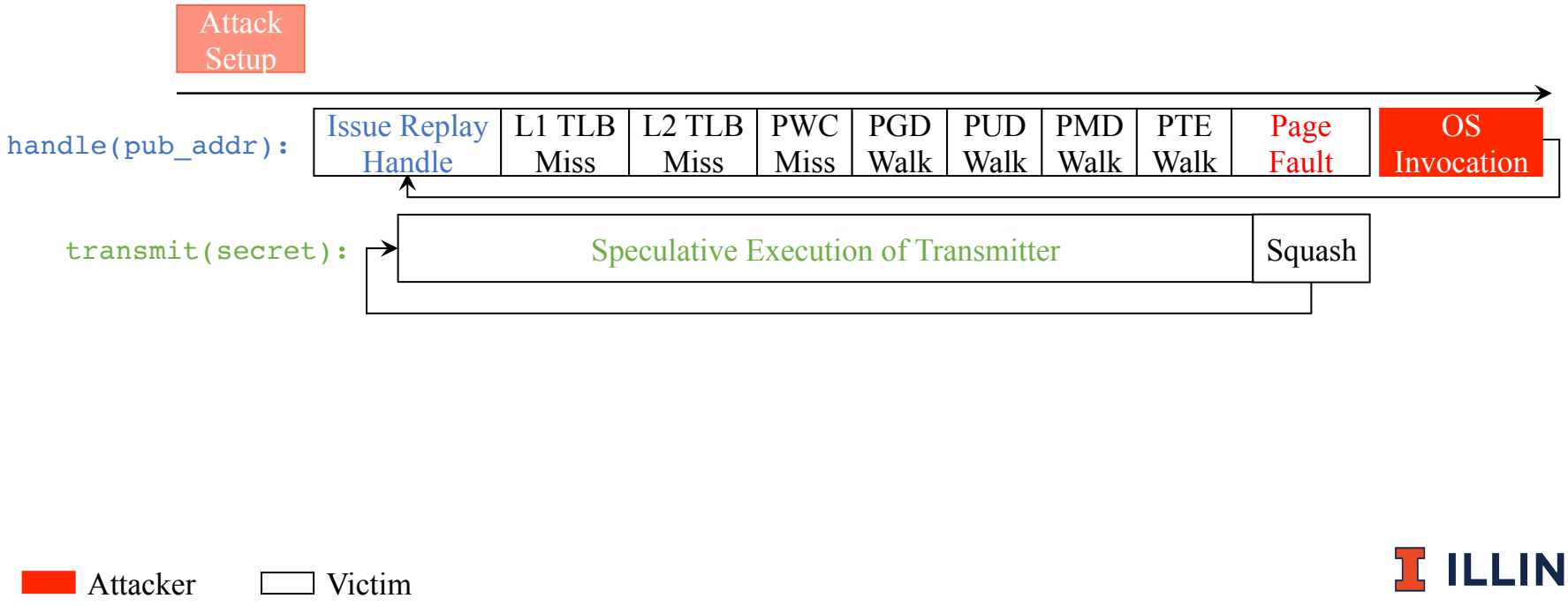

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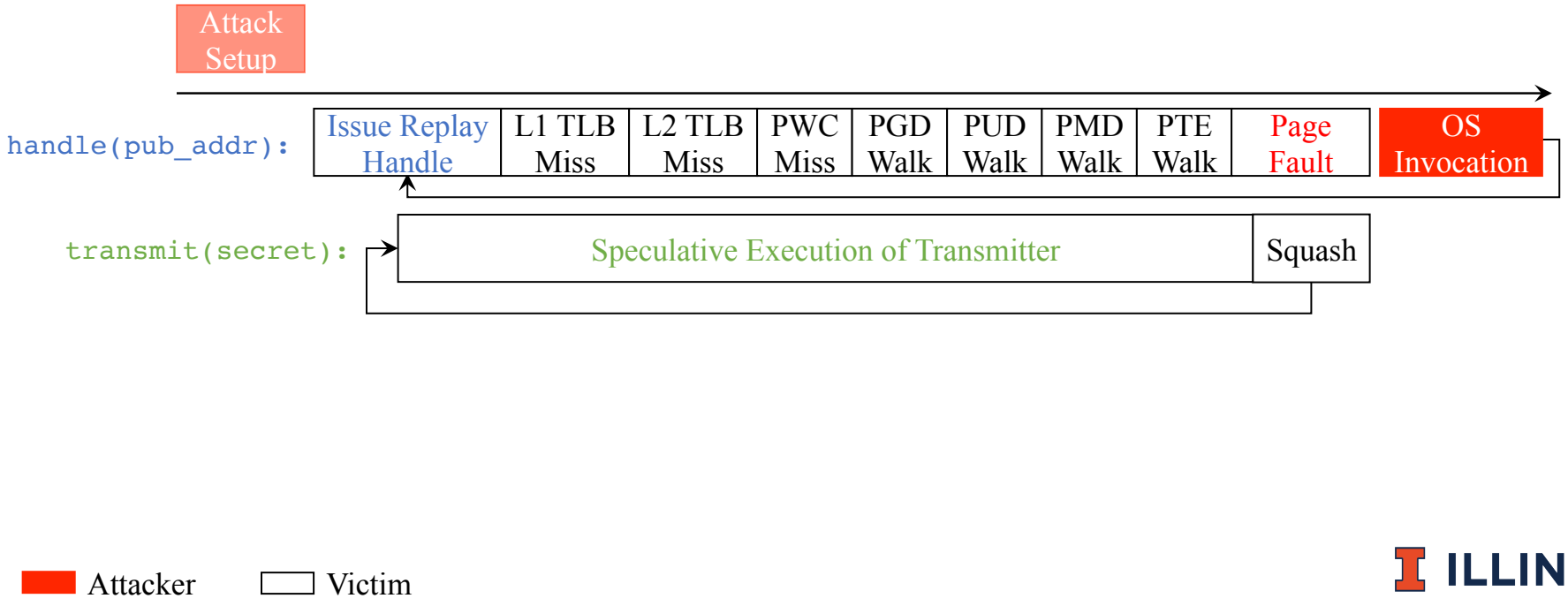

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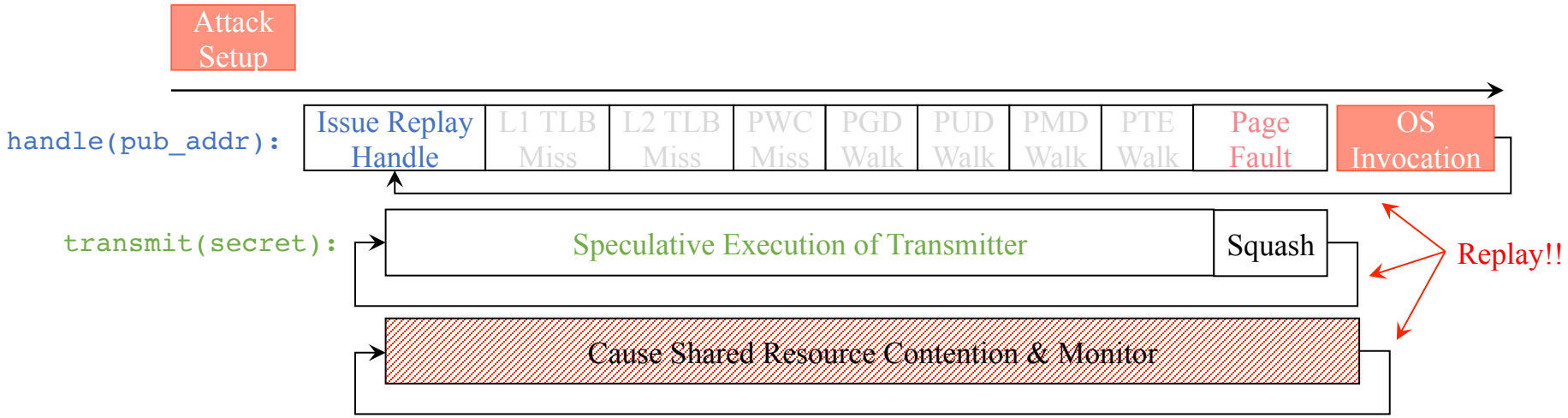

Attacker Victim Attacker Monitor/Contention thread

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Loop Example

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Loop Example

Victim:

```
for i in ...
  handle(pub_addrA);
  ...
  transmit(secret[i]);
  ...
  memOp(pub_addrB);
  ...
```

