GoFetch: Breaking Constant-Time Cryptographic Implementations Using Data Memory-Dependent Prefetchers

Boru Chen, Yingchen Wang, Pradyumna Shome,
Christopher Fletcher, David Kohlbrenner, Riccardo Paccagnella,
Daniel Genkin




Carnegie Mellon University

Timing Attacks

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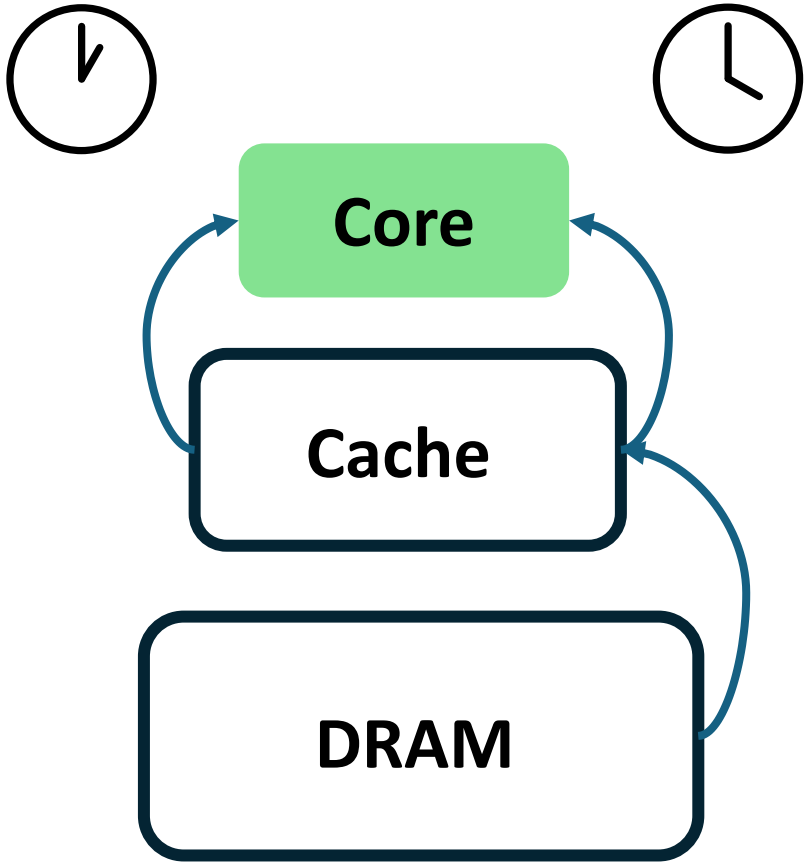

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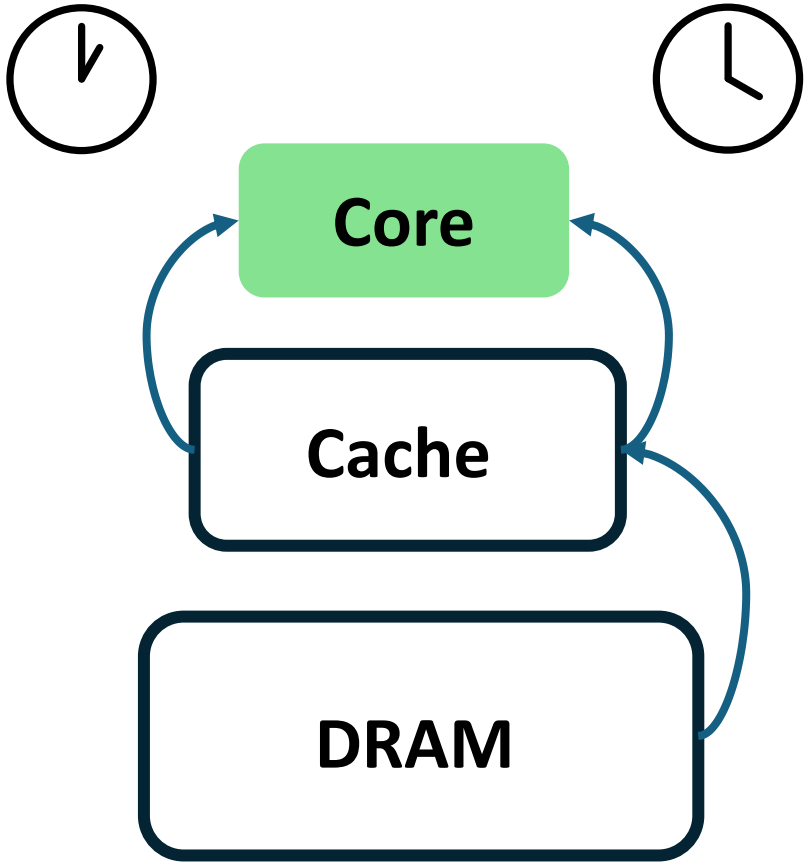


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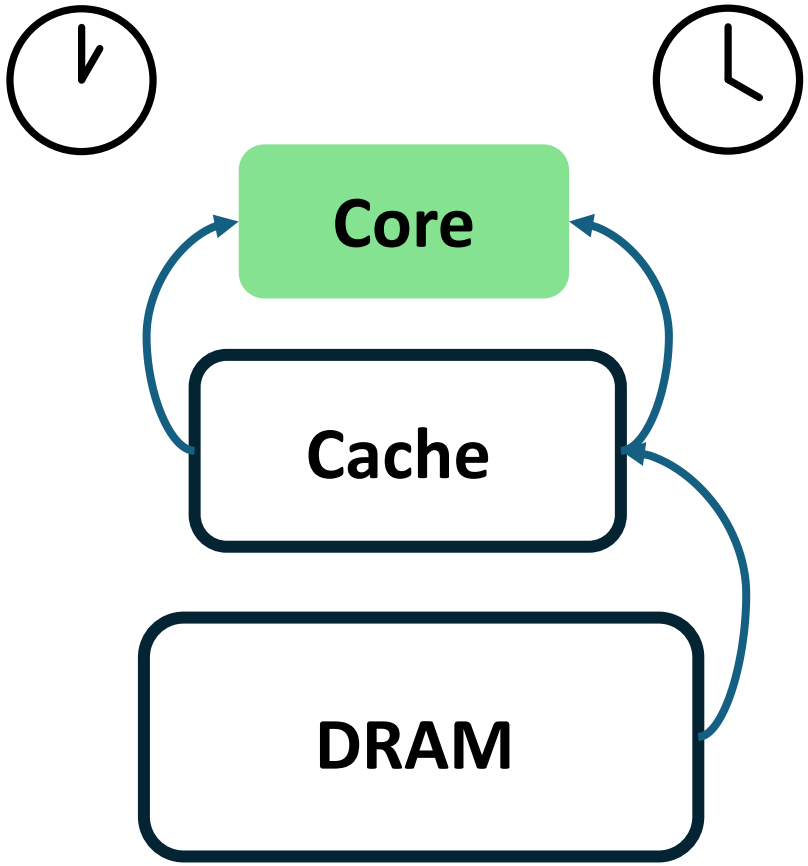


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Flush
Cache

Load
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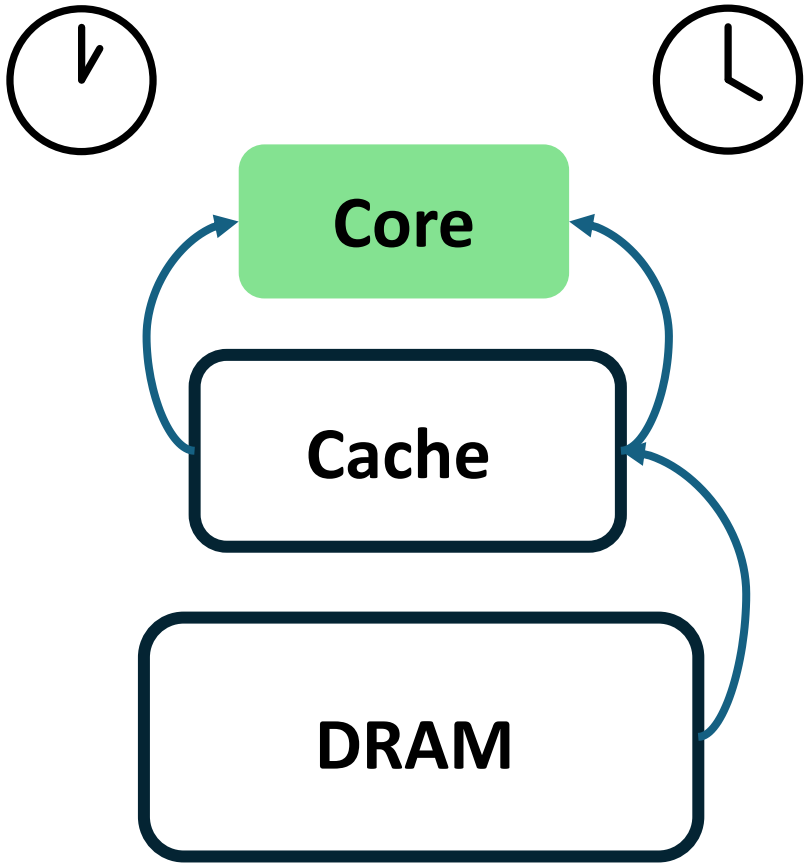


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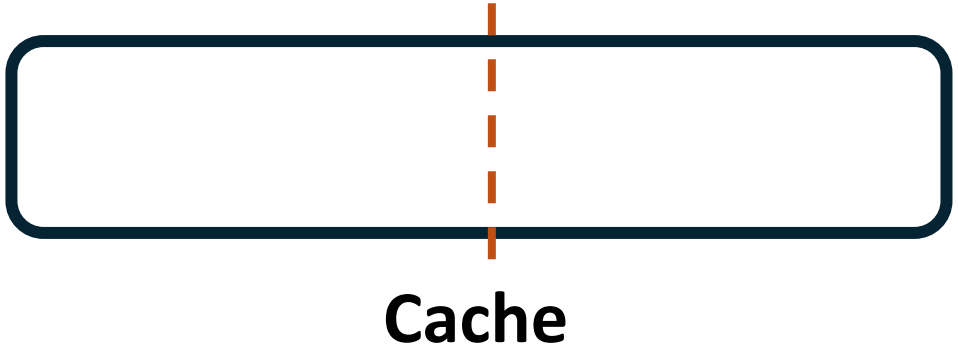

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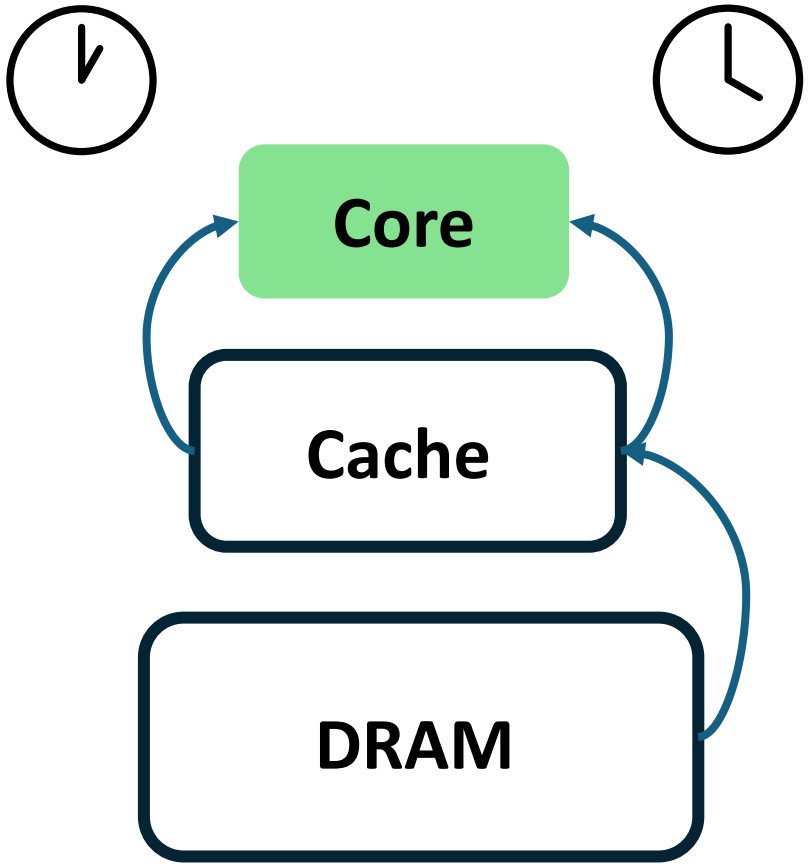


