# Practical Byte-Granular Memory Blacklisting using Califorms

Hiroshi Sasaki, Miguel A. Arroyo, Mohamed Tarek Ibn Ziad, Koustubha Bhat, Kanad Sinha, Simha Sethumadhavan

Columbia University
IN THE CITY OF NEW YORK

# Californs

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**Computing** Sep 6

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The tech giant gave a rare statement that bristled at Google's analysis of the novel hacking operation.

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# IT'S EASY TO MAKE MISTAKES

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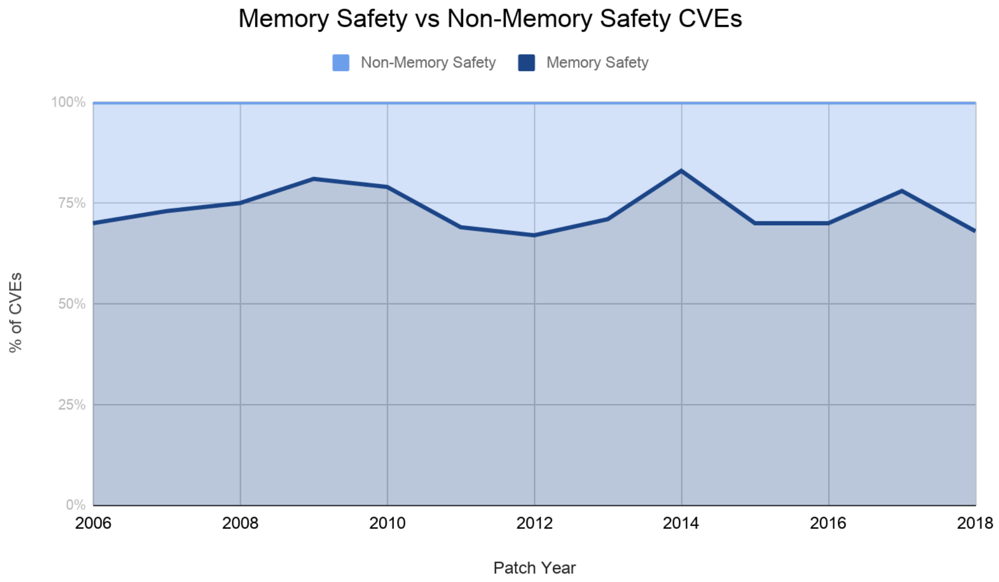
SEGFAULT!

# PREVALENCE OF MEMORY SAFETY VULNS




Microsoft Product CVEs



***Source:*** *Matt Miller, Microsoft Security Response Center (MSRC) - BlueHat 2019*

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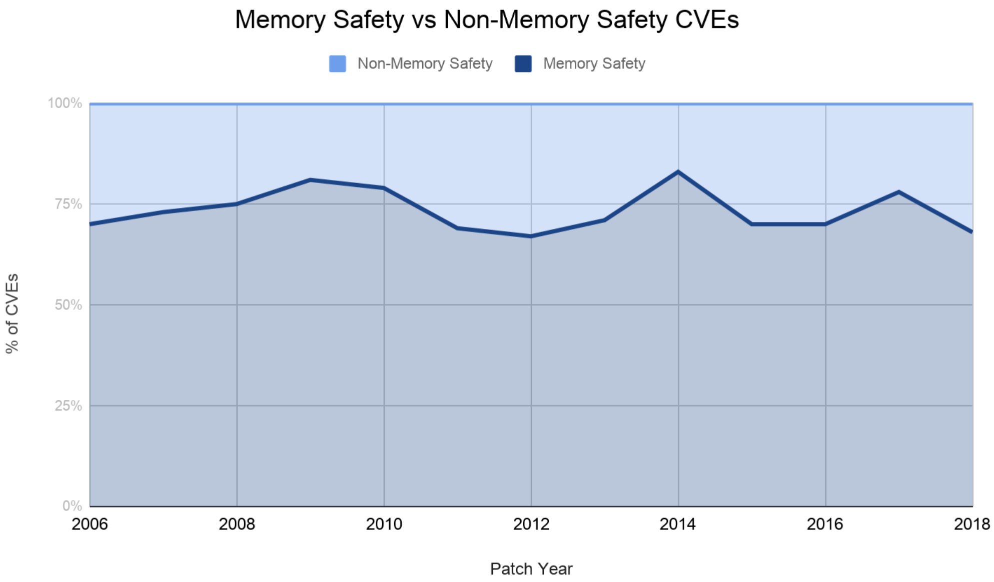


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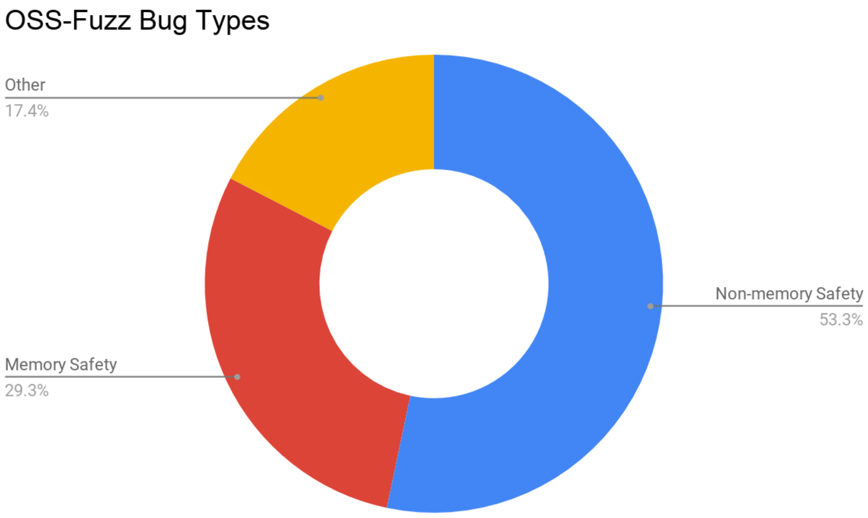



Google OSS-Fuzz bugs from 2016-2018.



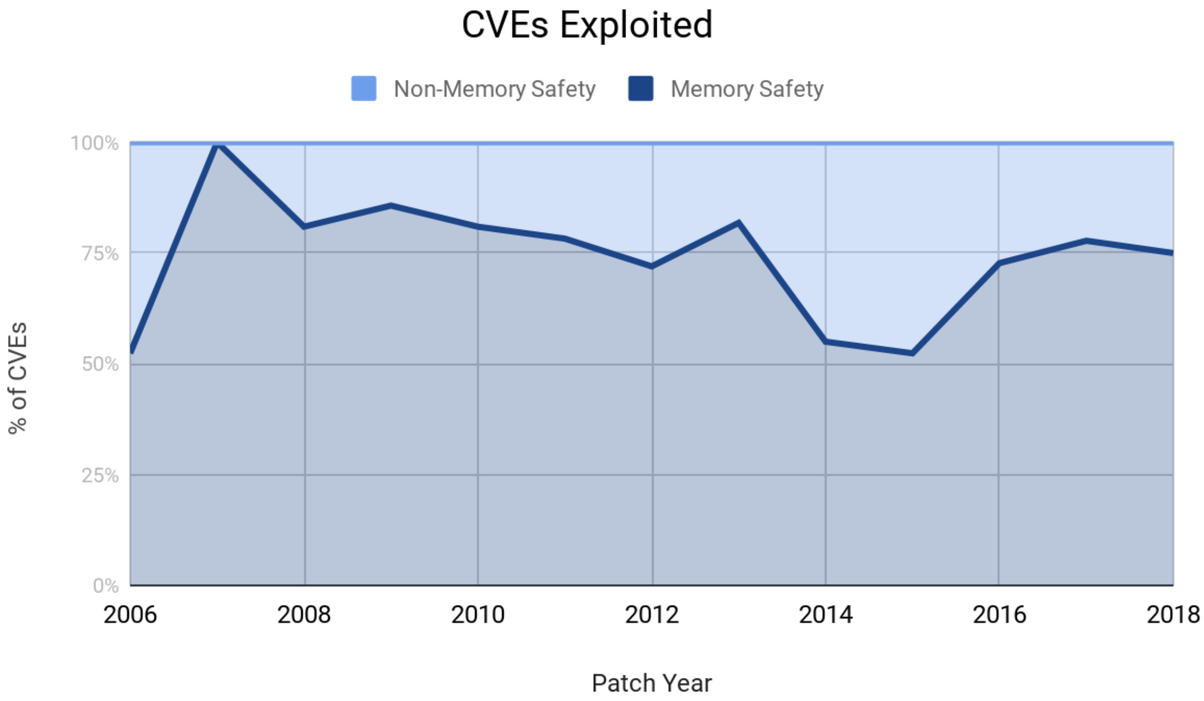
**Source:** *Matt Miller, Microsoft Security Response Center (MSRC) - BlueHat 2019*

**Source:** *https://security.googleblog.com/2018/11/a-new-chapter-for-oss-fuzz.html*

# ATTACKERS

# MEMORY SAFETY

# ATTACKERS PREFER MEMORY SAFETY VULNS




Microsoft Product Exploits



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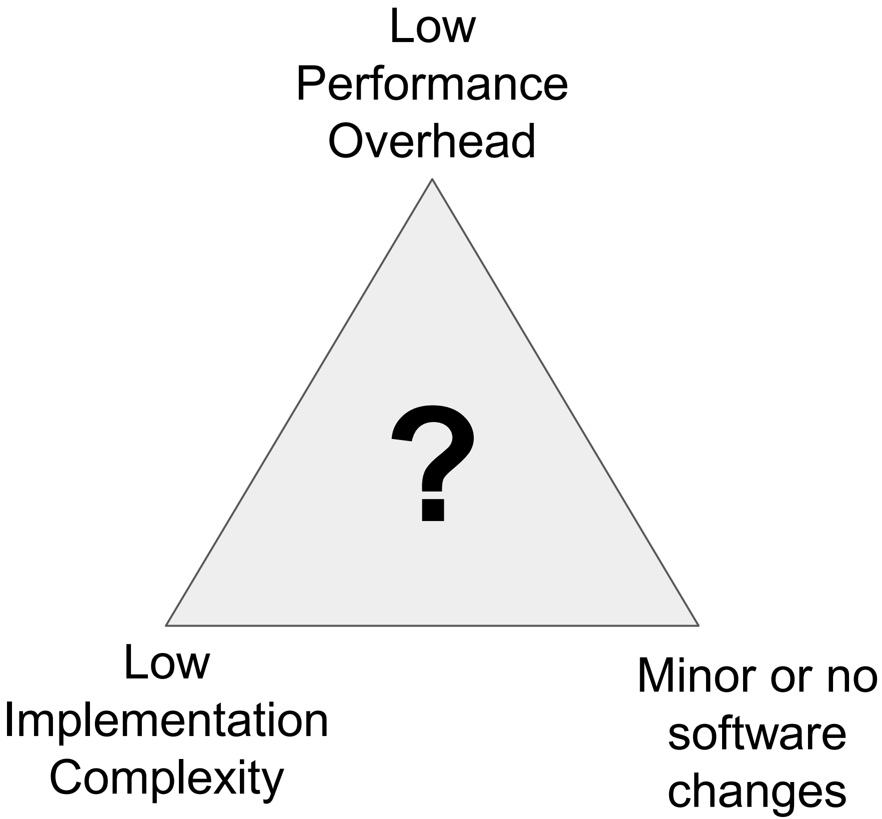
RESEARCHERS TOO