- **Goal:**
  - Leak secret in every iteration
- **Challenge:**
  - Monitor window of a replay handle < ROB length

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Loop Example

Victim:

```
1. for i in ...
2.   handle(pub_addrA);
3.   ...
4.   transmit(secret[i]);
5.   ...
6.   pivot(pub_addrB);
7.   ...
```

Instruction used to pivot around transmit instructions

Replay Handle Transmit Code Pivot Instruction

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In a Loop

Static Code

```
for i in ...
  handle(pub_addrA);
  ...
  transmit(secret[i]);
  ...
  pivot(pub_addrB);
  ...
```

Dynamic code

Iteration i=0

```
handle(pub_addrA);
...
transmit(secret[0]);
...
pivot(pub_addrB);
...
```

Iteration i=1

```
handle(pub_addrA);
...
transmit(secret[1]);
....
pivot(pub_addrB);
```

Monitor window

Replay Handle Transmit Code Pivot Instruction

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In a Loop

Static Code

```
1. for i in ...
2.   handle(pub_addrA);
3.   ...
4.   transmit(secret[i]);
5.   ...
6.   pivot(pub_addrB);
7.   ...
```

Dynamic code

```
1. handle(pub_addrA);
2. ...
3. transmit(secret[0]);
4. ...
5. pivot(pub_addrB);
6. ...
7. handle(pub_addrA);
8. ...
9. transmit(secret[1]);
10....
11.pivot(pub_addrB);
```

Pivot page fault

Replay Handle Transmit Code Pivot Instruction

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In a Loop

Static Code

```
1. for i in ...
2.   handle(pub_addrA);
3.   ...
4.   transmit(secret[i]);
5.   ...
6.   pivot(pub_addrB);
7.   ...
```

Dynamic code

```
1. handle(pub_addrA);
2. ...
3. transmit(secret[0]);
4. ...
5. pivot(pub_addrB);
6. ...
7. handle(pub_addrA);
8. ...
9. transmit(secret[1]);
10....
11.pivot(pub_addrB);
```

Retired instructions

Cause page fault on pivot

Replay Handle Transmit Code Pivot Instruction

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In a Loop

Static Code

```
1. for i in ...
2.   handle(pub_addrA);
3.   ...
4.   transmit(secret[i]);
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```

Dynamic code

```
1. handle(pub_addrA);
2. ...
3. transmit(secret[0]);
4. ...
5. pivot(pub_addrB);
6. ...
7. handle(pub_addrA);
8. ...
9. transmit(secret[1]);
10....
11.pivot(pub_addrB);
```

Retired instructions

Cause page fault in new replay handle

Replay Handle Transmit Code Pivot Instruction

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In a Loop

Static Code

```
1. for i in ...
2.   handle(pub_addrA);
3.   ...
4.   transmit(secret[i]);
5.   ...
6.   pivot(pub_addrB);
7.   ...
```

Dynamic code

```
1. handle(pub_addrA);
2. ...
3. transmit(secret[0]);
4. ...
5. pivot(pub_addrB);
6. ...
7. handle(pub_addrA);
8. ...
9. transmit(secret[1]);
10....
11.pivot(pub_addrB);
```

Retired Instructions

New Monitor Window

Use this idea to denoise side channels on AES (see paper)

Replay Handle Transmit Code Pivot Instruction

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Port Contention Attack

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Port Contention Attack with MicroScope

Victim:

```
1. handle(pub_addrA);
2. if (secret)
3.     victim_mul()
4. else
5.     victim_div()
```

No Loop!

Attacker:

```
1. Setup replay attack
2. …
3. for …
4.     t1 = time()
5.     attacker_div()
6.     t2 =time()
7. }
```

Replay Handle Transmit Code Attacker Code

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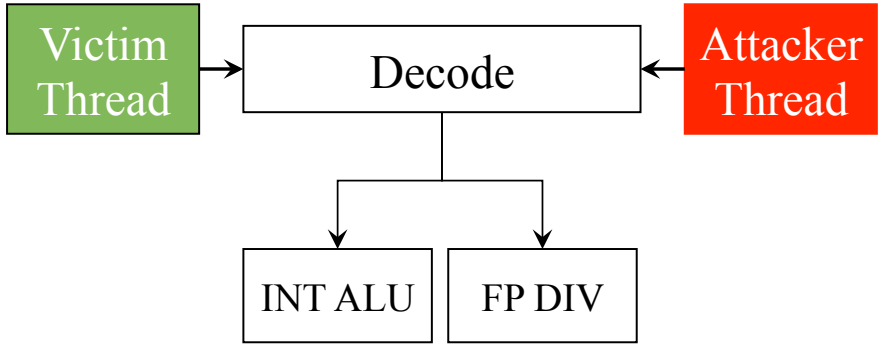
Port Contention Attack with MicroScope



Victim:

```
handle(pub_addrA);
if (secret)
    victim_mul()
else
    victim_div()
```

Attacker:

```
Setup replay attack
...
for ...
    t1 = time()
    attacker_div()
    t2 =time()
}
```

Replay Handle Transmit Code Attacker Code

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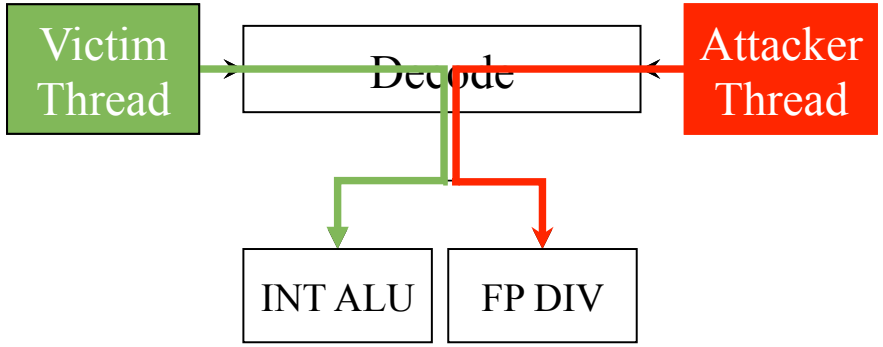
Port Contention Attack with MicroScope



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Attacker:

1. Setup replay attack
2. …
3. for …
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6. t2 =time()
7. }

Replay Handle Transmit Code Attacker Code

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Port Contention Attack with MicroScope

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4. else
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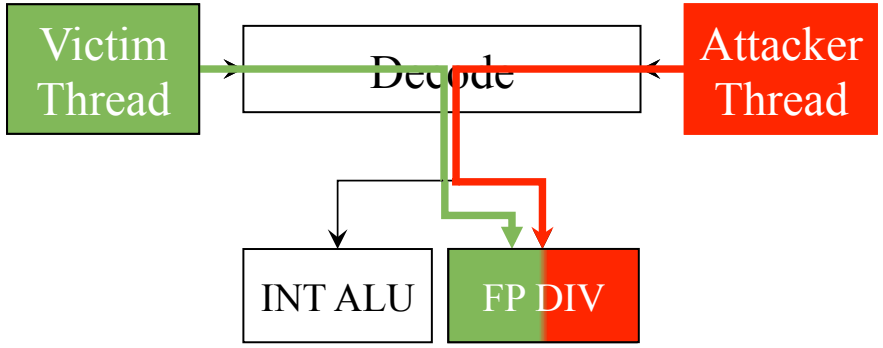
```



Attacker:

1. Setup replay attack
2. …
3. for …
4. t1 = time()
5. attacker_div()
6. t2 =time()
7. }

10,000 → 1

Replay Handle Transmit Code Attacker Code

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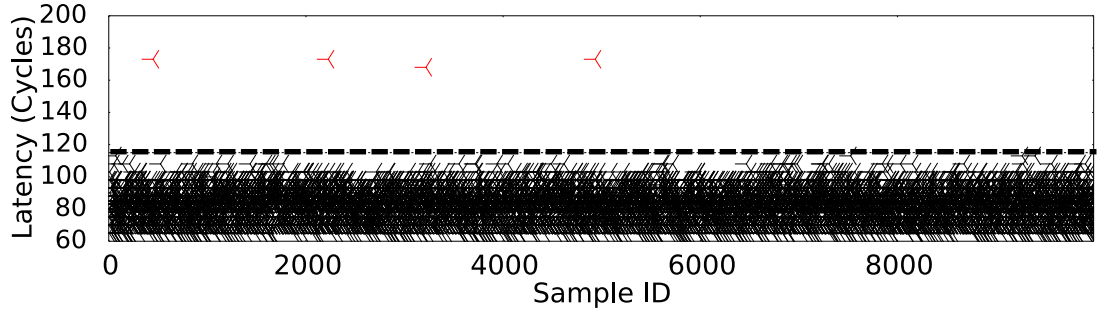
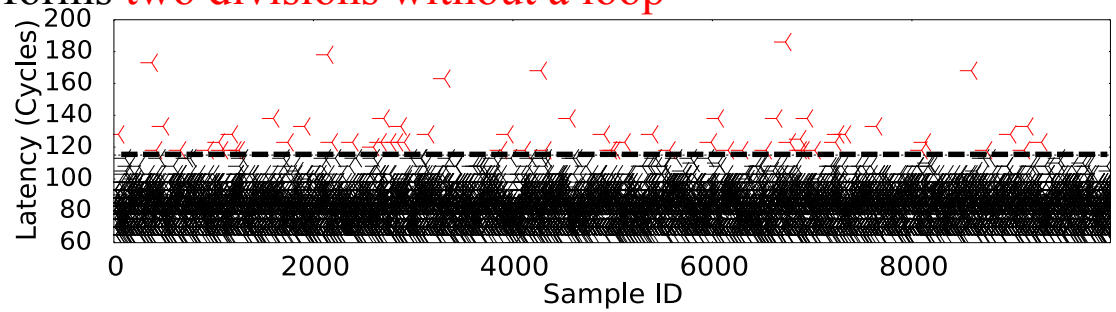
Port Contention Results

- Victim and attacker run on adjacent SMT contexts of same core
- Attacker performs divisions in a loop and measures time
- Victim performs two multiplications without a loop



- Victim performs two divisions without a loop



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Generalizing Microarchitectural Replay Attacks

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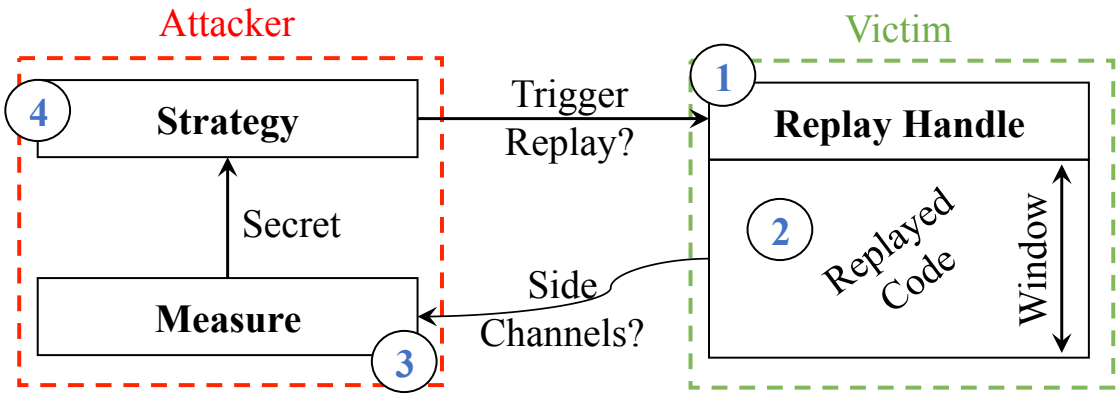
Microarchitectural Replay Attacks



This work:

1. Replay Handle → Page fault-inducing load
2. Replayed Code → Leaky instruction
3. Side Channel → uarch structures
4. Attacker strategy → Page fault until denoise

Changing each can result in different attacks!!

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More On the Paper

- Other attack examples
- MicroScope framework implementation
- Attacks on AES
- Countermeasures discussion

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Open source!

- MicroScope Framework
  - Denoise nearly arbitrary microarchitectural side channels using page faults
  - Only a *single* run of the victim
  - Demonstrate attacks on notoriously noisy side channels
    - Detect the presence or absence of two divide instructions
    - Single-step and denoise cache-based attacks on AES

https://github.com/dskarlatos/MicroScope

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Takeaways

Microarchitectural Replay Attacks
→ New class of attacks

- Opens large new attack surface (noisy side channels)
- Implications for integrity, TSX, physical side channels

- Exploits core microarchitectural feature
  - Dynamic instructions can be replayed through controlled squashes!

- We need new security properties to mitigate these attacks!

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