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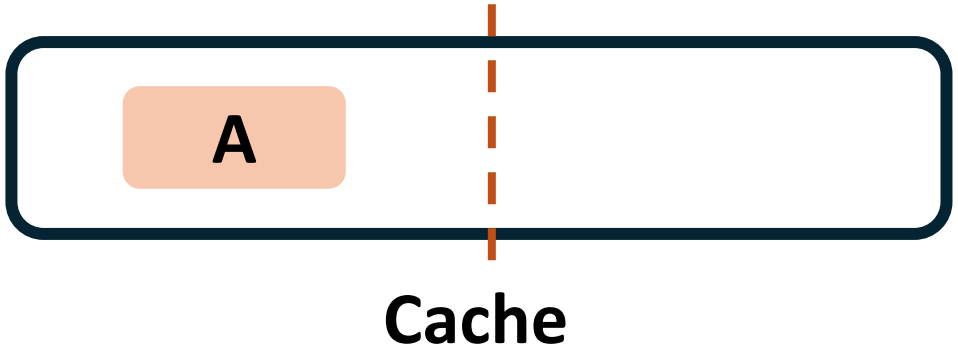

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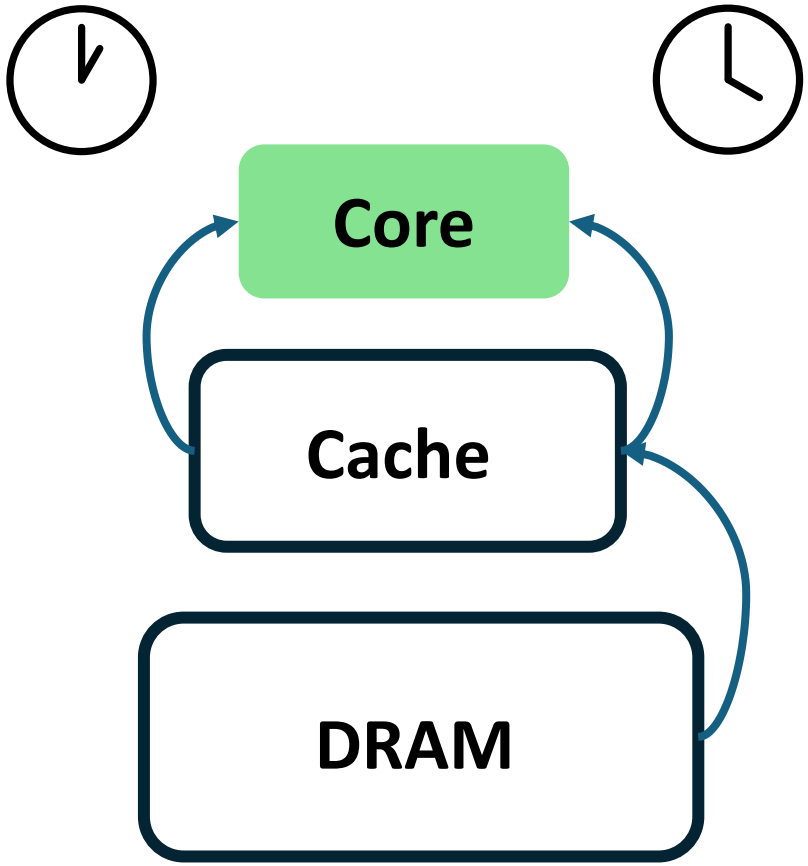


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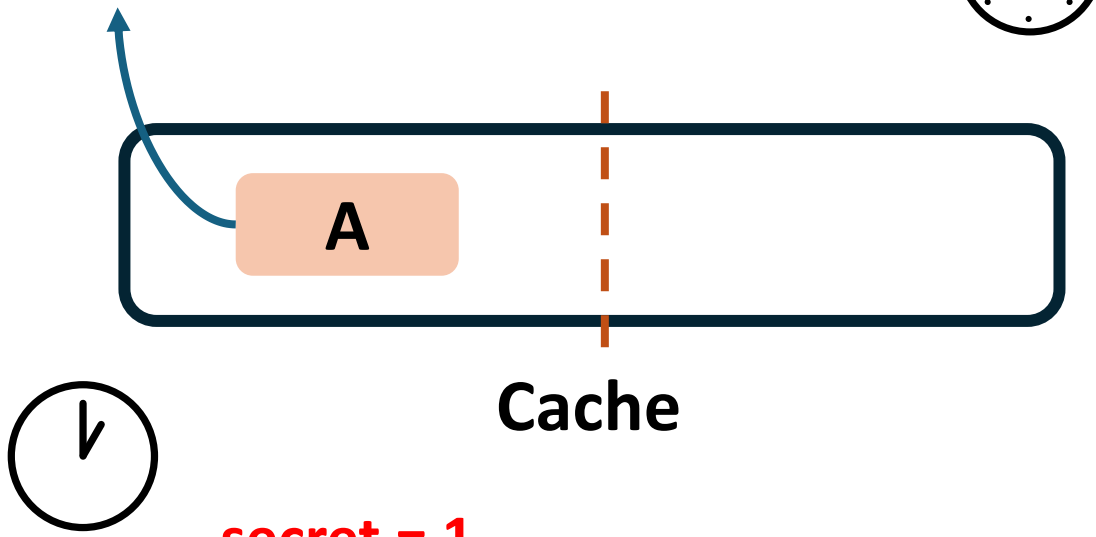

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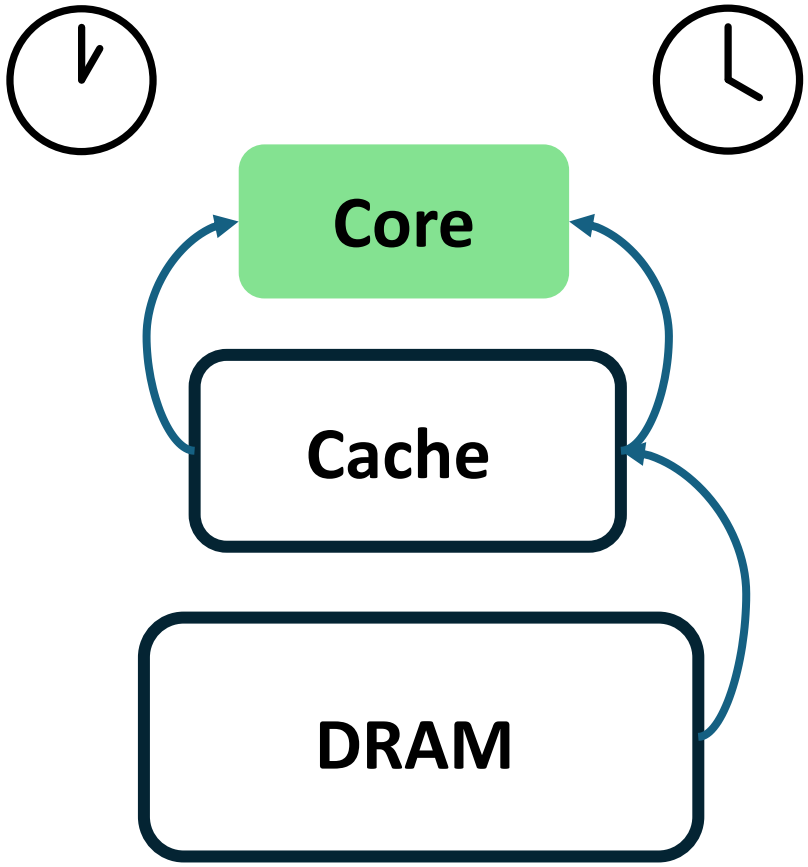


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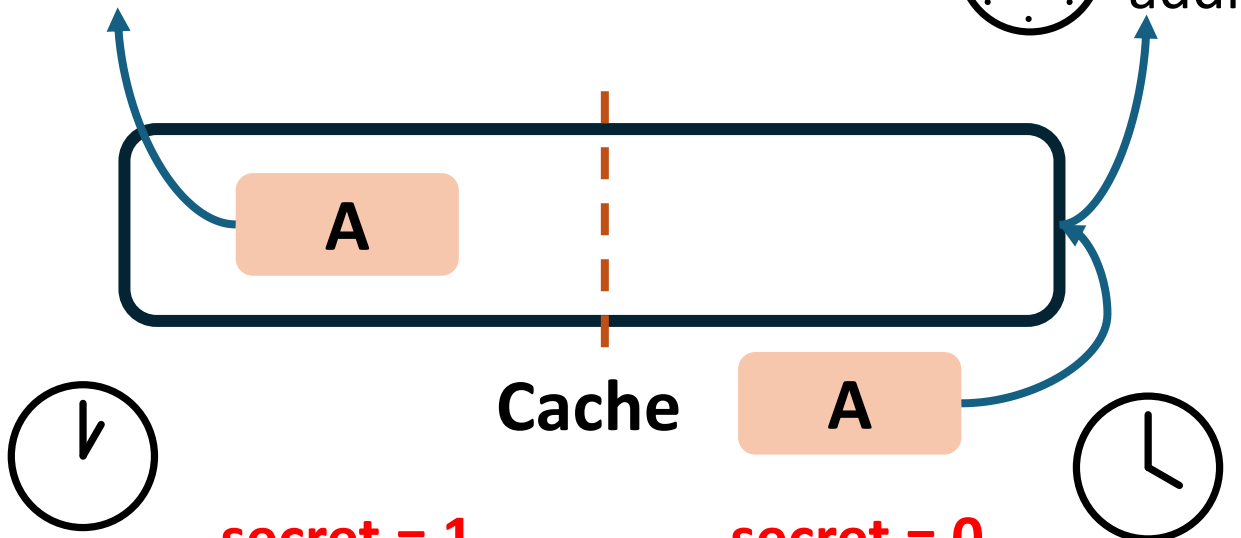
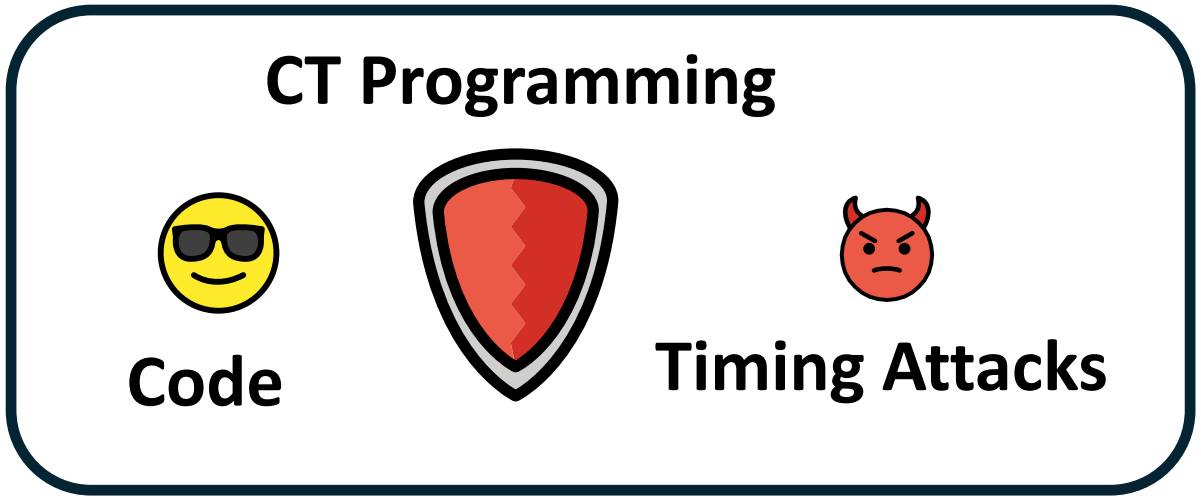