MEMORY SAFETY

# CURRENT SOLUTIONS AREN'T PRACTICAL

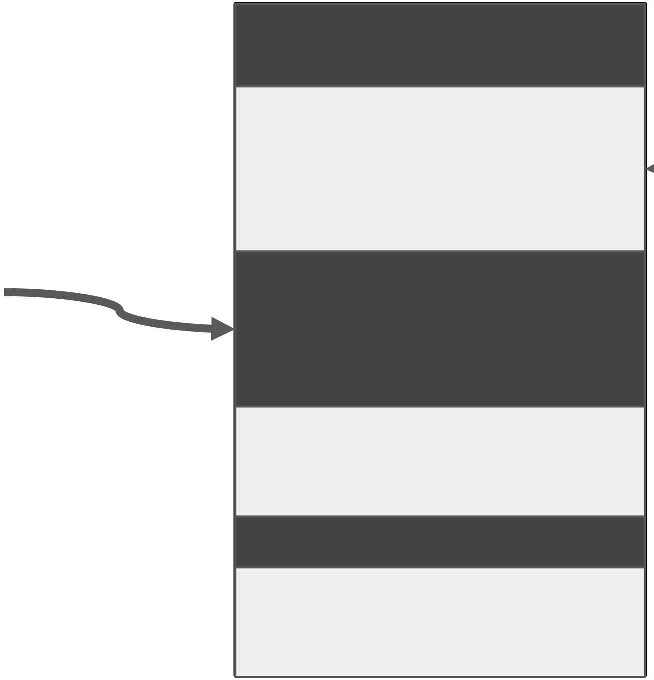


# CALIFORMS

- Low Overhead
- Robust Security
- Legacy Software Compatibility
- Easy to Implement
- 32-bit Compatible

# MEMORY BLACKLISTING

*A tripwire is a **blacklisted** location.*

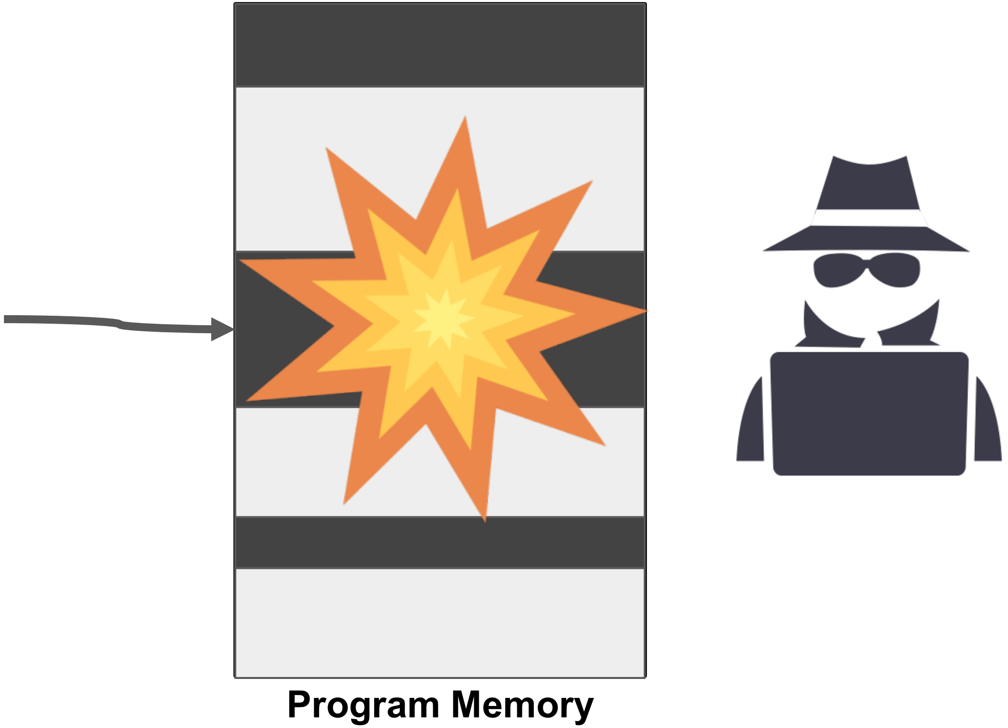


*This is program data.*

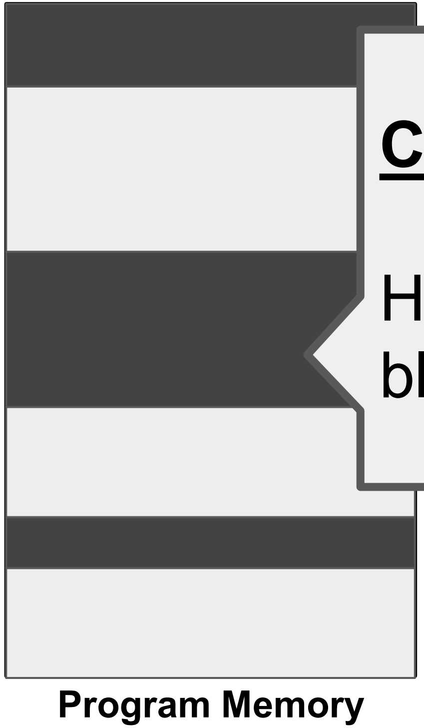
**Program Memory**

# MEMORY BLACKLISTING

*Accesses to this region trigger an **exception!***



# MEMORY BLACKLISTING

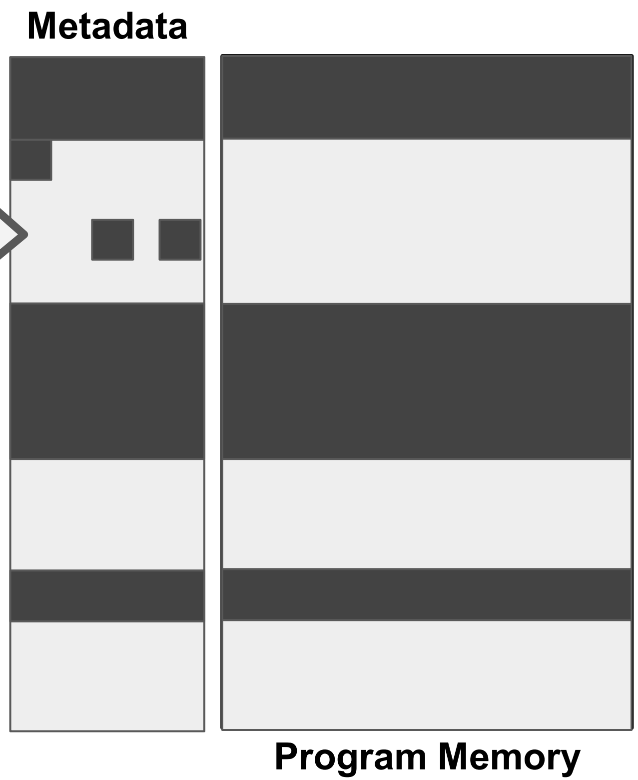



**<u>Challenge</u>**

How to efficiently **identify** blacklisted locations?

# MEMORY BLACKLISTING

**Simple**
1-bit per byte



# MEMORY BLACKLISTING

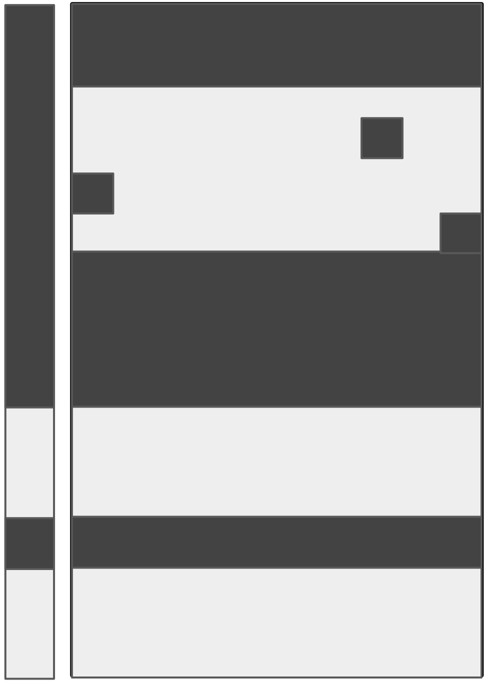
**Simple**
1-bit per byte


**12.5% memory** overhead!

**~200% runtime** overhead!

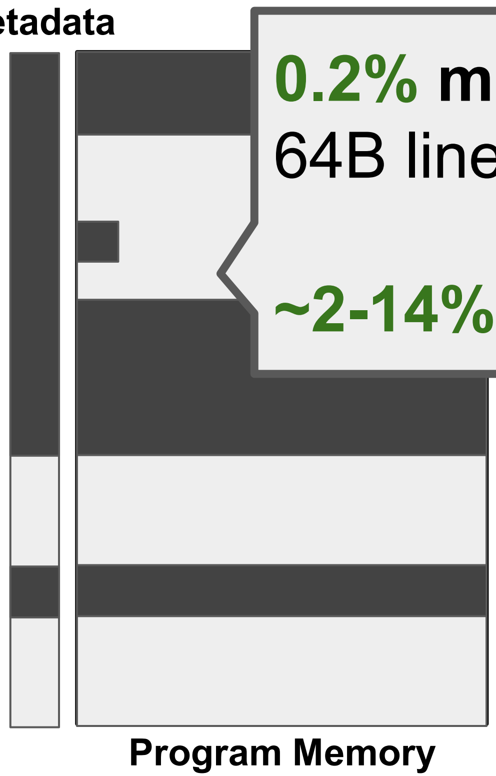
# MEMORY BLACKLISTING

**Califorms**
1-bit per cache line



# MEMORY BLACKLISTING

**Califorms**
1-bit per cache line




**0.2% memory** overhead for 64B line!

**~2-14% runtime** overhead!

# OUR TALK

- Califorms
- Benefits
  - Performance, Security
- Related work
  - State-of-the-art Memory Safety Mitigations
- Conclusion

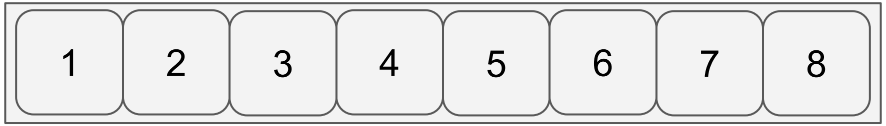
# CALIFORMS

## MEMORY BLACKLISTING

# CALIFORMS: CACHE LINE FORMATS

**Our Metadata:** Encoded within unused data.

**Normal**



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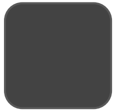
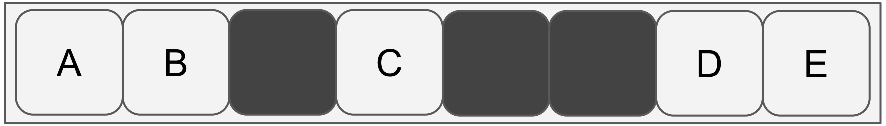


Blacklisted
Location

**Normal**



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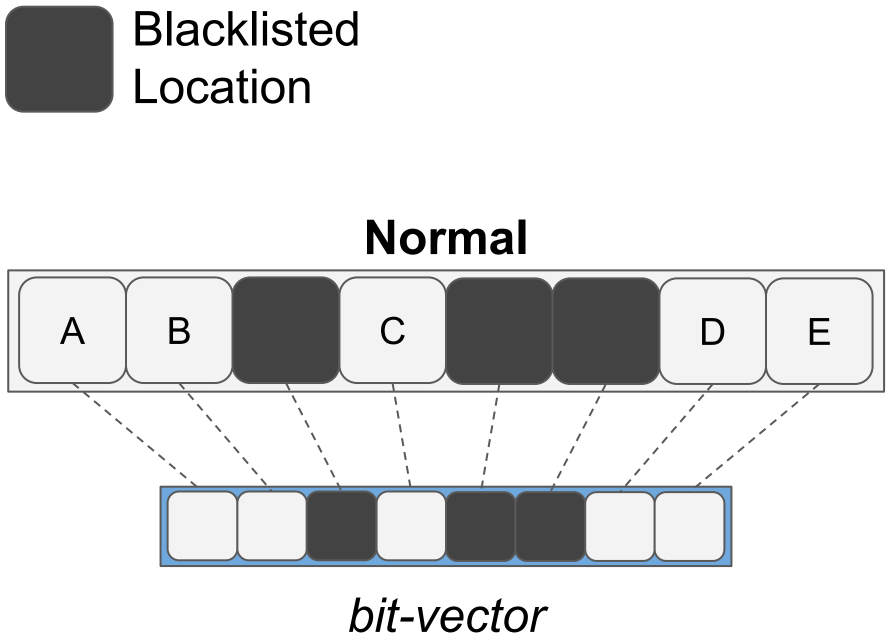