Constant-Time Programming



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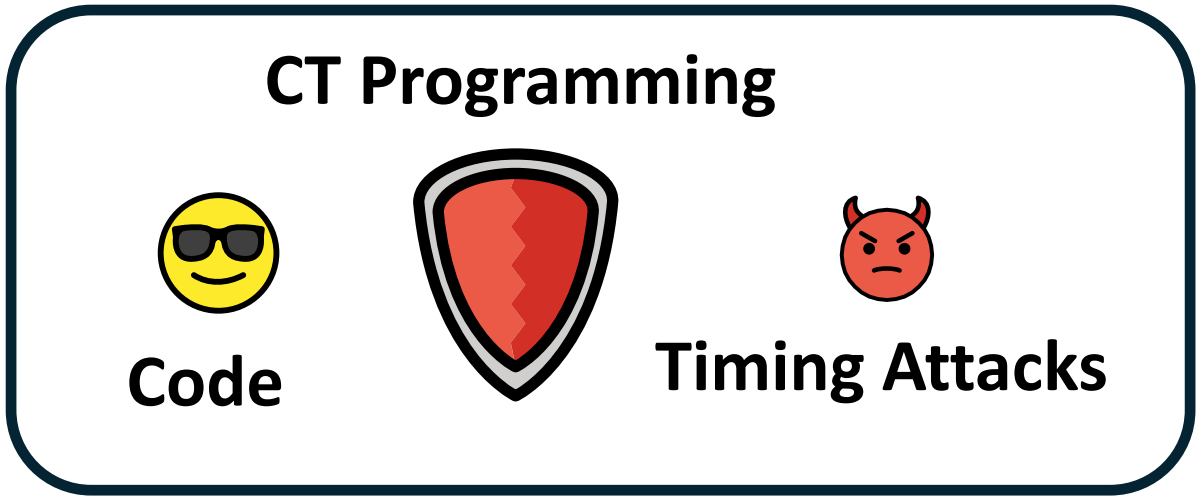

Independent

`secret` ⟷ `time`

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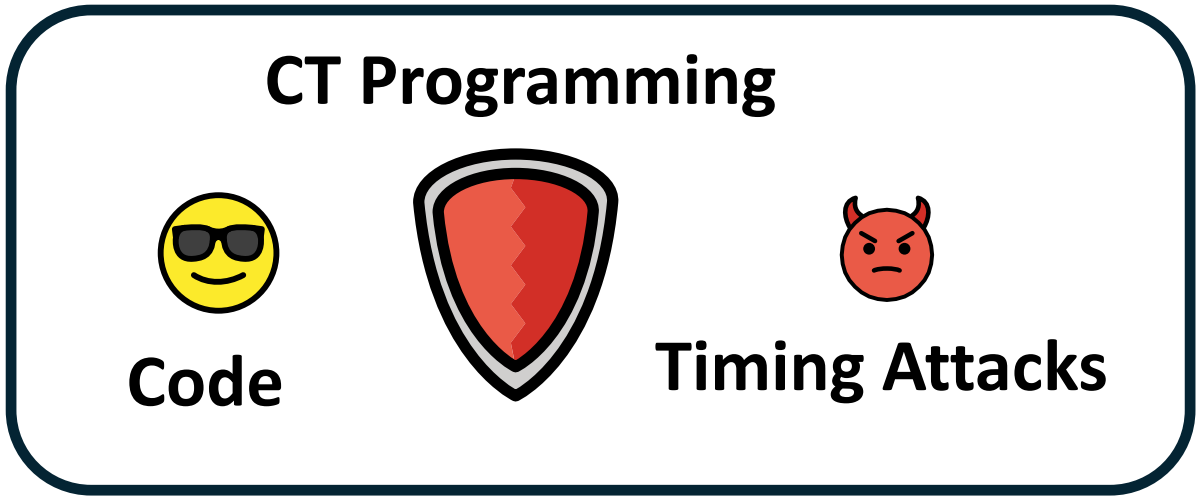

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❌ **Control-Flow**

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if (secret)
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❌ **Time-Variable**

```
secret / 100.0
```

❌ **Memory Address**

```
trash = *secret
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Constant-Time Programming

CT Programming

Code

Timing Attacks

Independent

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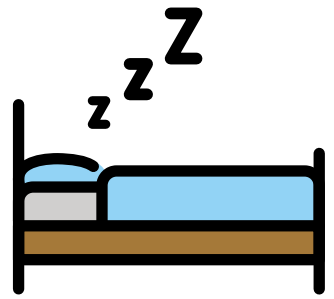

CT Cryptographic Implementation

Constant-Time Programming

<u>This talk:</u>

Show that these principles are insufficient.

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Data Memory Dependent Prefetcher

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program *without* secret-dependent load

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Cache Timing Attacks

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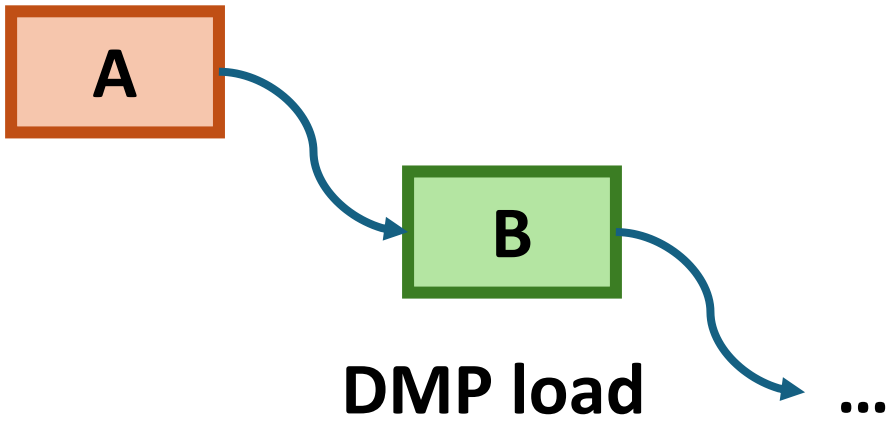

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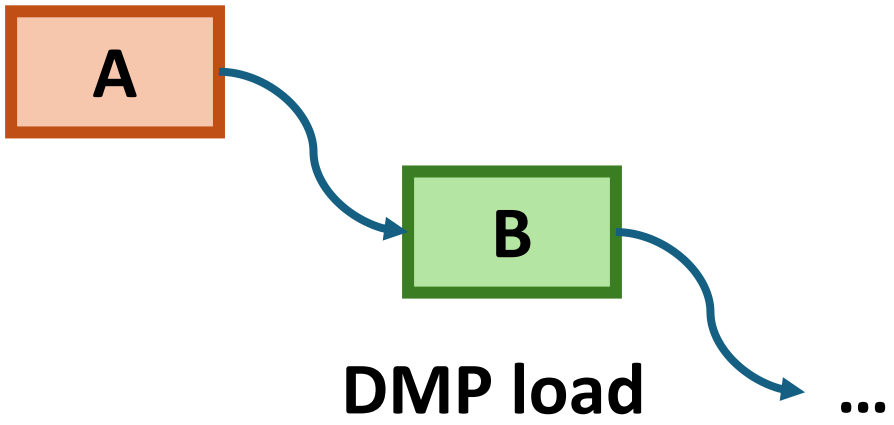

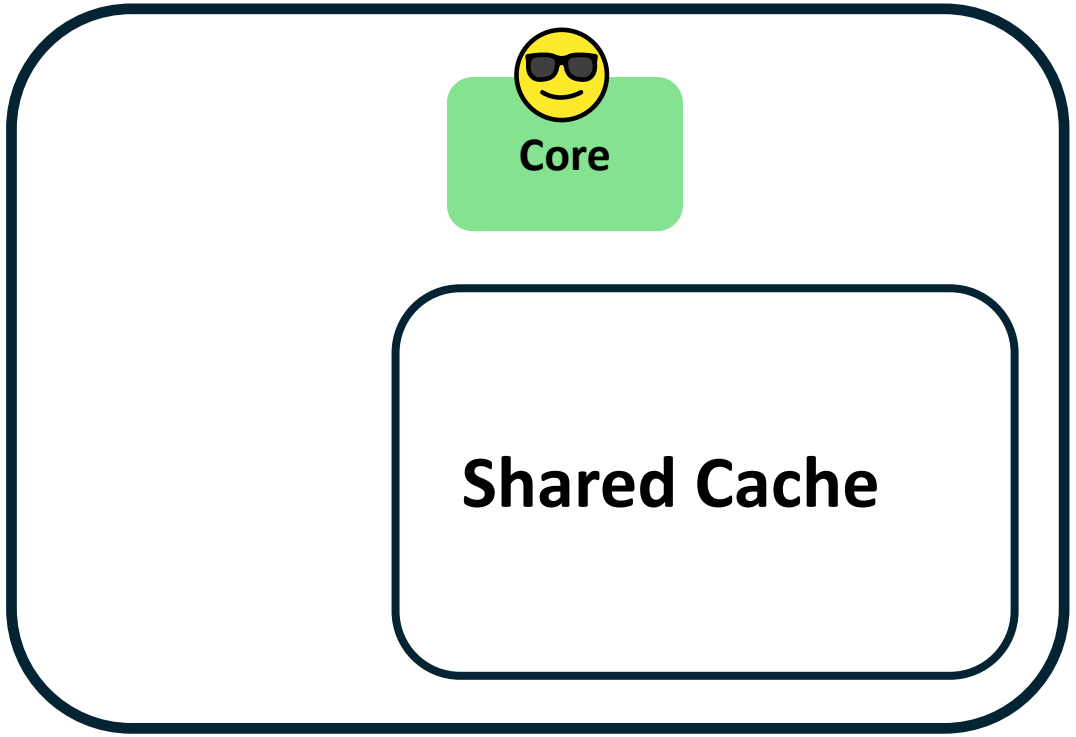

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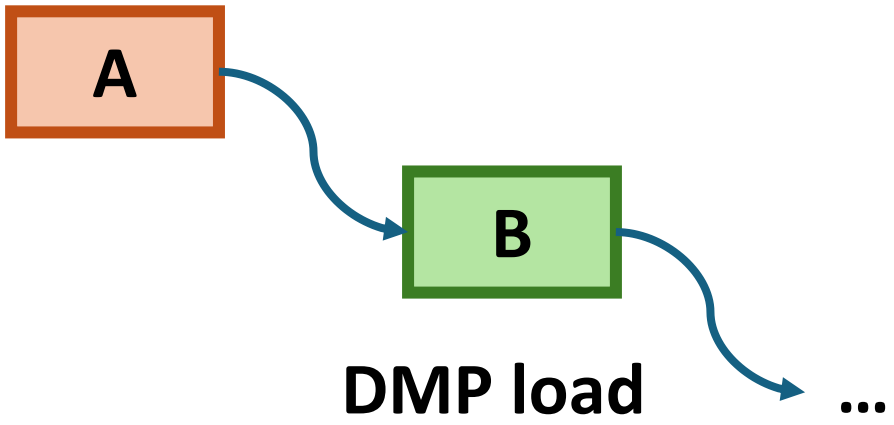

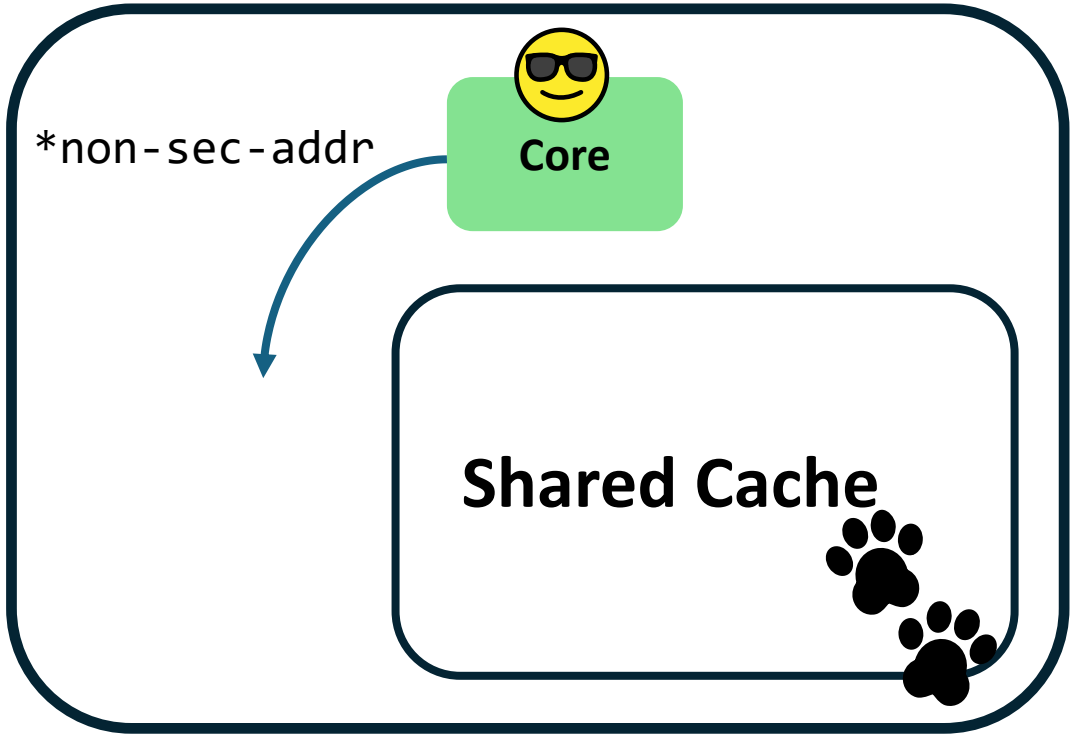

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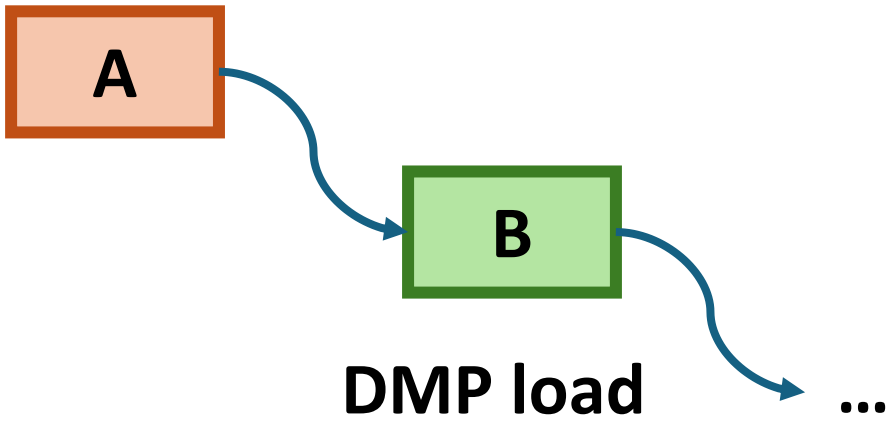

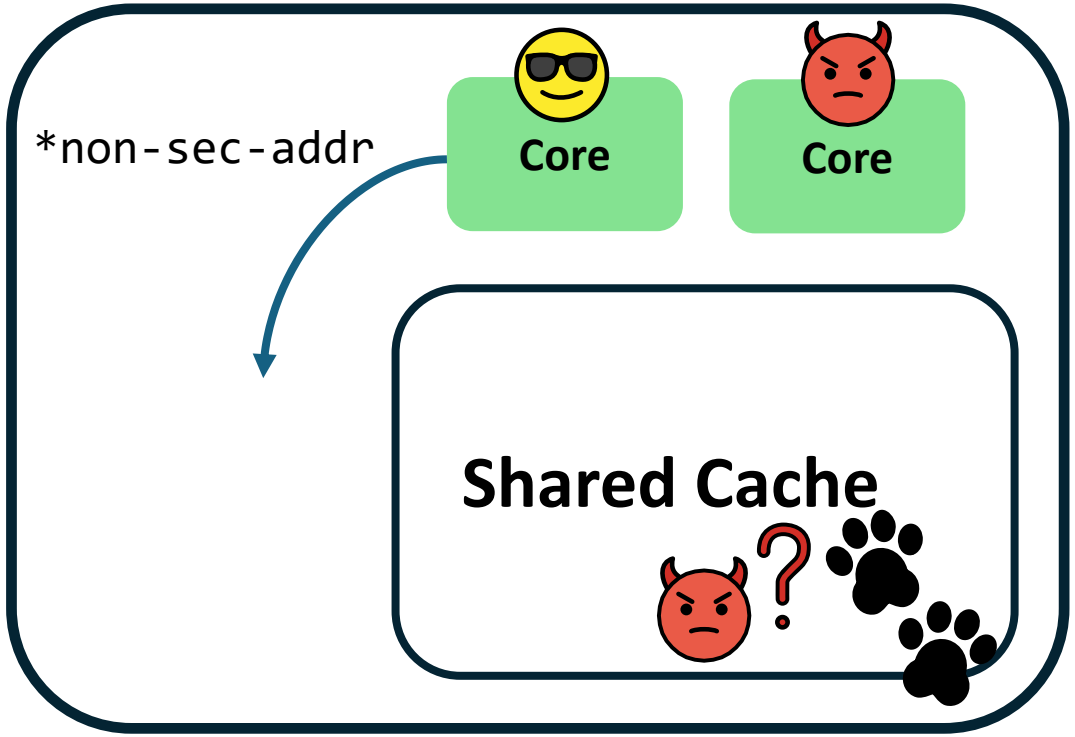

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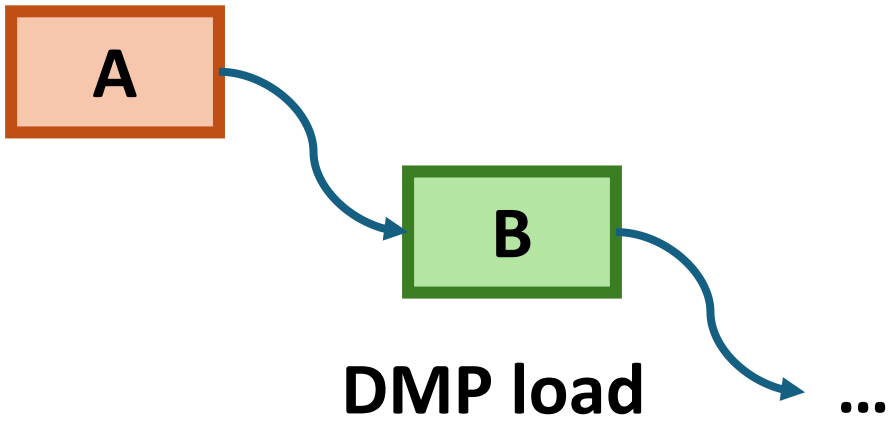

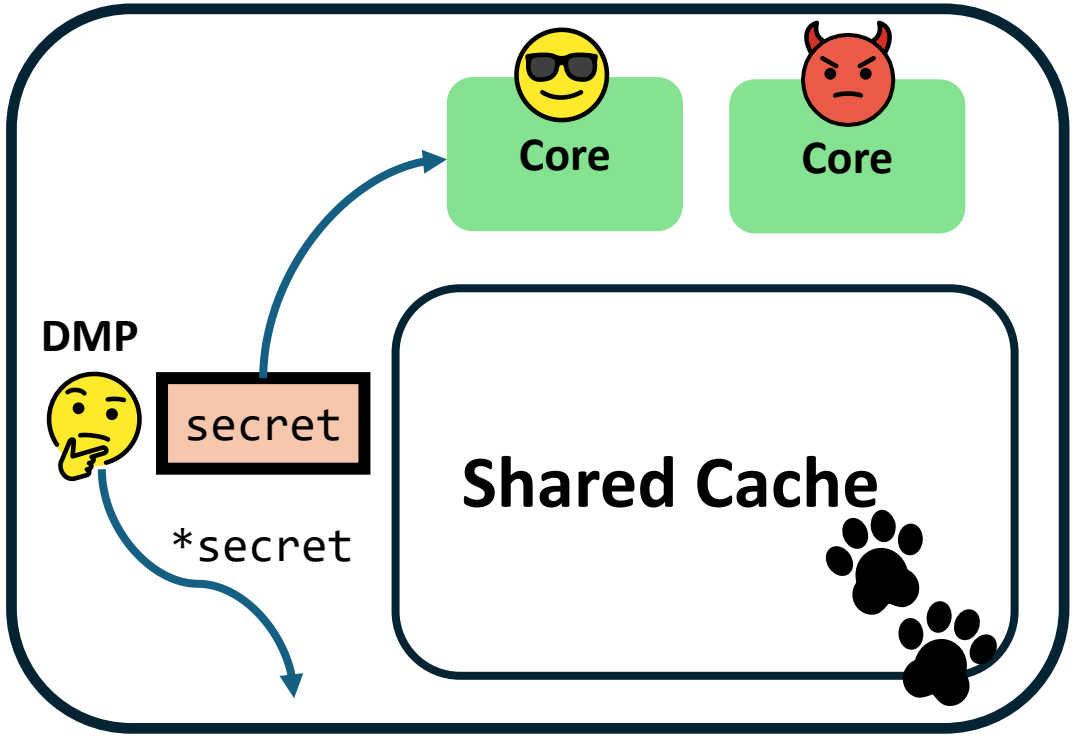

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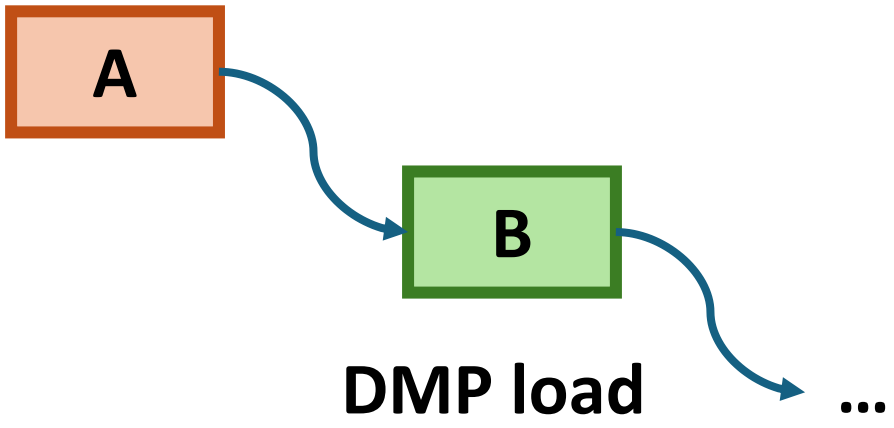

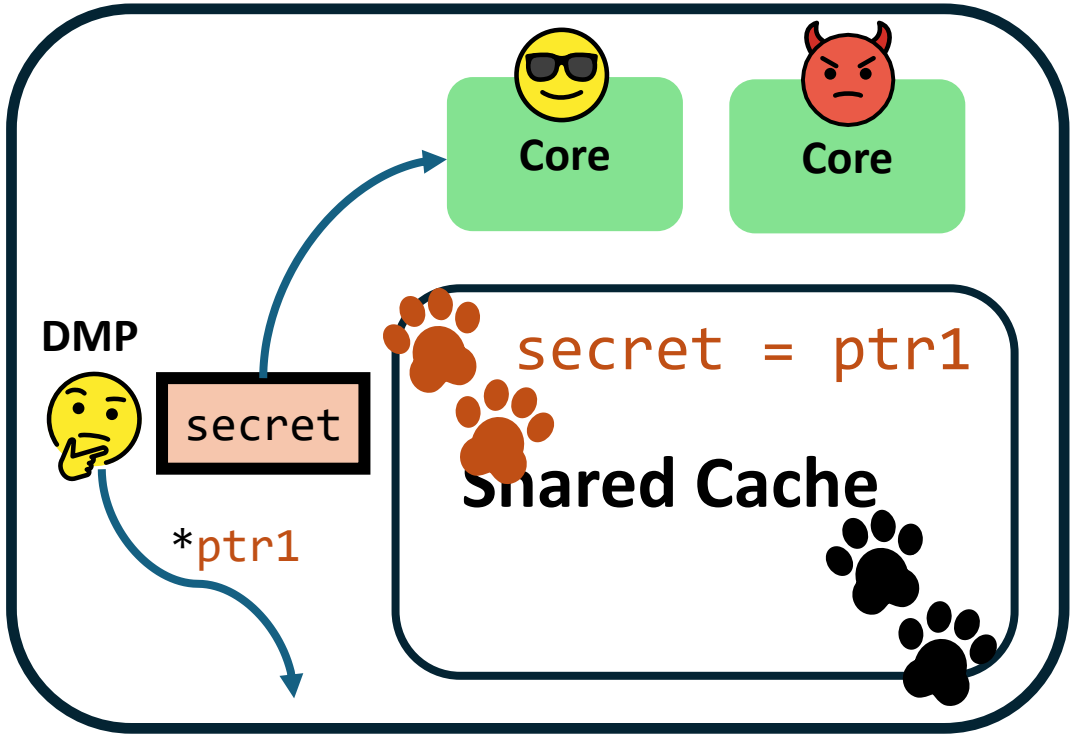

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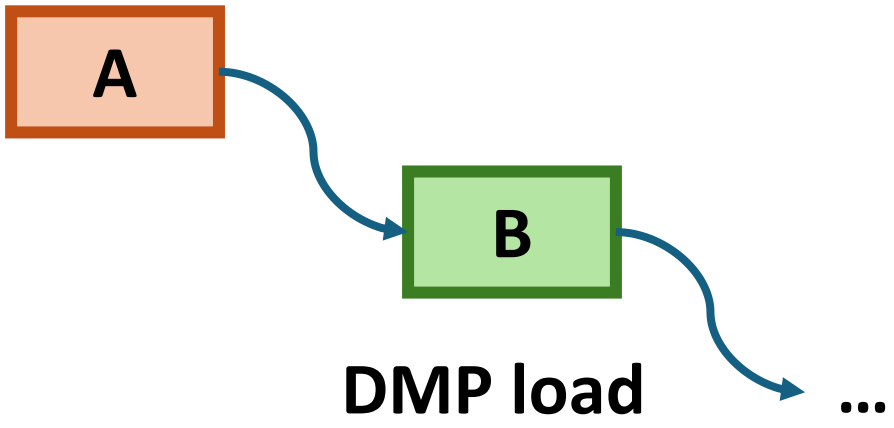

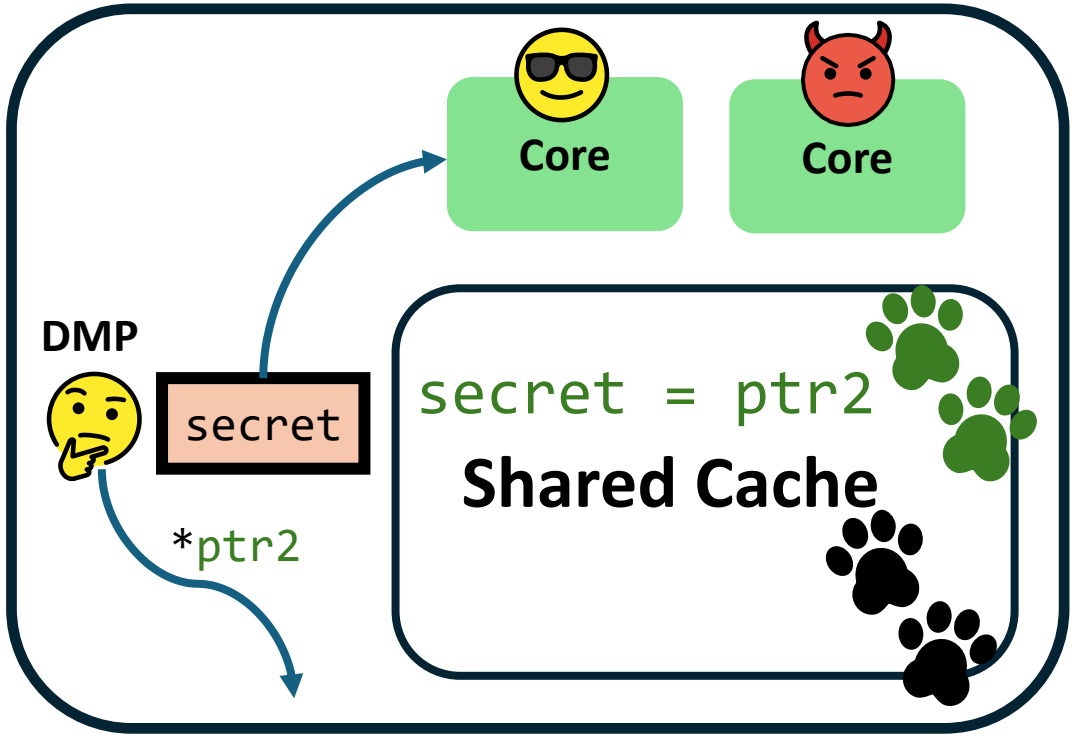

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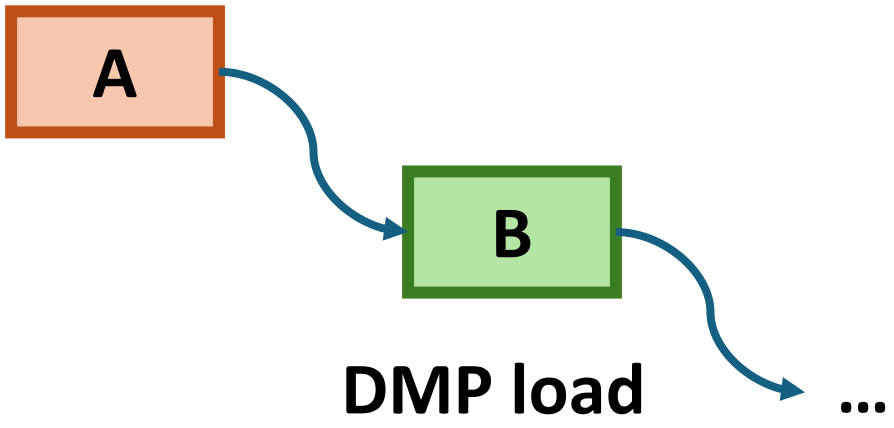

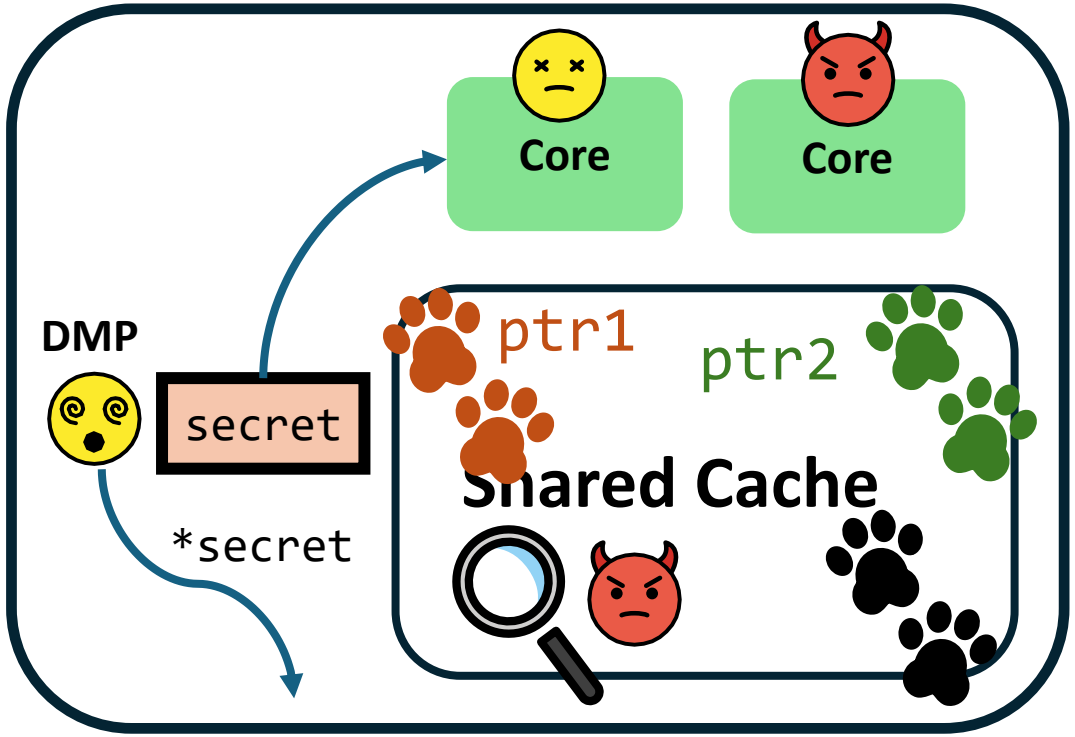

Contribution

Augury[1]

1 Vicarte, et al., "Augury: Using data memory-dependent prefetchers to leak data at rest", SP'22.

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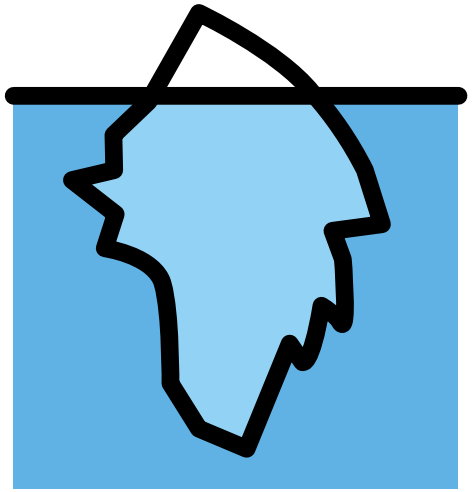

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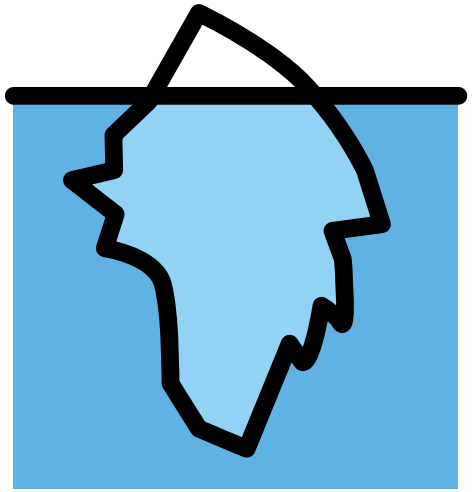
Contribution

- Comprehensive reverse engineering of Apple DMPs.
- Develop DMP-aided chosen-input attack framework.
- Undermine four cryptographic implementations in the wild or submitted to NIST PQC standardization.



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Key Observations of Apple DMP

How do classical prefetchers work?

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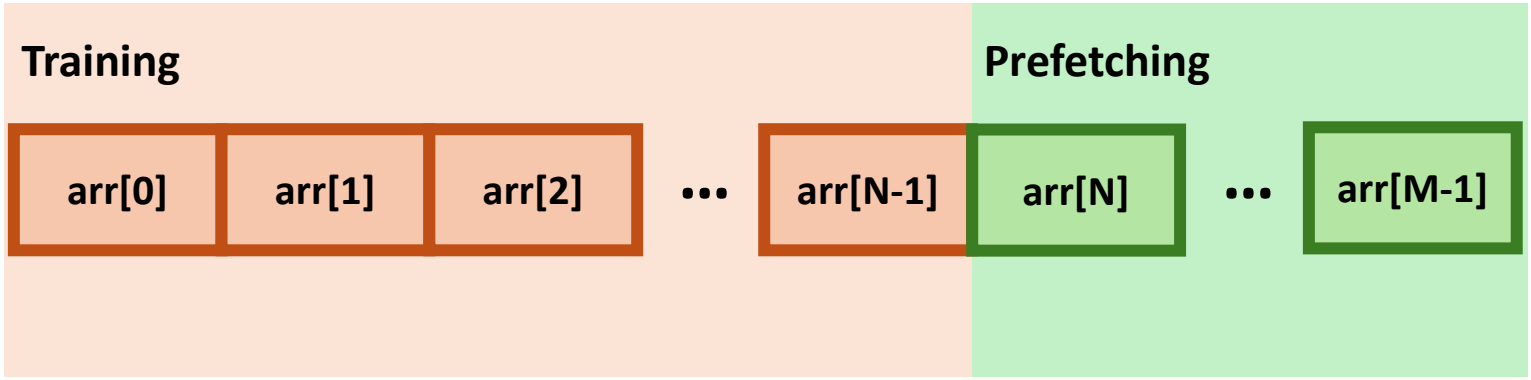
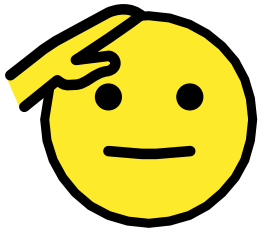
```
// stride pattern
for (i = 0; i < M; i++)
    trash += arr[i];
```



The program reads arr[0], arr[1], …
The stride is 1! Prefetch arr[N], arr[N+1],…



stride prefetcher

Key Observations of Apple DMP

What is the finding of prior work, Augury?

DMP recognizes and prefetches Array-of-pointers access pattern!