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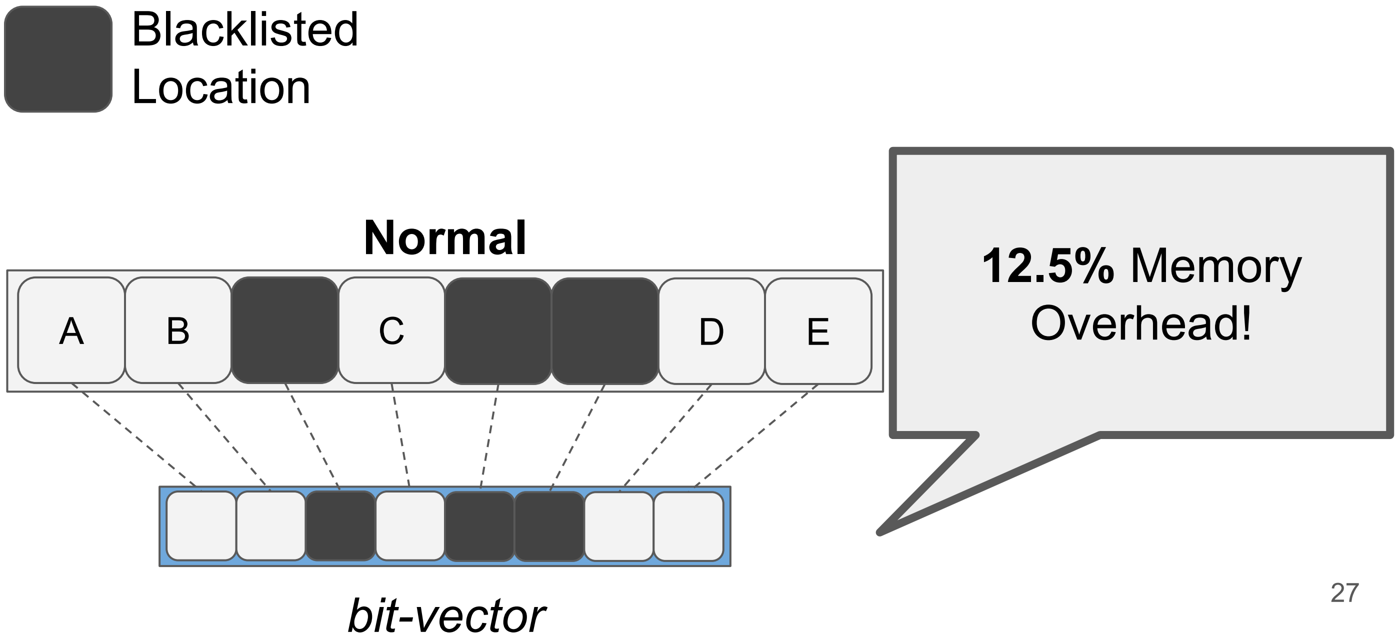

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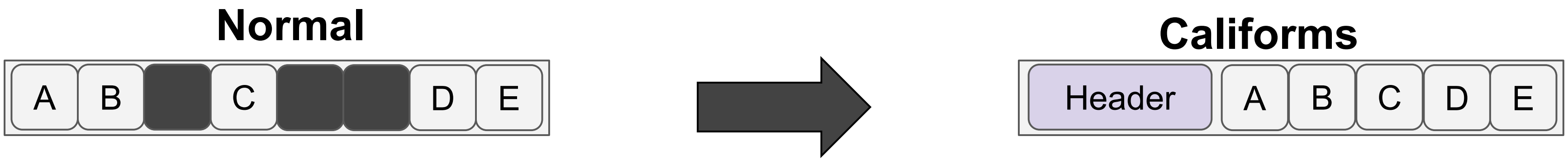

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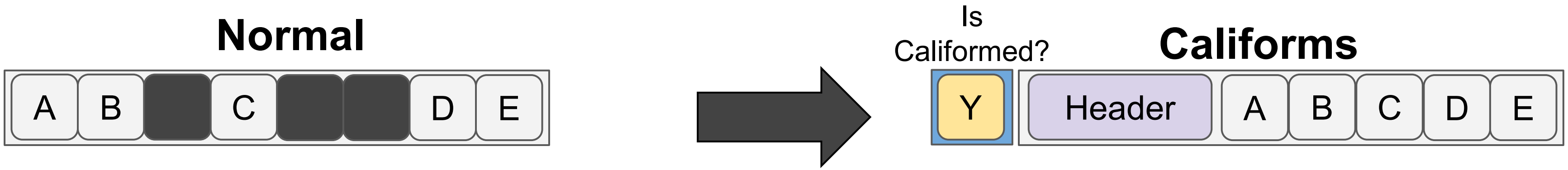

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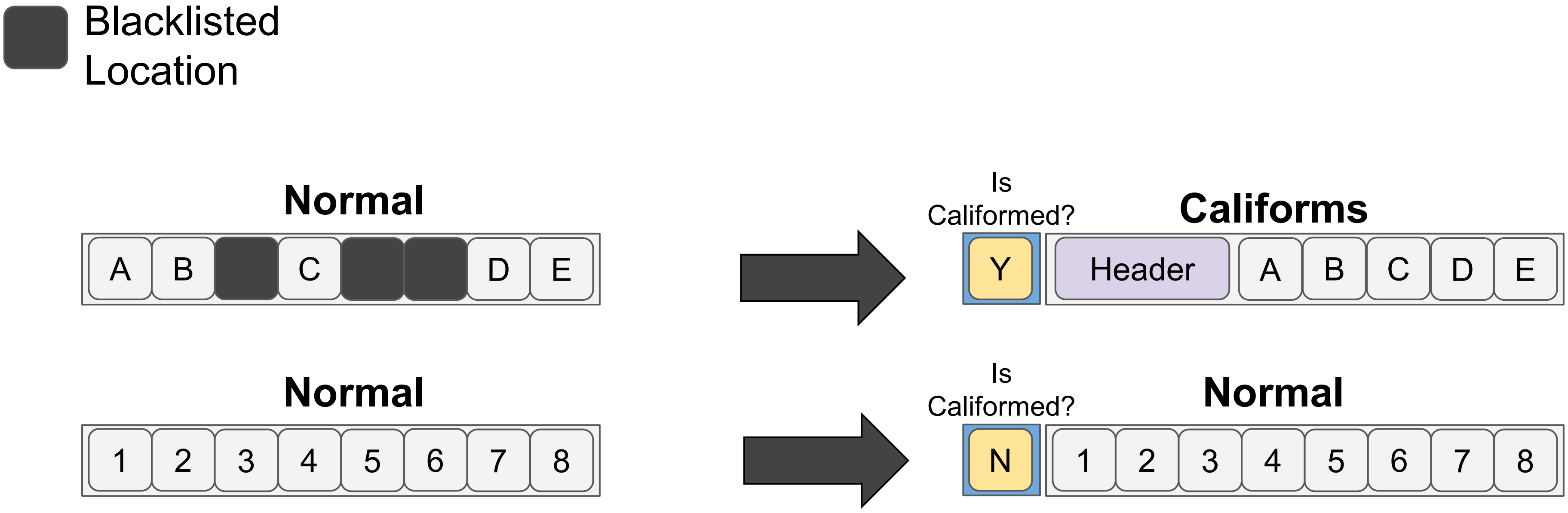
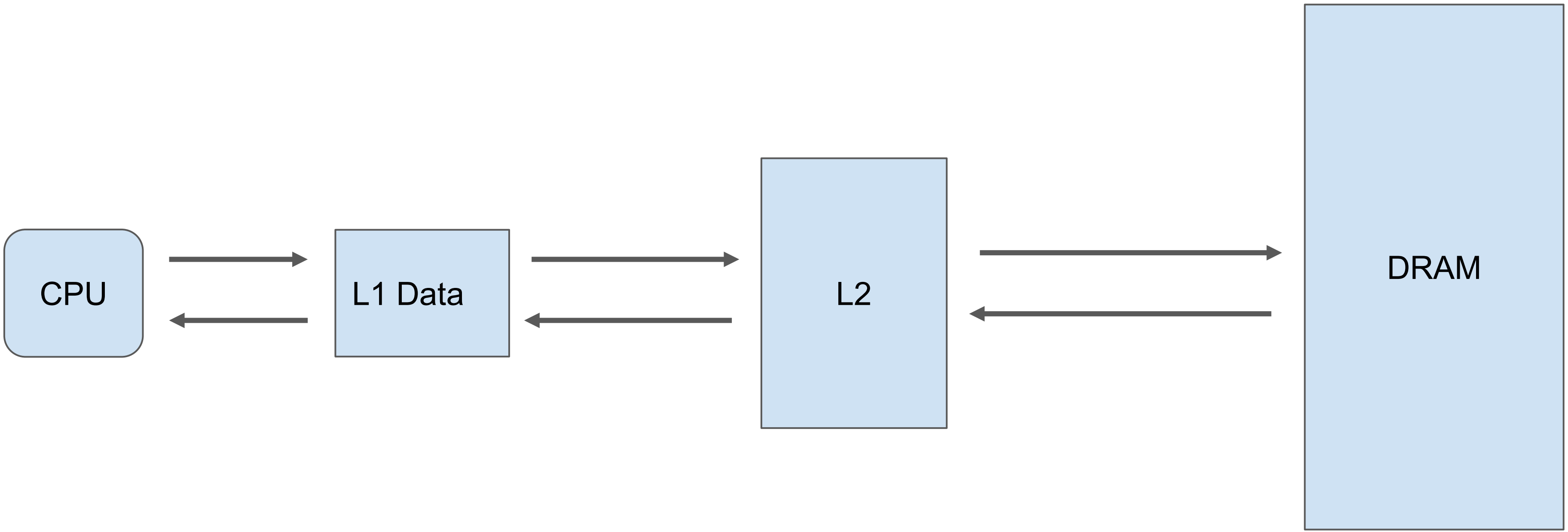