```
// Array-of-pointer pattern
for (i = 0; i < M; i++)
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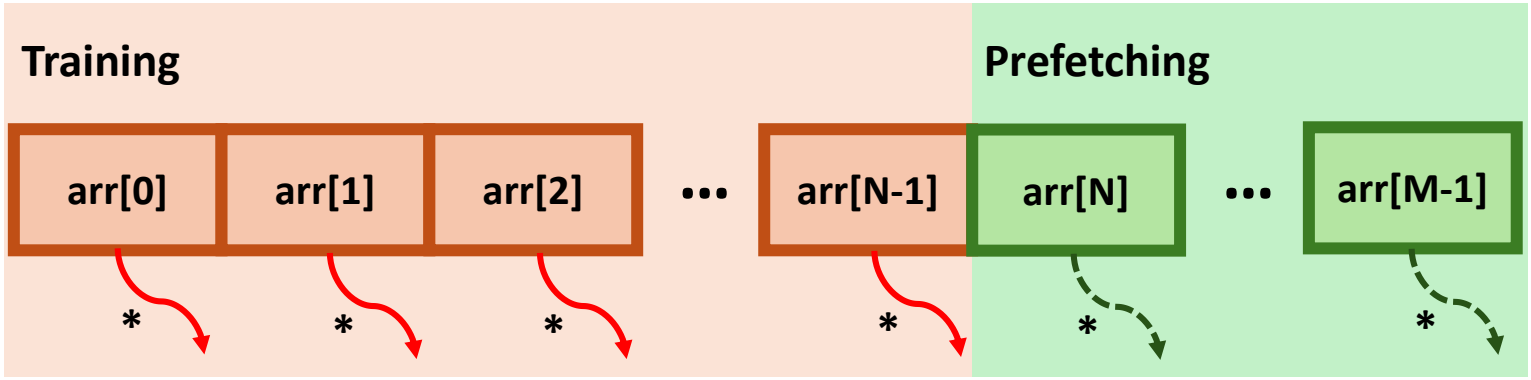