# CALIFORMS: FULL SYSTEM

- **Microarchitecture**
- **Architecture Support**
- **Software**

# CALIFORMS: MICROARCHITECTURE



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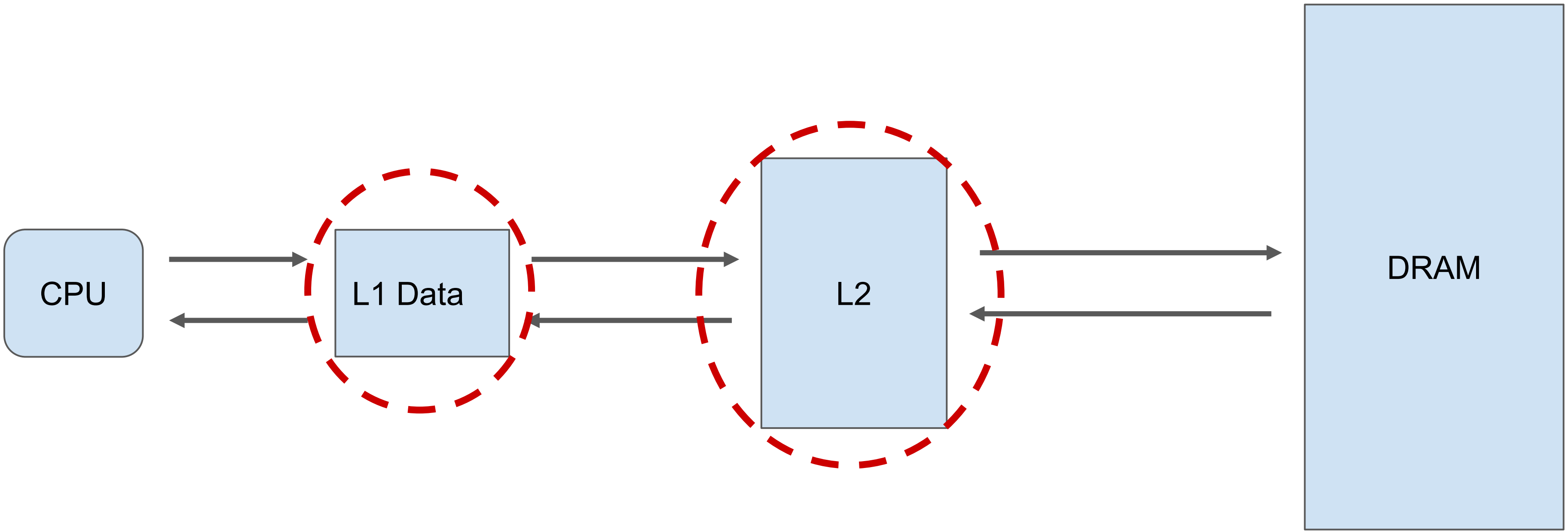

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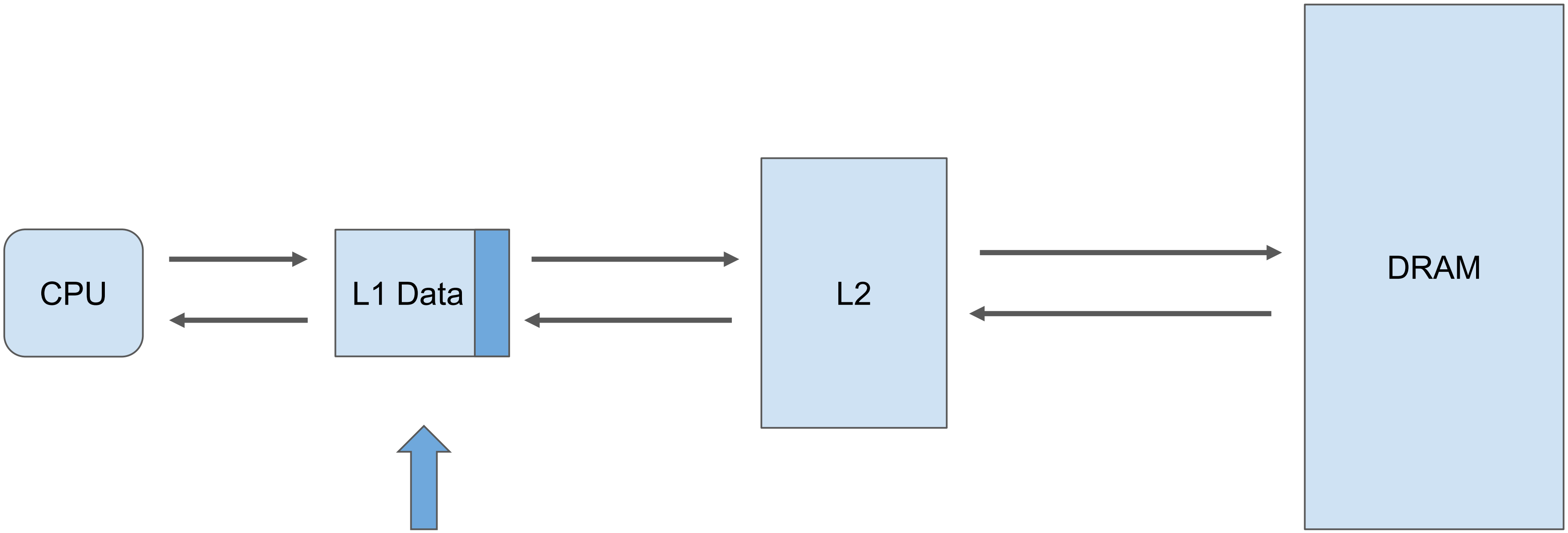
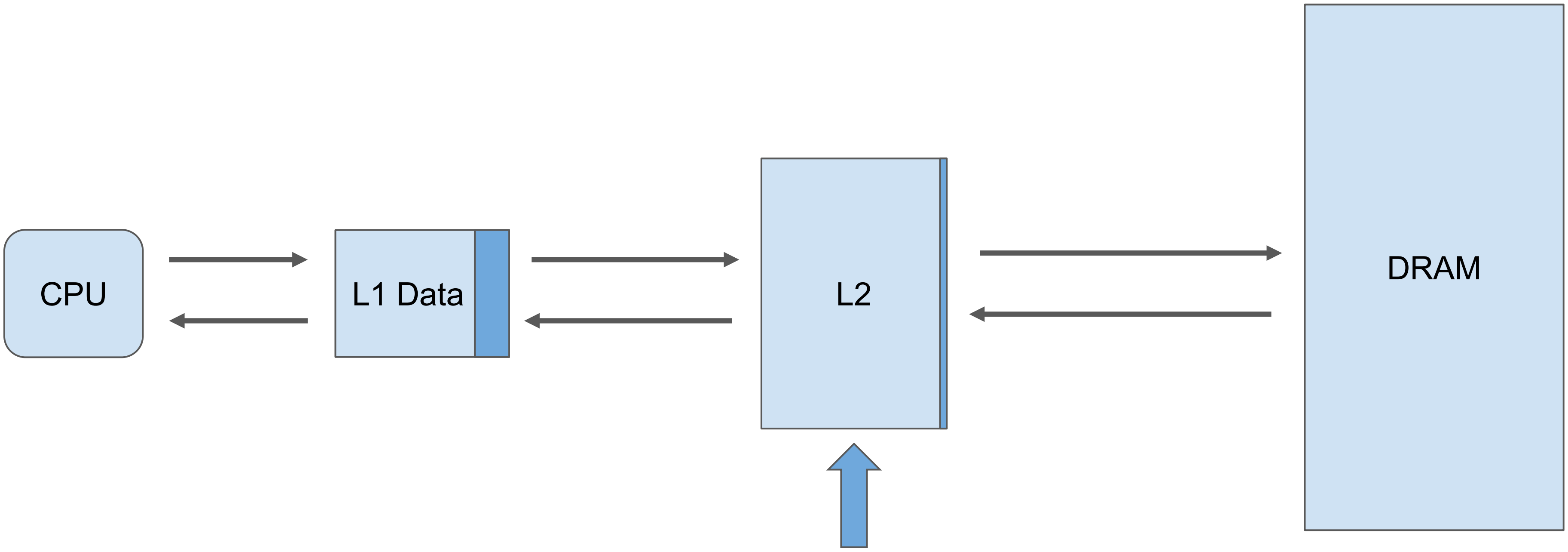



*BitVector Califorms*

No Latency Overhead

12.5% memory overhead

# CALIFORMS: MICROARCHITECTURE

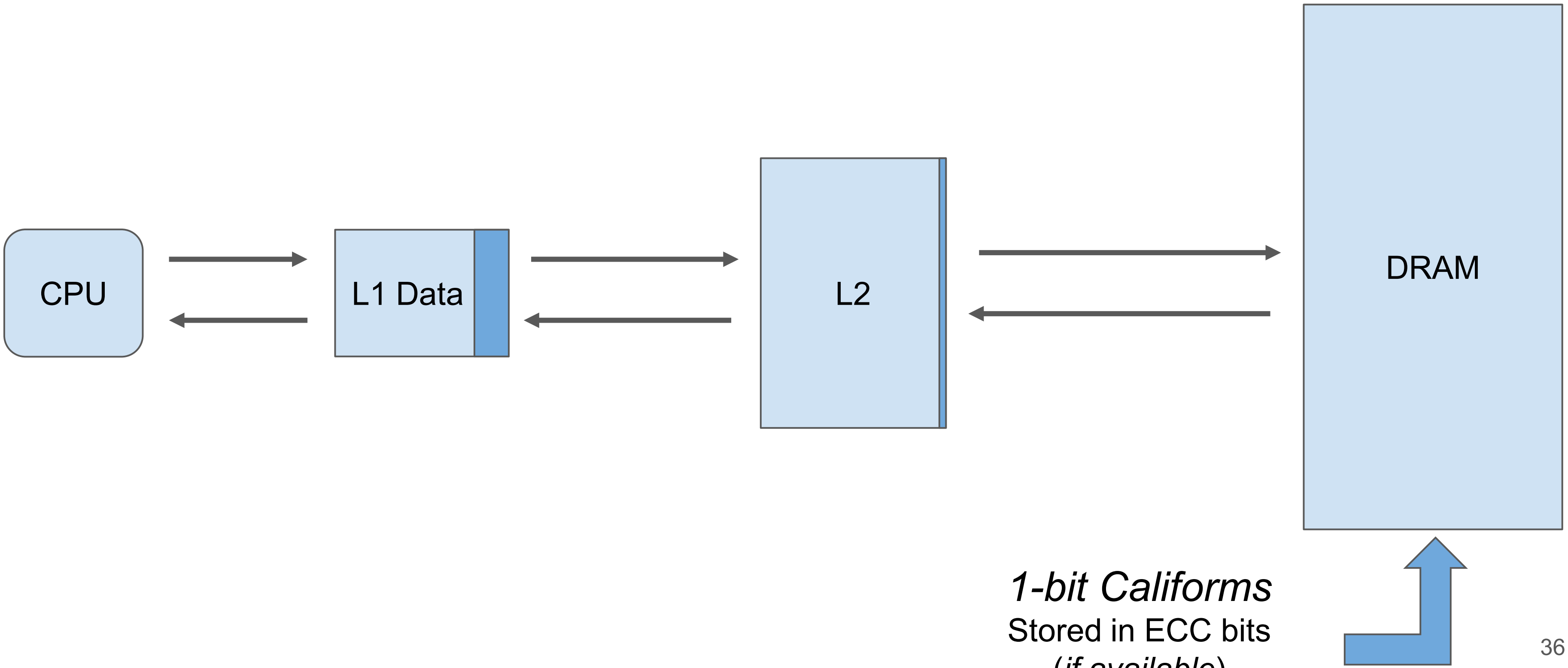



*1-bit Califorms*

1 Cycle *or can be hidden*

0.2% memory overhead

# CALIFORMS: MICROARCHITECTURE




*1-bit Califorms*
Stored in ECC bits
(*if available*)