Dereferenced by code

Dereferenced by DMP

Key Observations of Apple DMP

Does memory access pattern even matter?

```
// Array-of-pointer pattern
for (i = 0; i < M; i++)
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Really? Is it necessary?

GoFetch

Key Observations of Apple DMP

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GoFetch

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// Single load
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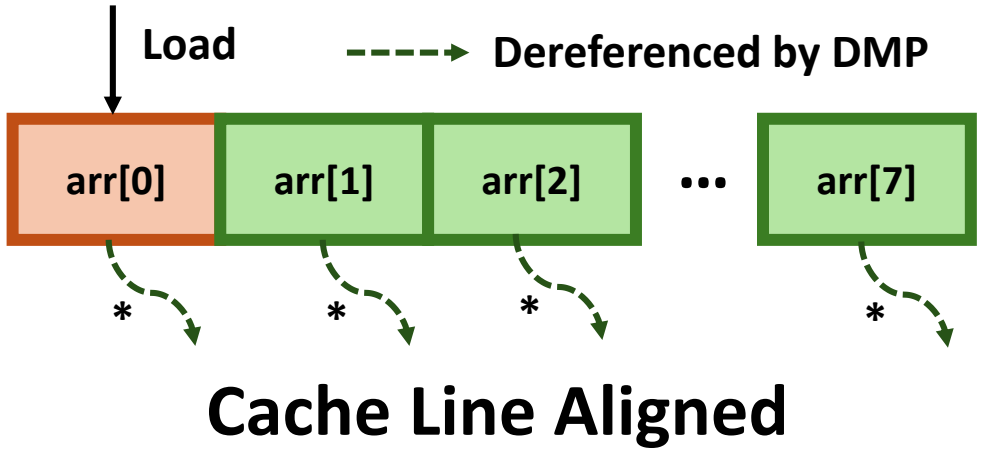
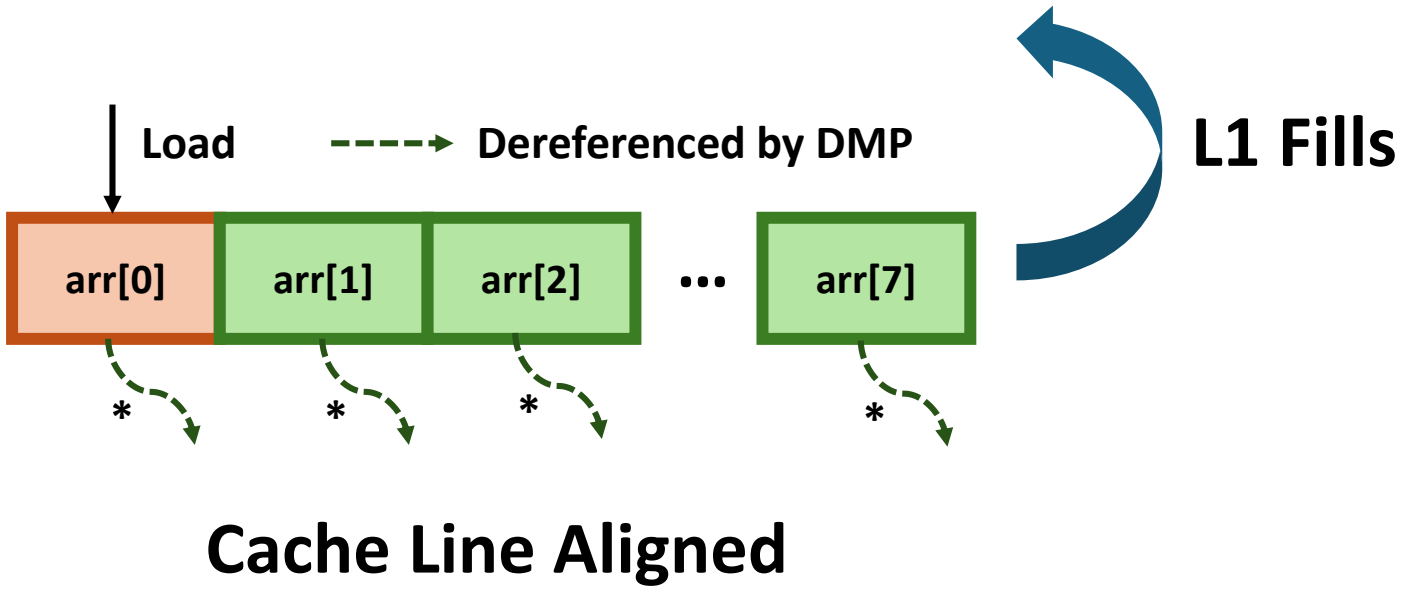


Cache Line Aligned

Key Observations of Apple DMP

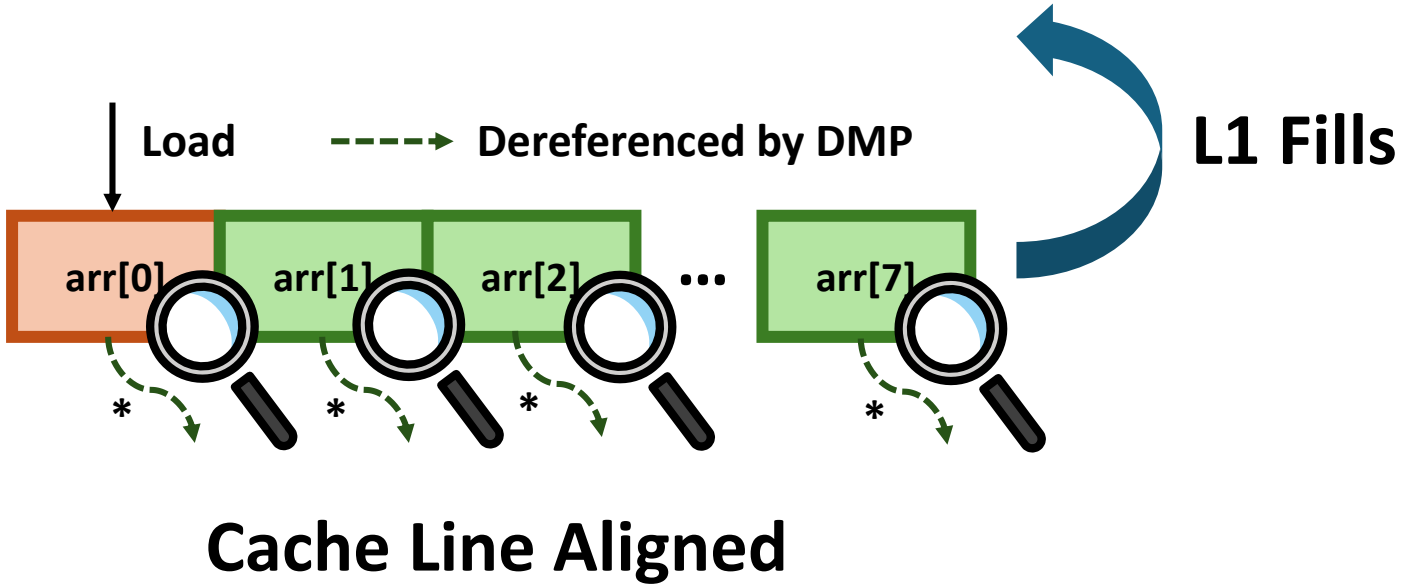
Where does the DMP scan for pointers?