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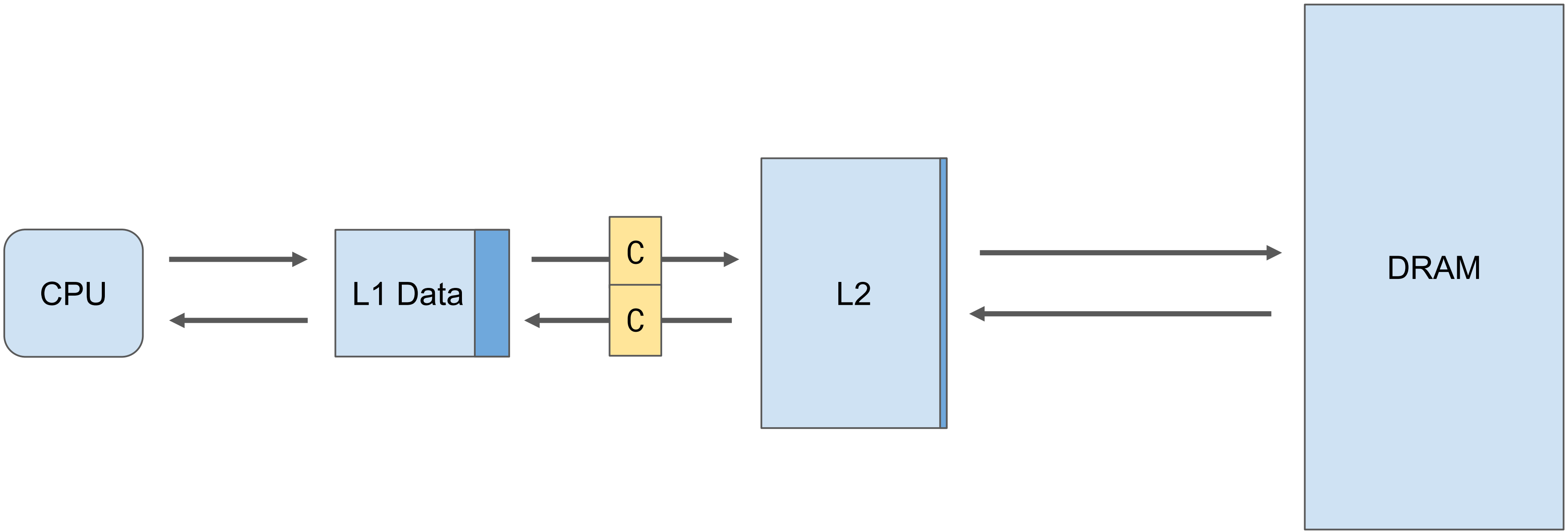

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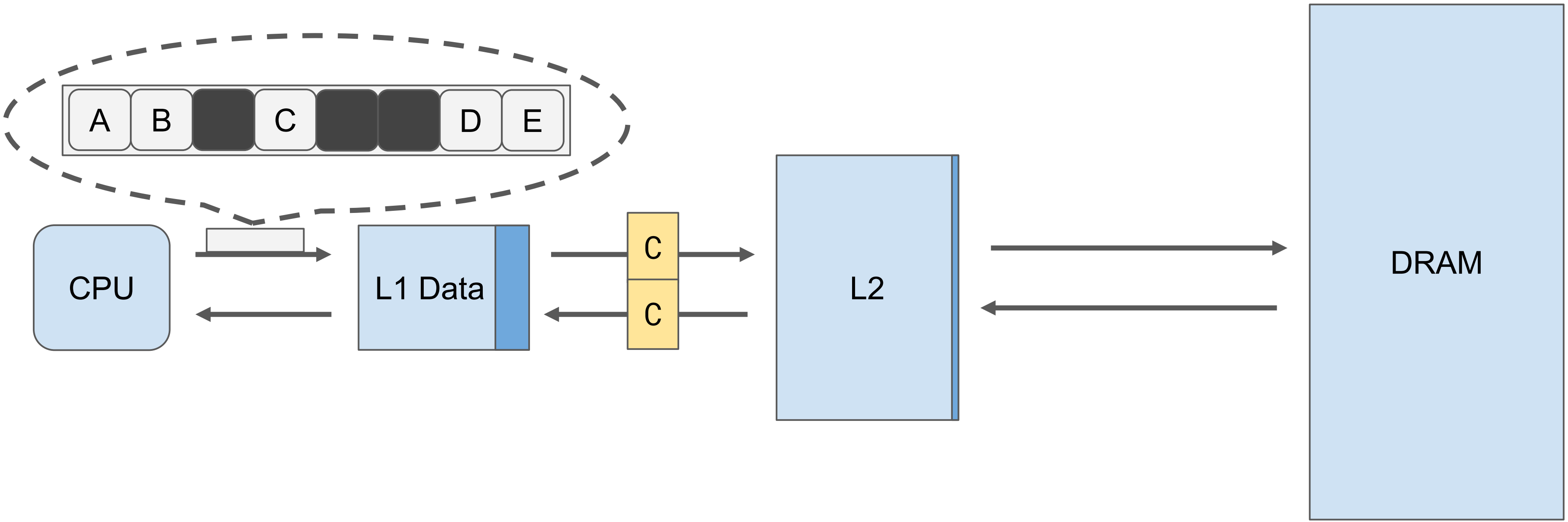

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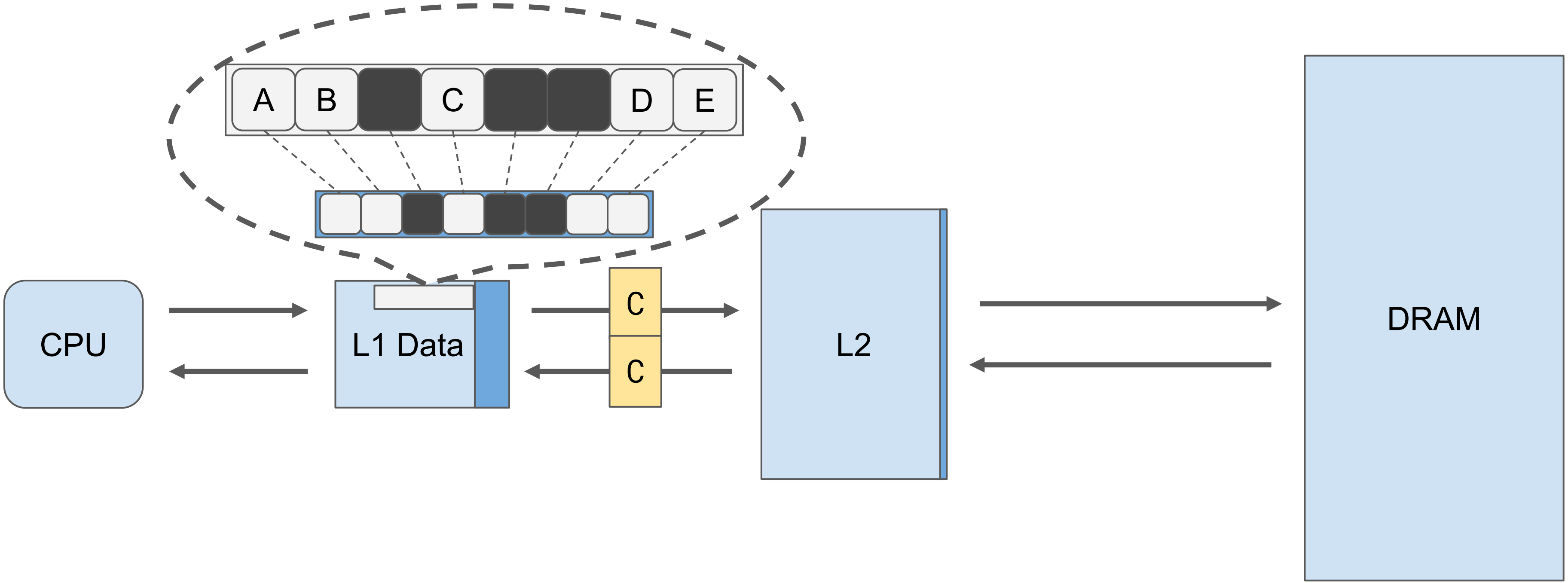

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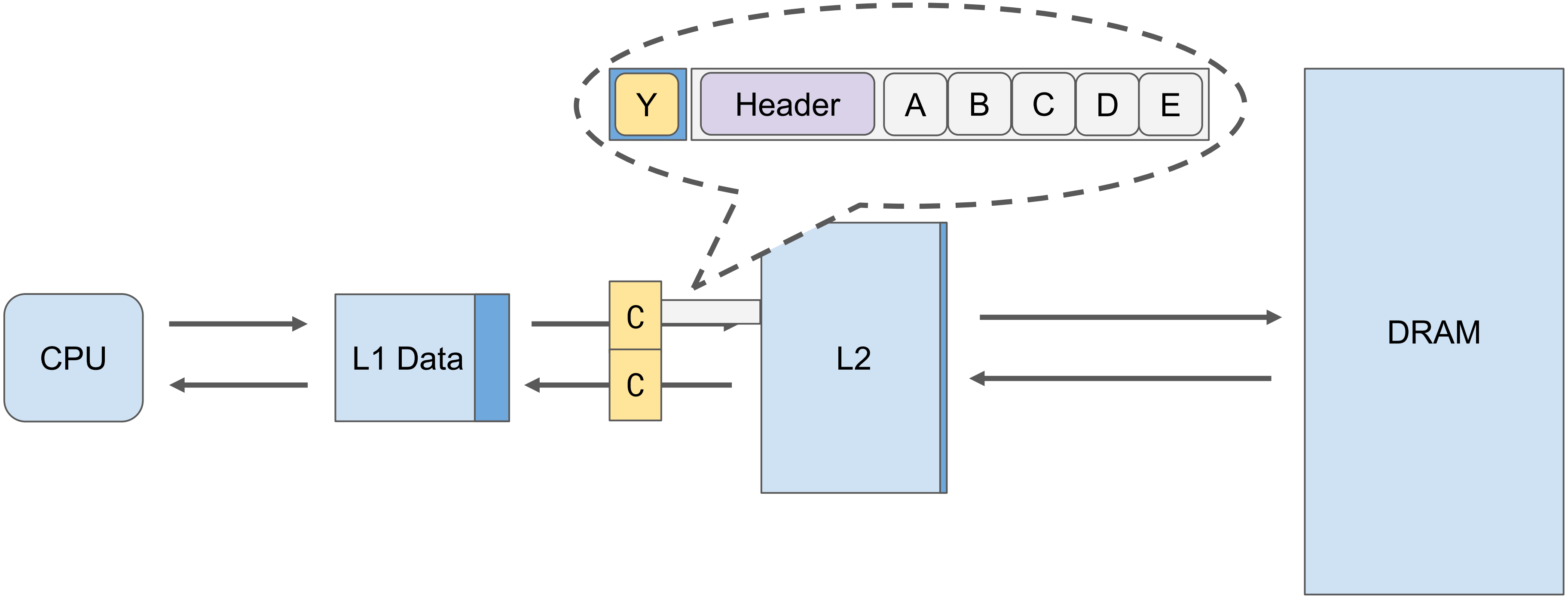

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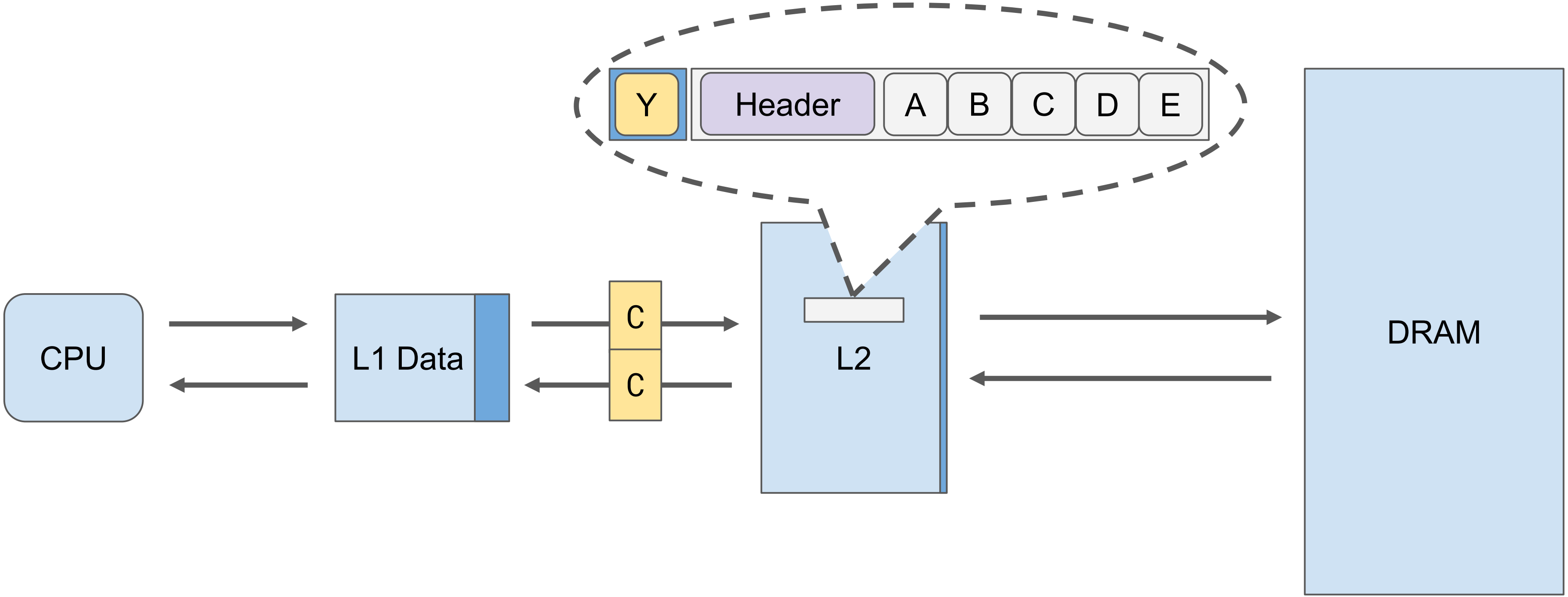

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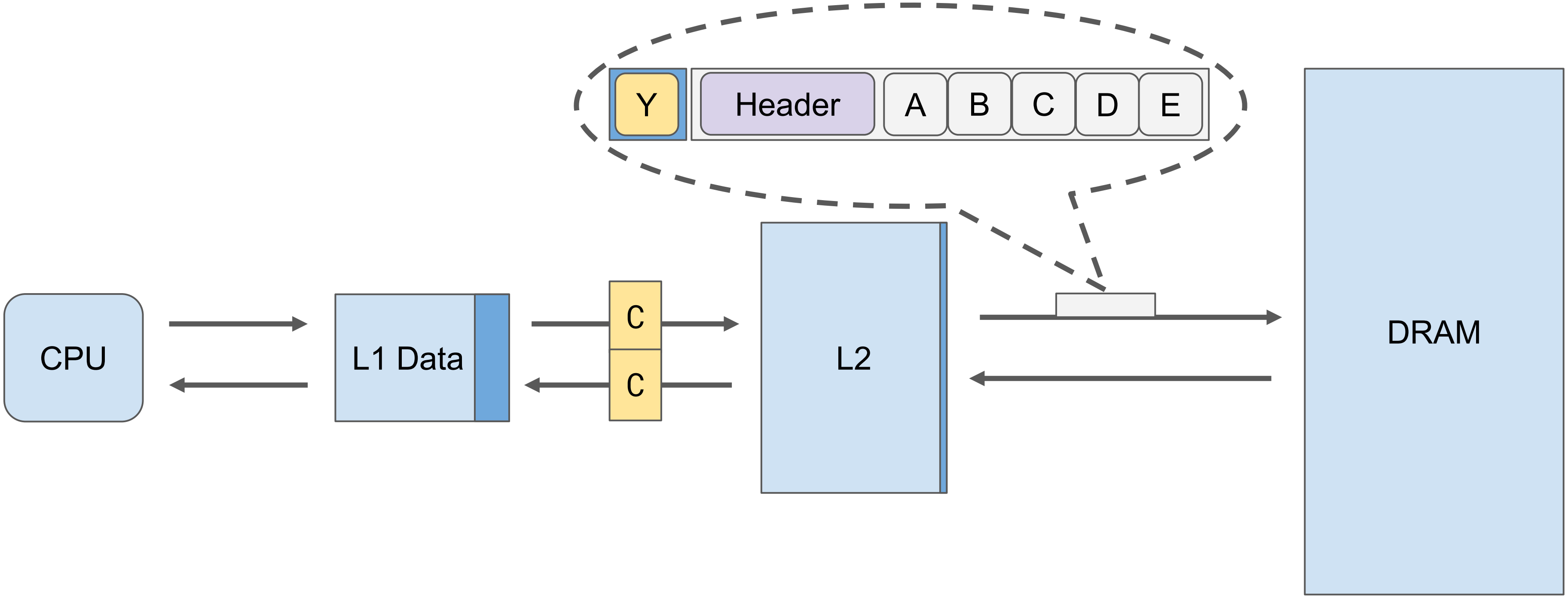

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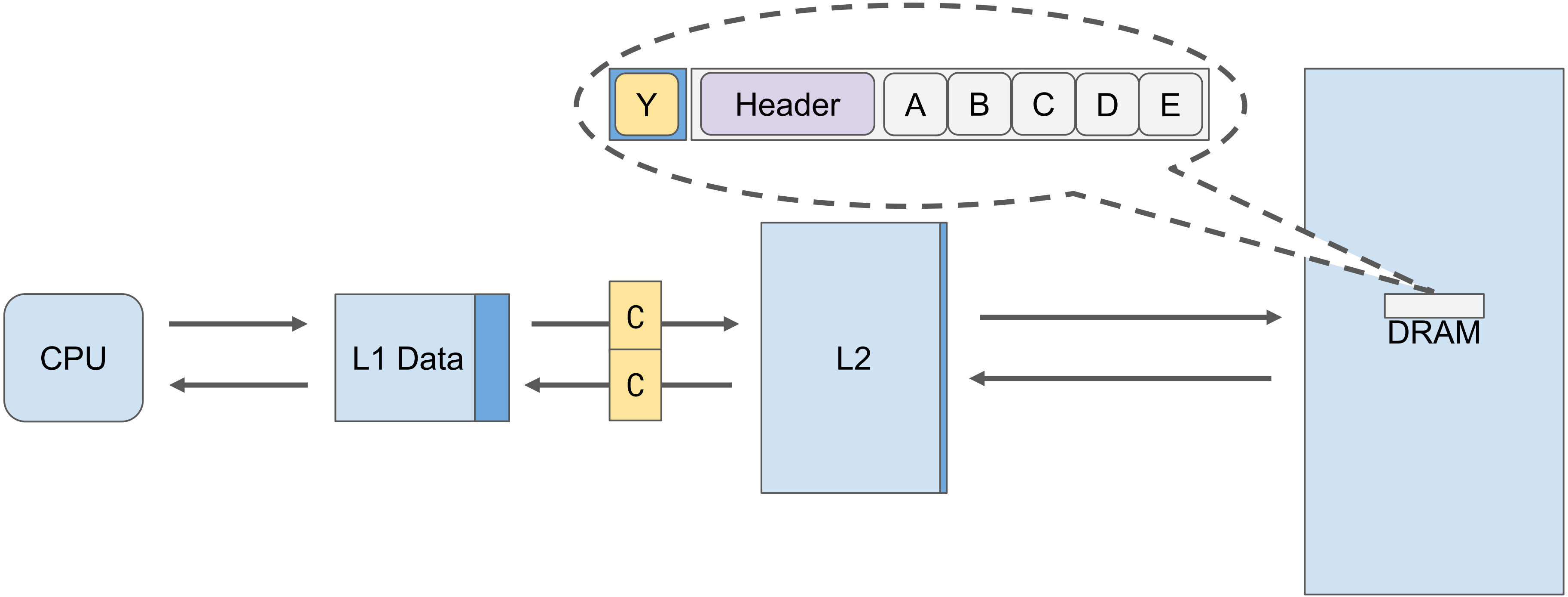

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# CALIFORMS: FULL SYSTEM

For more details, please refer to our paper.

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  - Precise storage (0-64 blacklisted locations per cache line).
- **Supports existing performance optimizations**
  - Critical word first.
- **Integrates into existing microarchitectures**
  - Does NOT disturb coherency.

# CALIFORMS

## PERFORMANCE

# CALIFORMS: PERFORMANCE OVERHEADS

- **Hardware Overheads**

- **Blacklisting Overheads**

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# CALIFORMS: INSERTION POLICIES

```
struct A_opportunistic
{
  char c;
  char tripwire[3];
  int i;
  char buf[64];
  void (*fp)();
}
```

**(1) Opportunistic**

***Tripwire Insertion Policies***

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**(1) Opportunistic**

```
struct A_full {
  char tripwire[2];
  char c;
  char tripwire[1];
  int i;
  char tripwire[3];
  char buf[64];
  char tripwire[2];
  void (*fp)();
  char tripwire[1];
}
```

**(2) Full**

***Tripwire Insertion Policies***

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  char tripwire[2];
  void (*fp)();
  char tripwire[1];
}
```

**(2) Full**