```
// Single load
trash += arr[0];
```



Key Observations of Apple DMP

How does DMP determine pointers to dereference in each line?



Key Observations of Apple DMP

History filter: ***how DMP avoids redundant dereference?***

4GByte region: ***heuristic of predicting pointer value.***

Do-not-scan hint: ***how DMP avoids redundant scan?***

Top byte ignore: ***how DMP synergizes with TBI?***

… **…**

Check out the paper!

How to use DMP to break CT Crypto?

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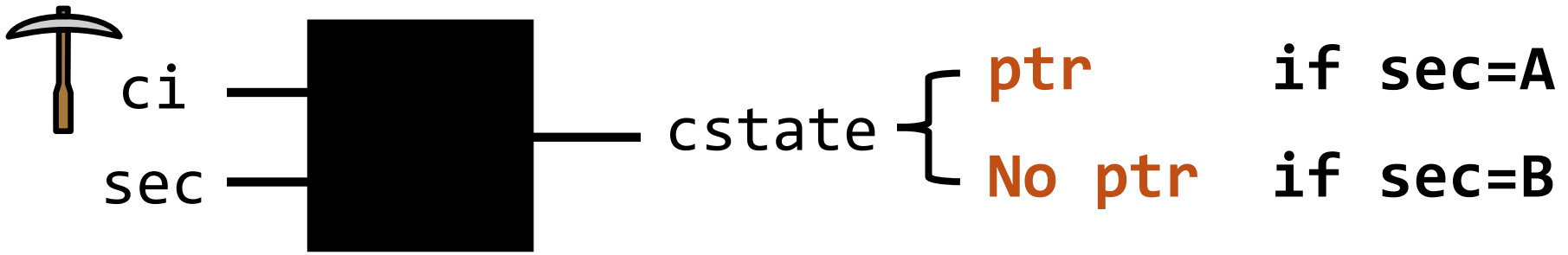
`cstate`: crypto state

`sec`: secret `ci`: chosen input



How to use DMP to break CT Crypto?

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```
cstate = ci AND sec
```

```
sec { 0xffffffffffffffff
      0x0000000000000000
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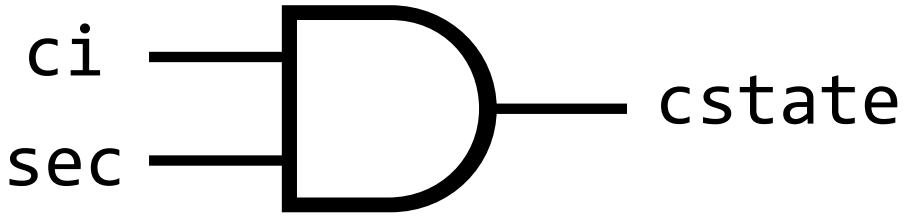

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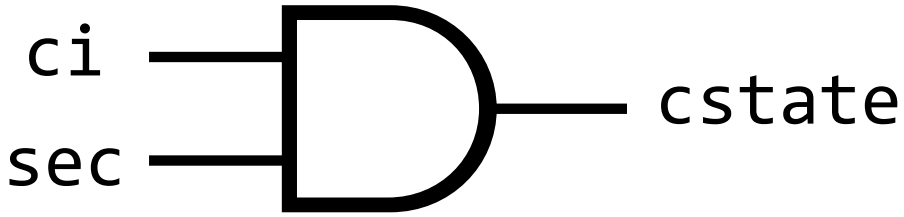

Choose `ci` as valid pointer!

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cstate = ptr AND sec
if sec = 0xffffffffffffffff
   => cstate = ptr

if sec = 0x0000000000000000
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```

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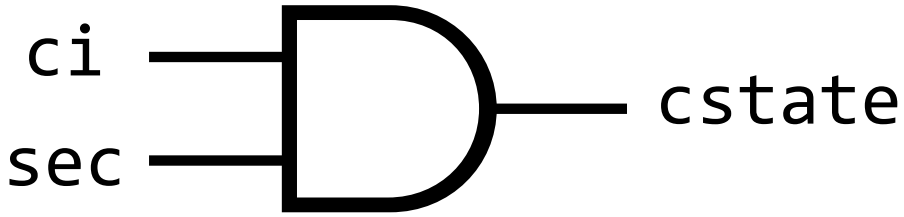

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DMP  *ptr

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DMP 

Proof-of-Concept Attacks

Cryptanalysis for DMP exploit

End-to-end key extraction PoCs

Proof-of-Concept Attacks

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OpenSSL DHKE

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Go RSA

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ML-DSA

ML-KEM

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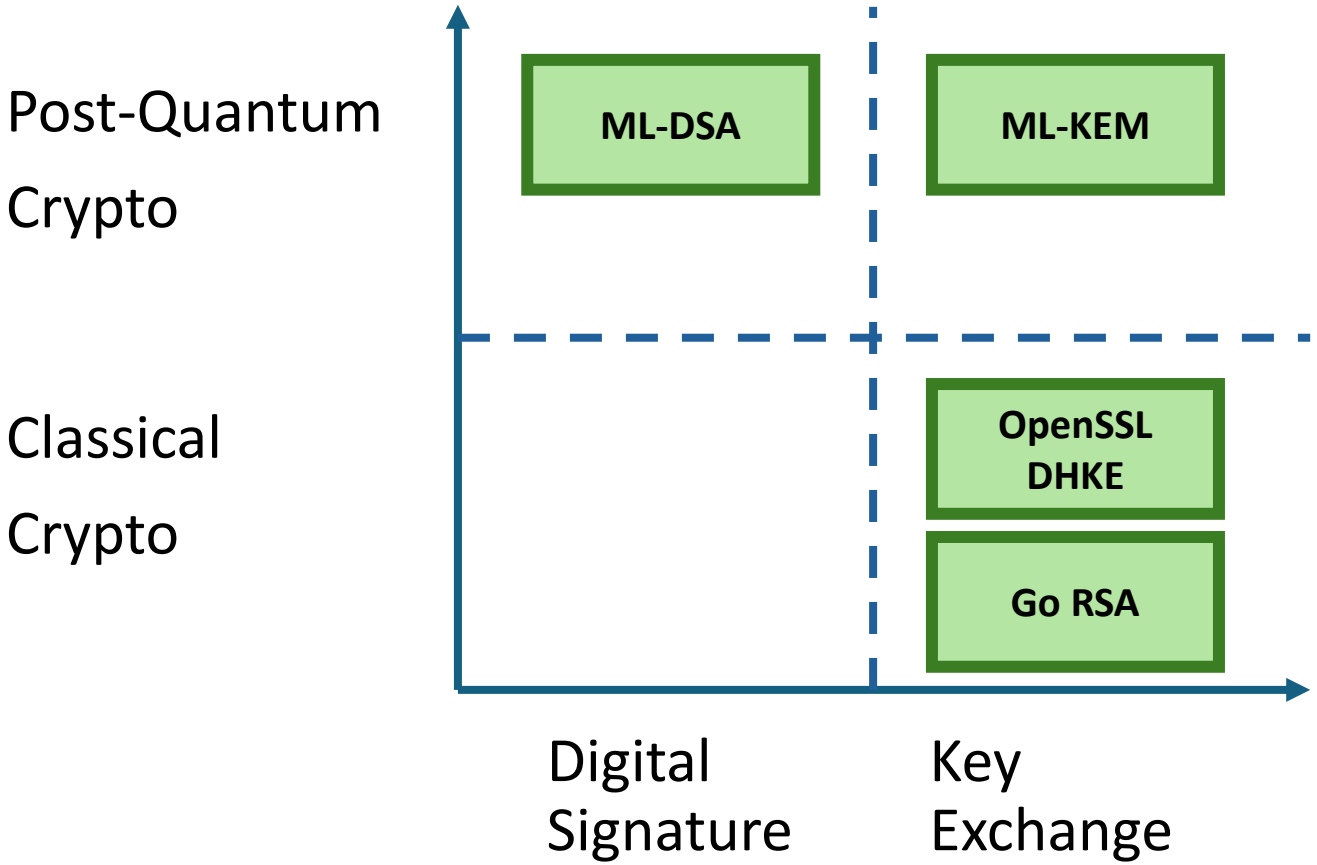

Go RSA

$$N = p \times q$$

Go RSA

RSA Decryption

$$m \equiv c^d \ mod \ N$$

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CRT Optimization

$$c^{D_p} \ mod \ p$$

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First Step

$$c \ mod \ p$$

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First Step

$$c \ mod \ p$$

Observations of crypto state $c \ mod \ p$:

- c is chosen input and p is secret.
- If $c < p$, then $c \ mod \ p = c$, else $c \bmod p = c - lp$.

Go RSA

Target i-th bit of p and set input as $c = prefix \parallel 10000 \ldots \parallel ptr$!

c $\quad$ $\boldsymbol{prefix} \parallel \mathbf{1}0000 \ldots \parallel \boldsymbol{ptr}$

p $\quad$ $\boldsymbol{prefix} \parallel \boldsymbol{x}xxxxxxxx \ldots x$

i-th bit

Observation of $c \bmod p$:

- c is chosen input and p is victim's secret.
- if $c < p$, $c \bmod p = c$
- if $c \geq p$, $c \bmod p = c - lp$

Go RSA

Target i-th bit of p and set input as $c = prefix \parallel 10000 \ldots \parallel ptr$!

c $\quad$ $prefix \parallel 10000 \ldots \parallel ptr$

p $\quad$ $prefix \parallel xxxxxxxxx \ldots x$

i-th bit

- if $p = prefix \parallel 1xxxxxxxx \ldots x$ ➡ $p > c$
  - then $c \bmod p = c = \cdots \parallel ptr$

- if $p = prefix \parallel 0xxxxxxxx \ldots x.$ ➡ $p < c$
  - then $c \bmod p = c - lp = unknown$

Observation of $c \bmod p$:

- c is chosen input and p is victim's secret.
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Target i-th bit of p and set input as $c = prefix \parallel 10000 \ldots \parallel ptr$!

c $\quad prefix \parallel 10000 \ldots \parallel ptr$

p $\quad prefix \parallel xxxxxxxxx \ldots x$

i-th bit

DMP recovers upper **560** bits
+ **Coppersmith**[2]
= **full** extraction!

Observation of $c \bmod p$:

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2 Coppersmith, "Finding a small root of a bivariate integer equation; factoring with high bits known", EUROCRYPT'96.

CRYSTALS-Kyber (ML-KEM)

- CCA-KEM built on a CPA-PKE scheme.

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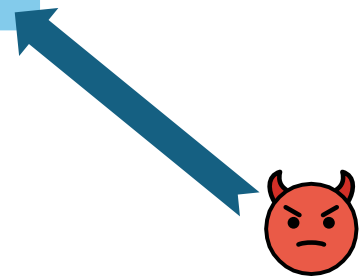

Key Mismatch Attack[3]

3 Qin et al., ”A Systematic Approach and Analysis of Key Mismatch Attacks on Lattice-Based NIST Candidate KEMs”, ASIACRYPT’21.

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$$c = Enc(m, pk, e)$$

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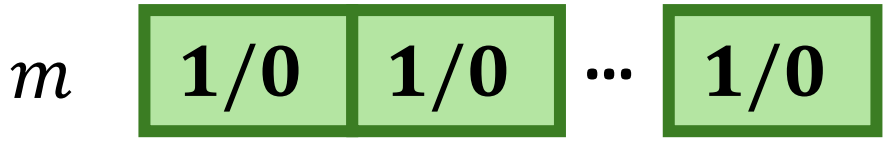

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CRYSTALS-Kyber (ML-KEM)

Key Mismatch Attack[3]

$$c = Enc(m, pk, e)$$

m | **1/0** | **1/0** | ⋯ | **1/0**

e | $\mathbf{0 \sim q}$ | $\mathbf{0 \sim q}$ | ⋯ | $\mathbf{0 \sim q}$

Kyber-512: $q = 3329$

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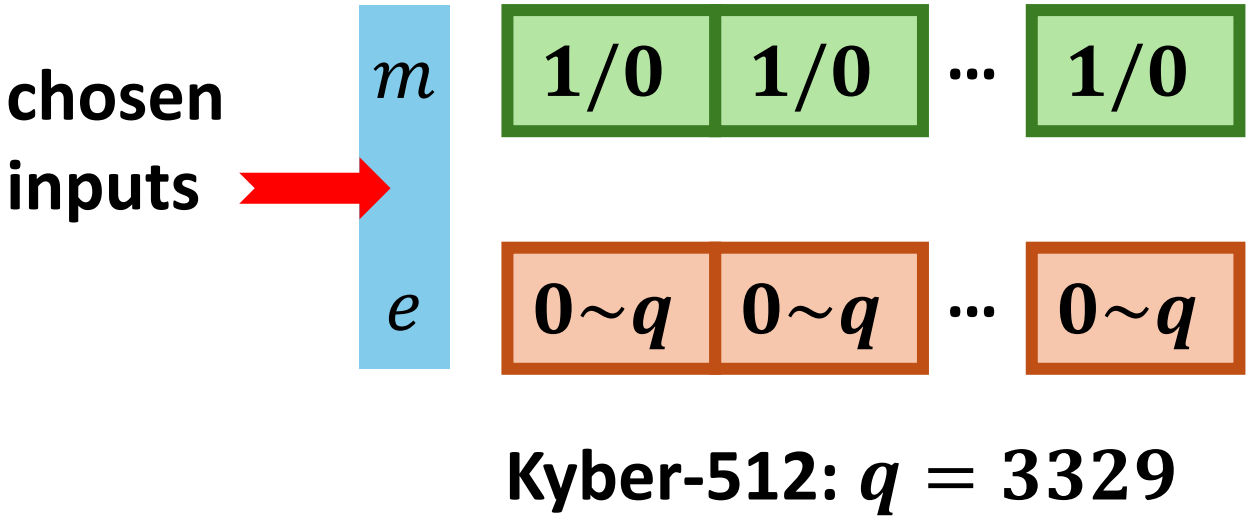

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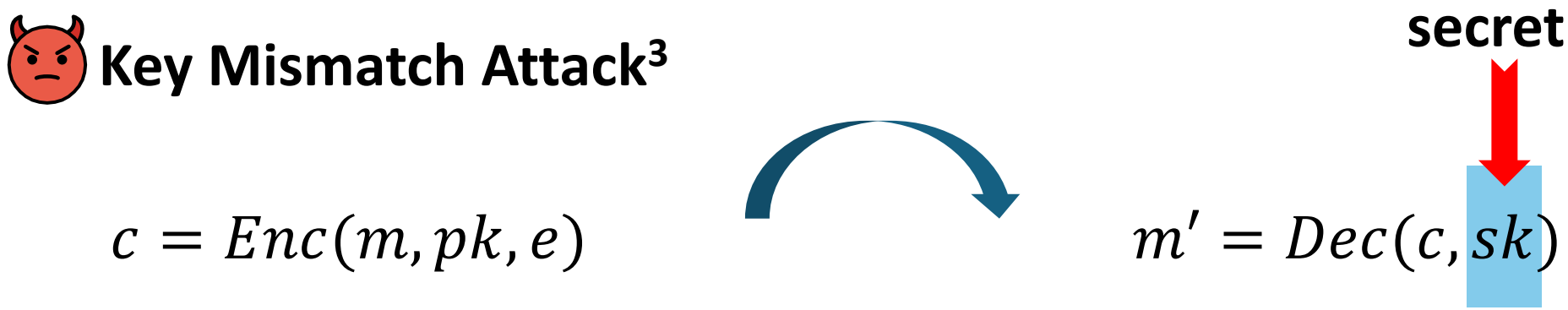

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CRYSTALS-Kyber (ML-KEM)

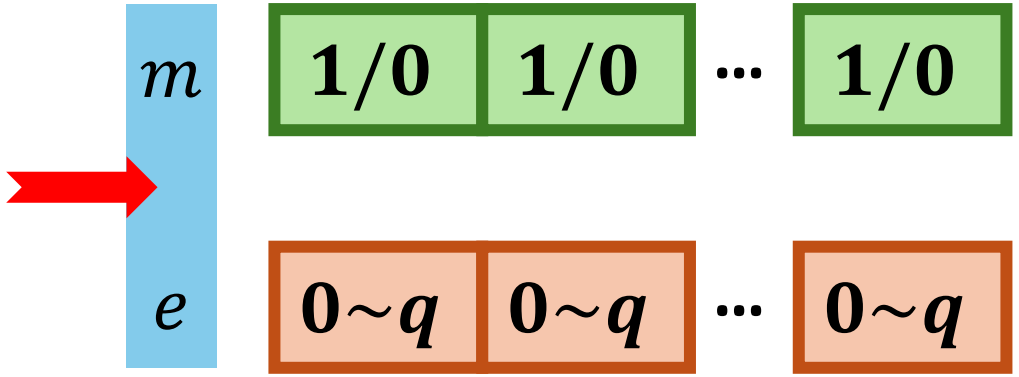
Key Mismatch Attack[3]

$c = Enc(m, pk, e)$

$m' = Dec(c, sk)$

secret

chosen inputs



Kyber-512: $q = 3329$

$m' = m$

$(sk^*, e^*) \rightarrow m' \neq m$

3 Qin et al., "A Systematic Approach and Analysis of Key Mismatch Attacks on Lattice-Based NIST Candidate KEMs", ASIACRYPT'21.

CRYSTALS-Kyber (ML-KEM)

Key Mismatch Attack[3]

$$sk[i] < \frac{q}{4} - e[i] \quad \Rightarrow \quad m'[i] = m[i]$$

$$sk[i] \geq \frac{q}{4} - e[i] \quad \Rightarrow \quad m'[i] \neq m[i]$$

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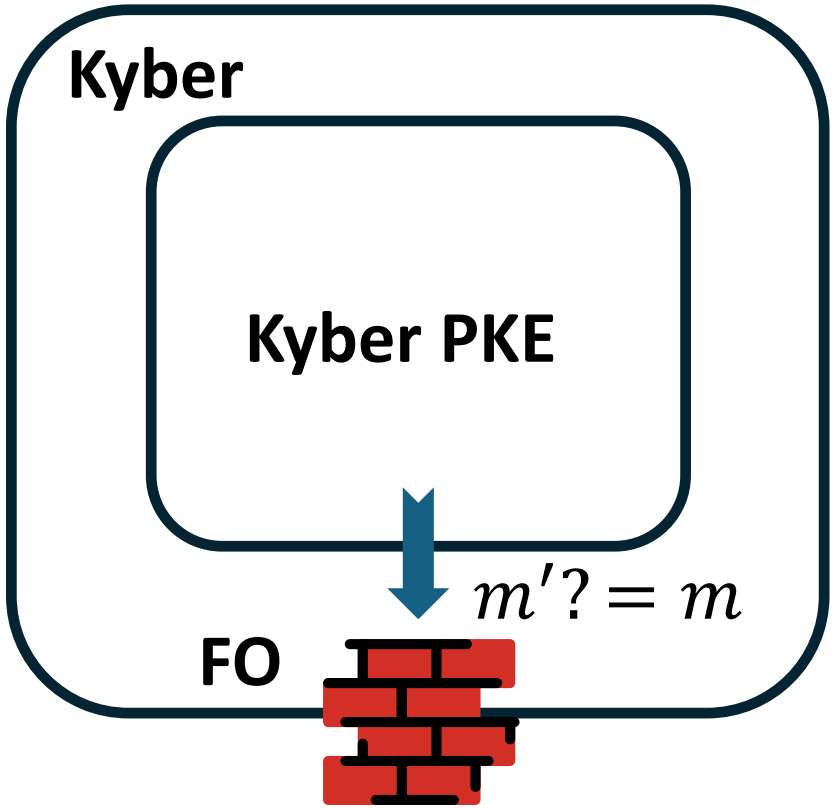

Observations of decrypted message m':

- sk is secret, m and e are chosen inputs.
- if $(e + sk)[i] < \frac{q}{4}$, $m'[i] = m[i]$.
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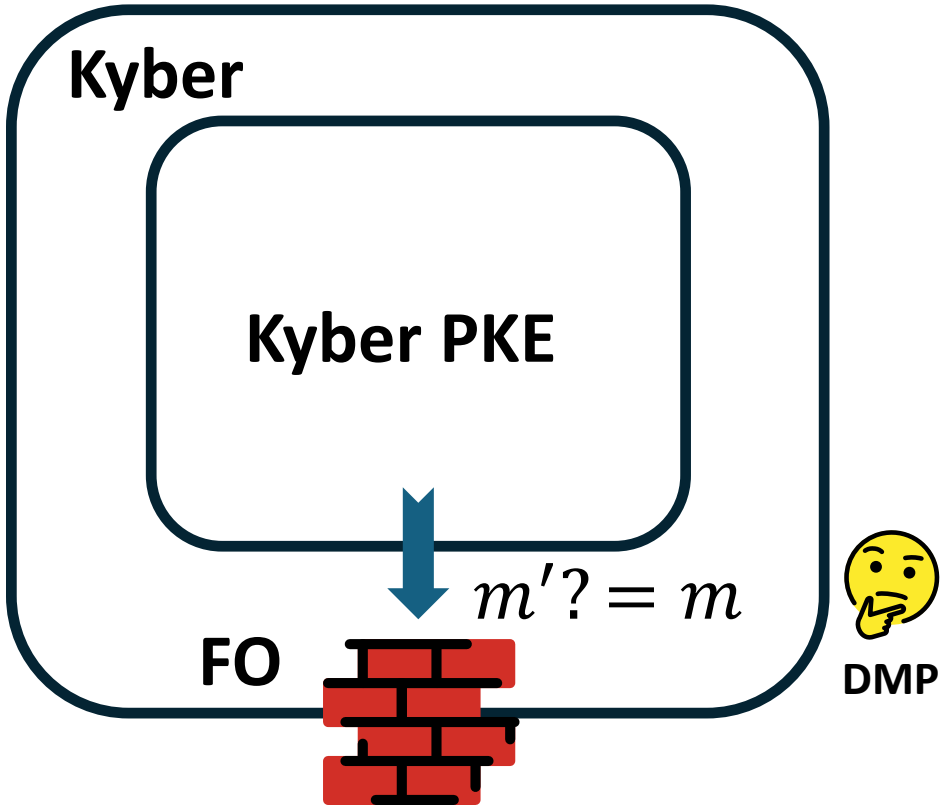

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CRYSTALS-Kyber (ML-KEM)

Set m as $ptr \parallel 0 \ldots 0$ and tweak $e[0]$!

- if $(e + sk)[\mathbf{0}] < \frac{q}{4}$
  - then $m' = \boldsymbol{ptr}||0 \ldots 0$ $\boldsymbol{ptr}$
- if $(e + sk)[\mathbf{0}] \geq \frac{q}{4}$
  - then $m' = \boldsymbol{ptr'}||0 \ldots 0$ **No** $\boldsymbol{ptr}$

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Kyber-512:

DMP recovers **392** indexes

+ **Lattice Reduction**[3]

= **full** extraction!

Observations of decrypted message m':

- sk is secret, m and e are chosen inputs.
- if $(e + sk)[i] < \frac{q}{4}$, $m'[i] = m[i]$.
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3 May et al., "Too Many Hints – When LLL Breaks LWE", ASIACRYPT'23.

Impact

Apple: Disable DMP with DIT=1

- Only works on M3.