```
struct A_intelligent {
  char c;
  int i;
  char tripwire[3];
  char buf[64];
  char tripwire[2];
  void (*fp)();
  char tripwire[3];
}
```

**(3) Intelligent**

***Tripwire Insertion Policies***

# CALIFORMS

## EVALUATION METHODOLOGY

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- **Emulating the Blacklisting instruction**
  - Inserting dummy stores to blacklisted bytes.

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- **Emulating the Blacklisting instruction**
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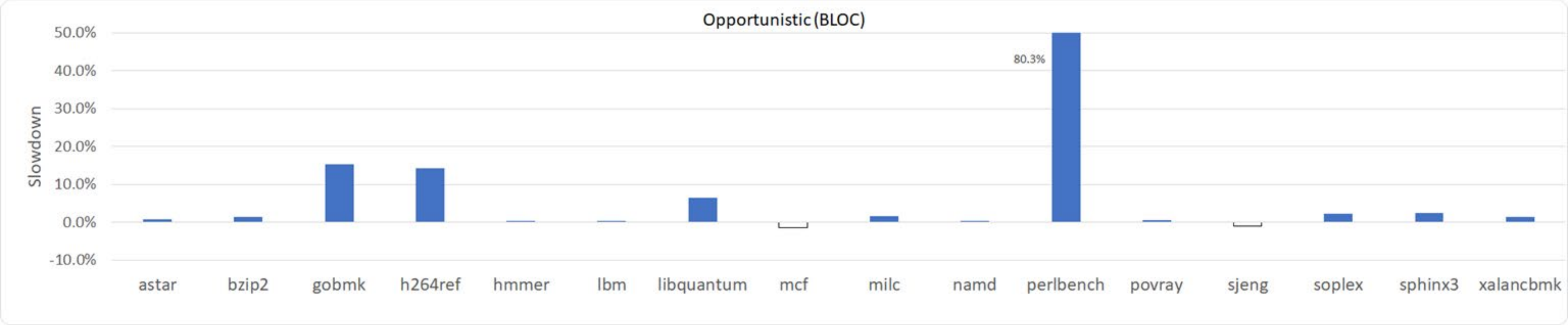
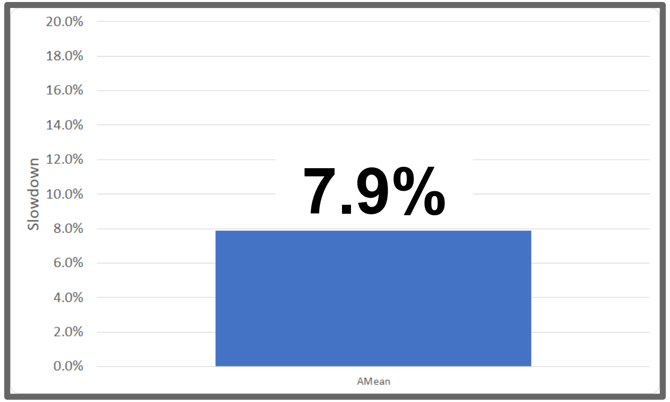
- **Using SPEC2006 benchmarks with reference inputs**
  - Running experiments to completion.

# CALIFORMS: POLICIES OVERHEADS



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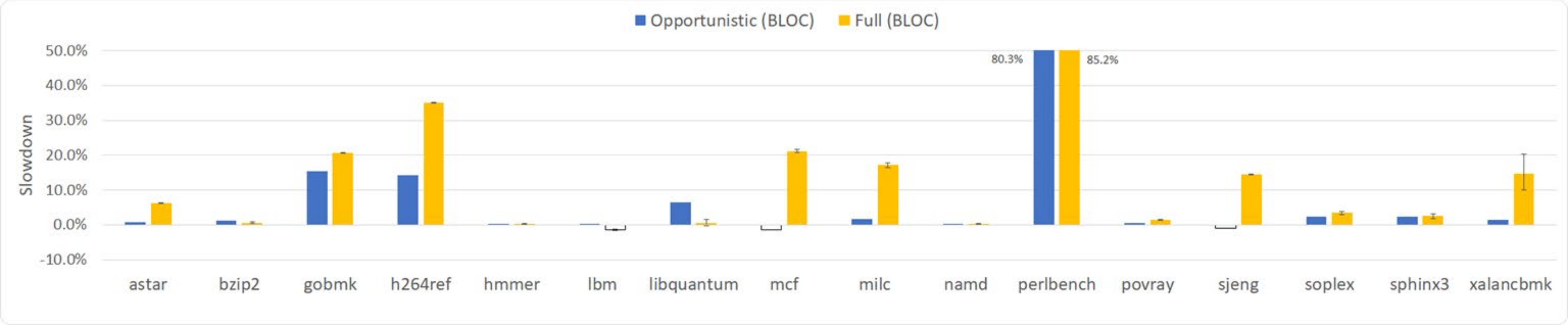


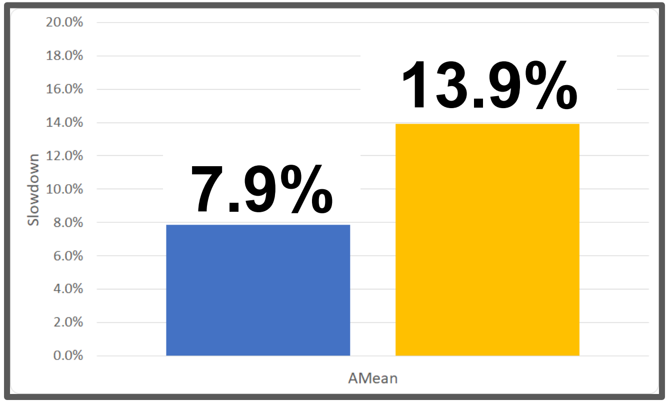

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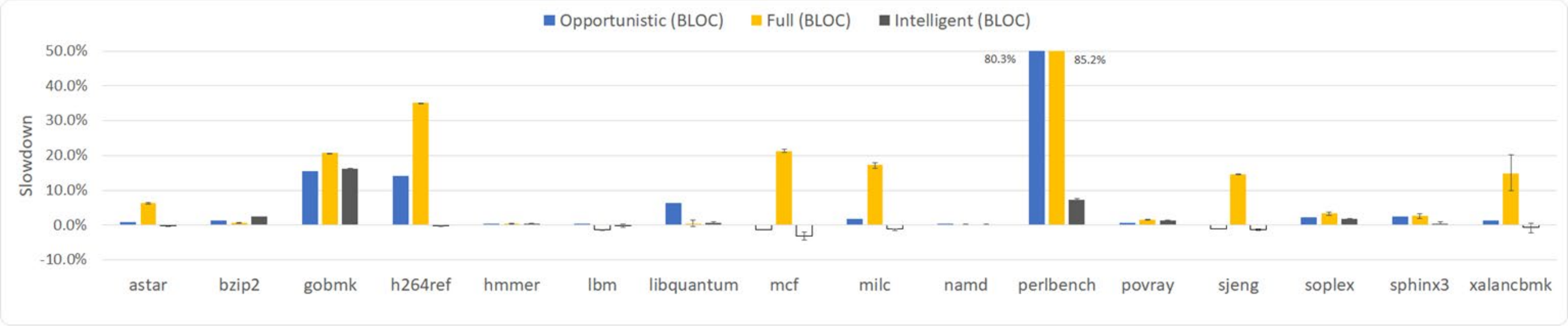


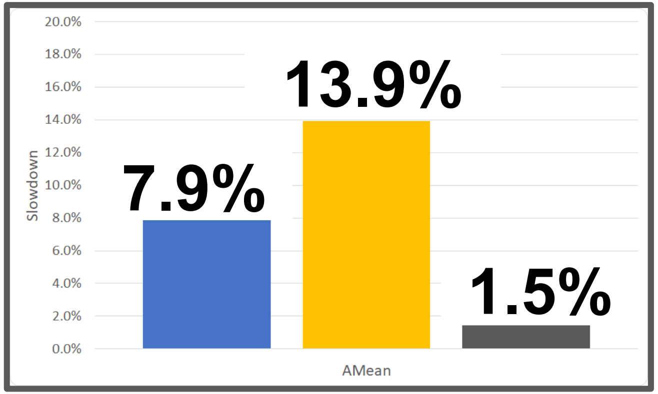

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{
  char c;
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  int i;
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```

**(1) Opportunistic**

Provides the best **performance-security tradeoff.**

**(2) Full**

```
struct A_intelligent {
  char c;
  int i;
  char tripwire[3];
  char buf[64];
  char tripwire[2];
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**(3) Intelligent**

***Tripwire Insertion Policies***

# CALIFORMS

## SECURITY BENEFITS

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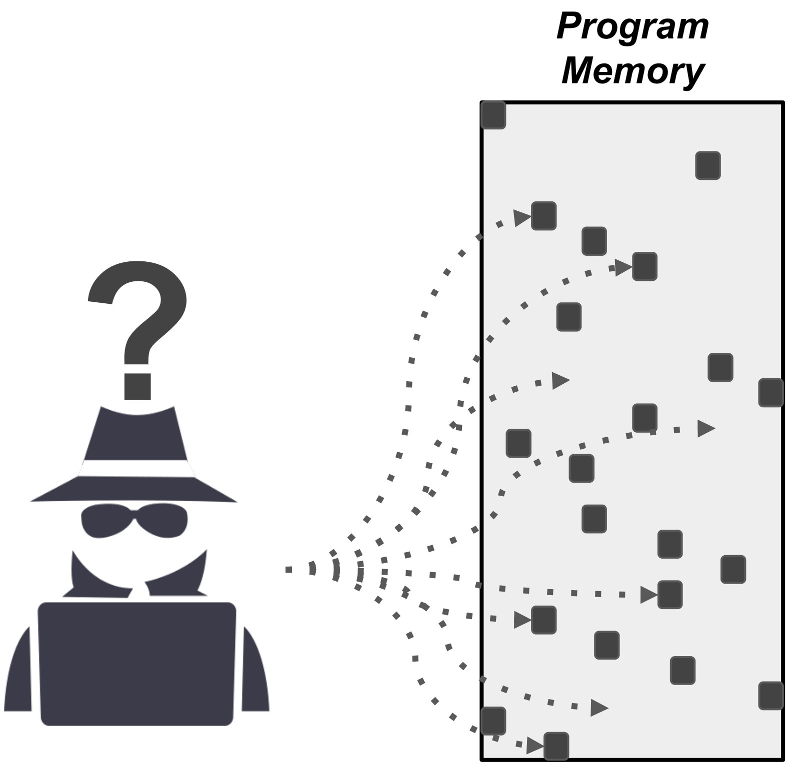
- Blacklisted locations must be placed ***unpredictably***.



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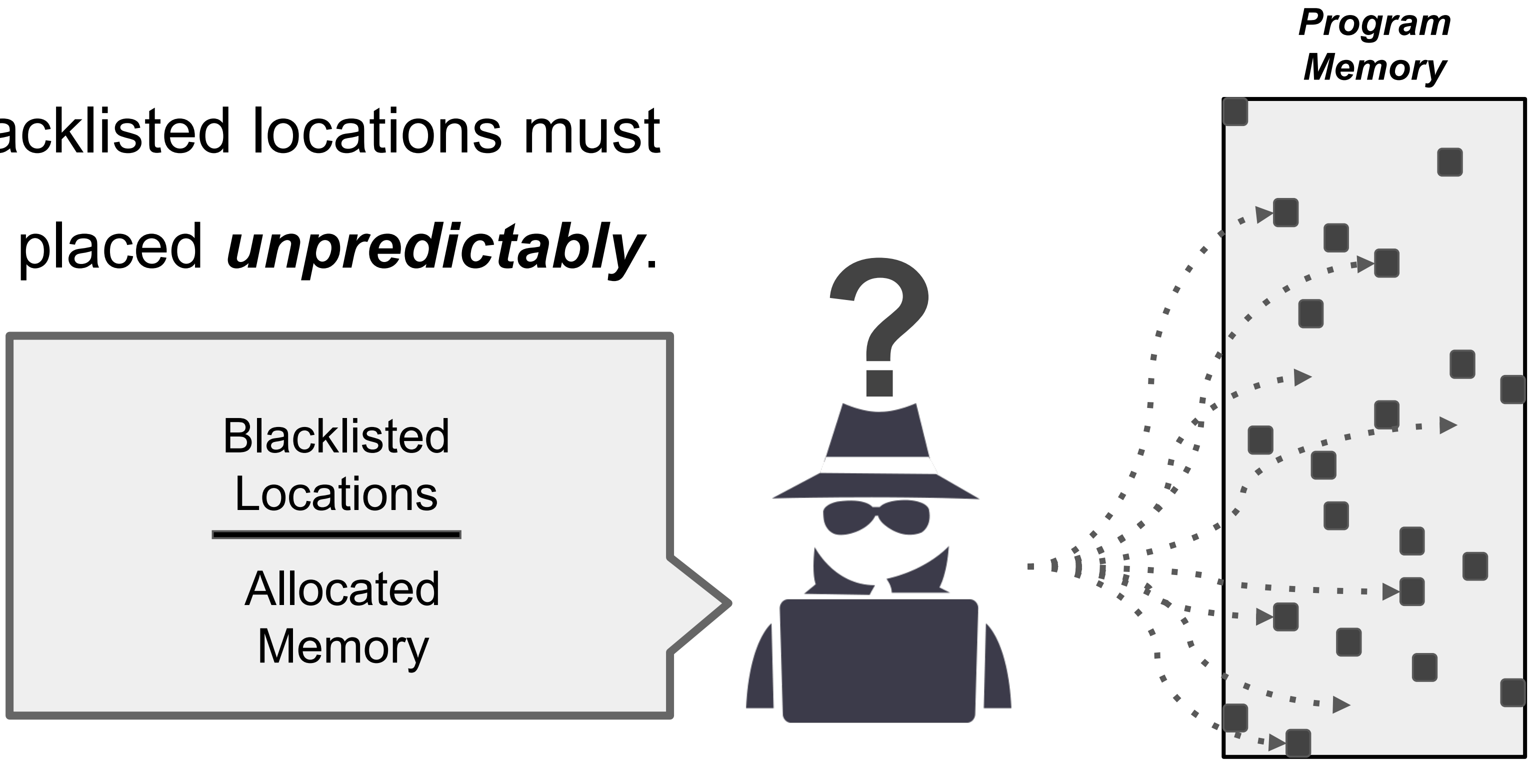


# CALIFORMS: SECURITY BENEFITS

This is the **best case** for me.
Only one object!