```
bool set_DIT_enabled(void) {
    bool was_DIT_enabled = get_DIT_enabled();
    __asm__ __volatile__("msr dit, #1");
    return was_DIT_enabled;
}
```

Enable DIT for constant-time cryptographic operations

Impact

Apple: Disable DMP with DIT=1

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Go: Propose an opt-in DIT mode in Go binary.

proposal: runtime: implement a DIT/DOIT mode #66450

Open rolandshoemaker opened this issue on Mar 21 · 20 comments

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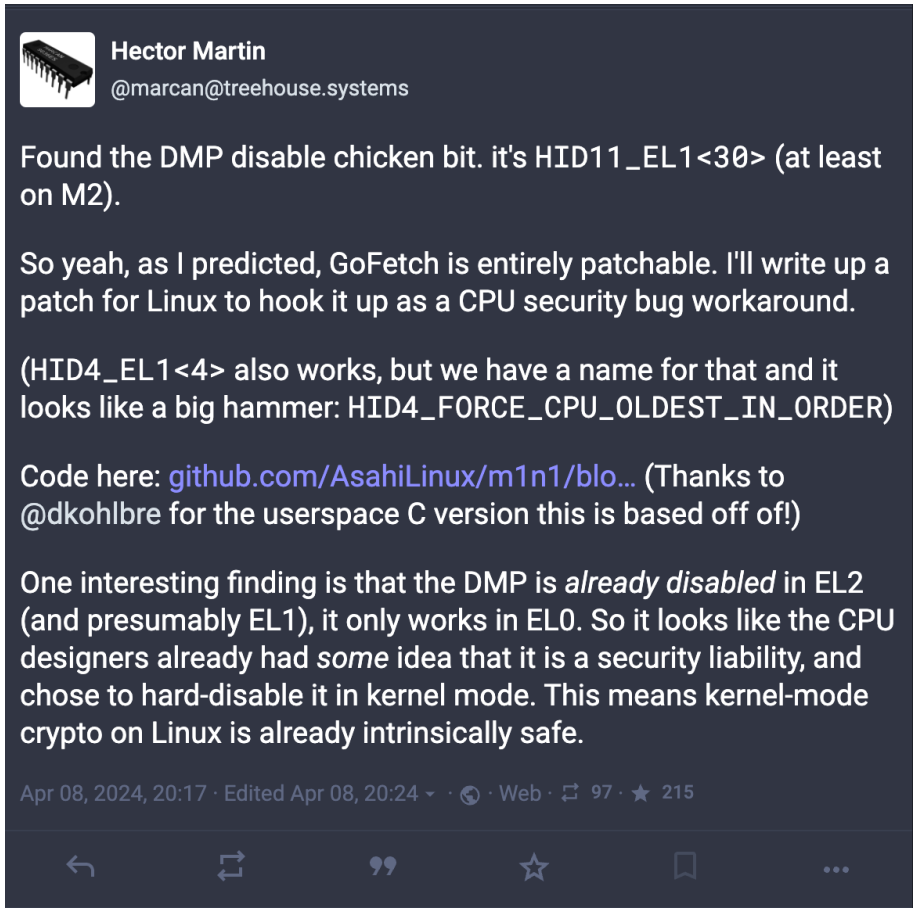
Asahi Linux: Found chicken bit to disable DMP on M1/M2.

Asahi Linux



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Asahi Linux

Pwine Awards: Best Cryptographic Attack winner.

Conclusion

- Data memory-dependent prefetchers (DMPs) performs secret-dependent memory access to leak data.
- Exploiting DMPs to perform key extraction attacks to constant-time cryptography is feasible.

GoFetch

Check our Website:
gofetch.fail

boruc2@illinois.edu