We insert **up to 7** tripwires between fields

| | |
|---|---|
| 0 | `int pin;` |
| 1 | |
| 2 | |
| 3 | |
| 4 | |
| 5 | |
| 6 | |
| 7 | |

# CALIFORMS: SECURITY BENEFITS

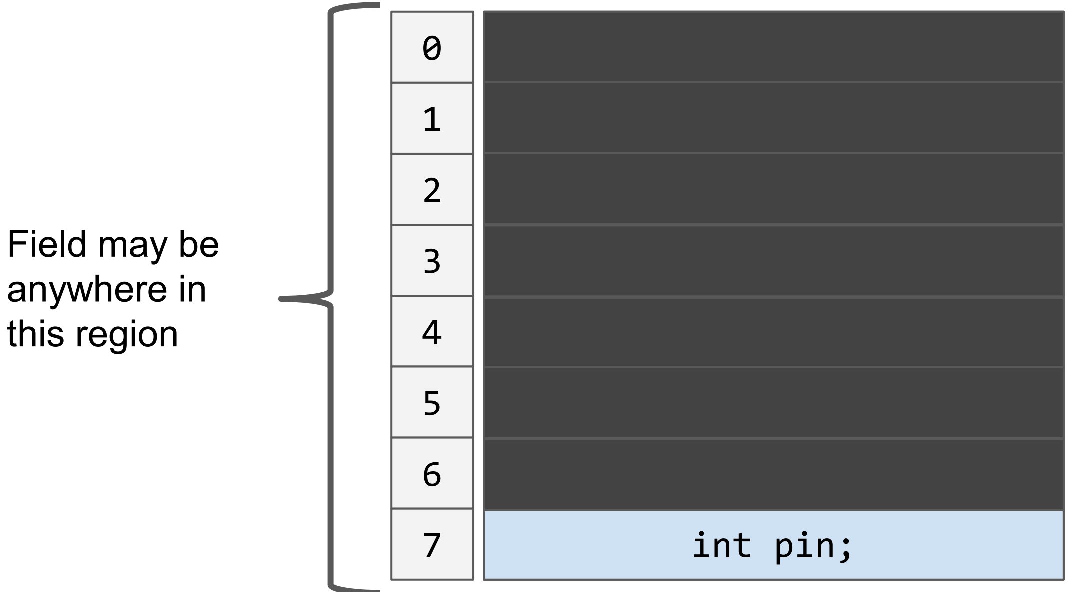
Let me **guess** where the field is.

Field may be anywhere in this region

| | |
|---|---|
| 0 | |
| 1 | |
| 2 | |
| 3 | |
| 4 | `int pin;` |
| 5 | |
| 6 | |
| 7 | |

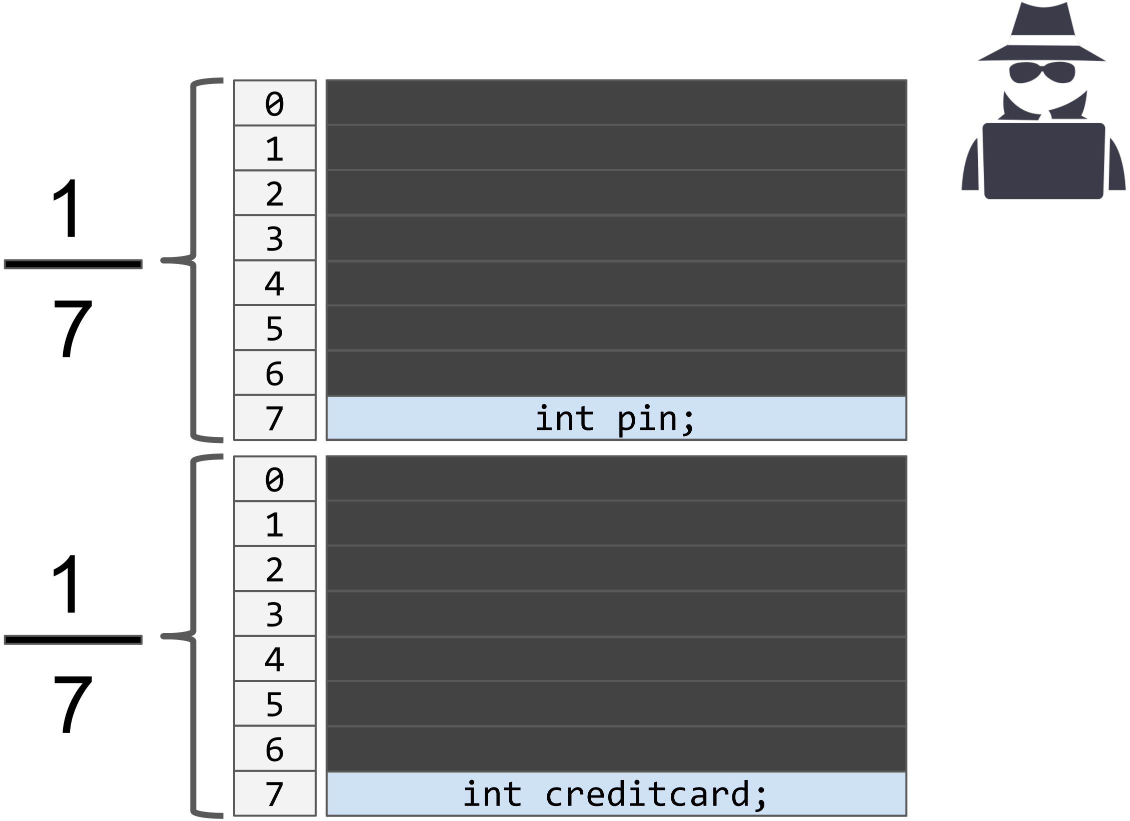
# CALIFORMS: SECURITY BENEFITS

Let me **guess** where the field is.



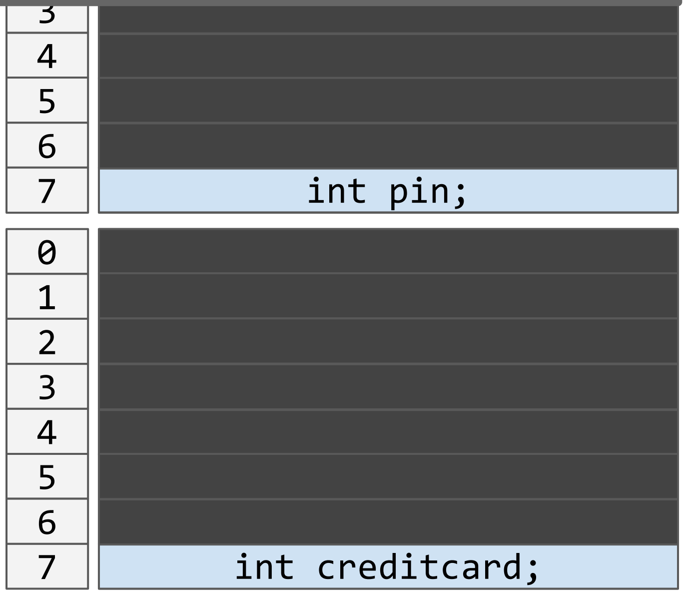

$$\frac{1}{7}$$

# CALIFORMS: SECURITY BENEFITS



# CALIFORMS: SECURITY BENEFITS

The more I need to disclose the **harder** it is!




$$\frac{1}{7^n}$$

where $n$ is the number of fields to be disclosed.

# CALIFORMS: SECURITY BENEFITS

Can I **disable** blacklisted memory?

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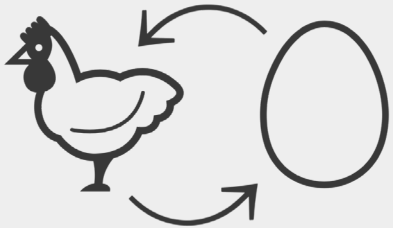
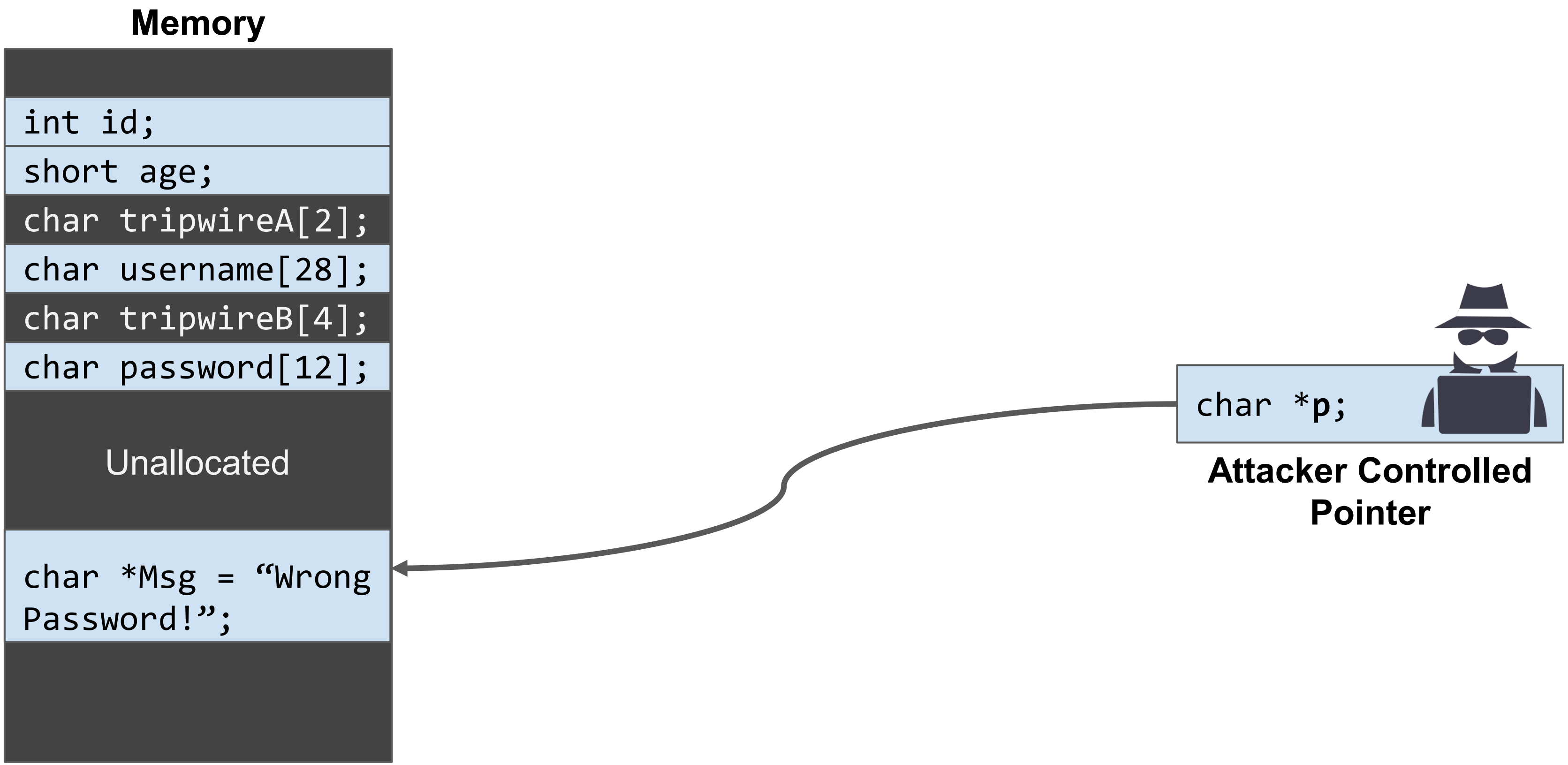


They would first need to bypass Califorms.

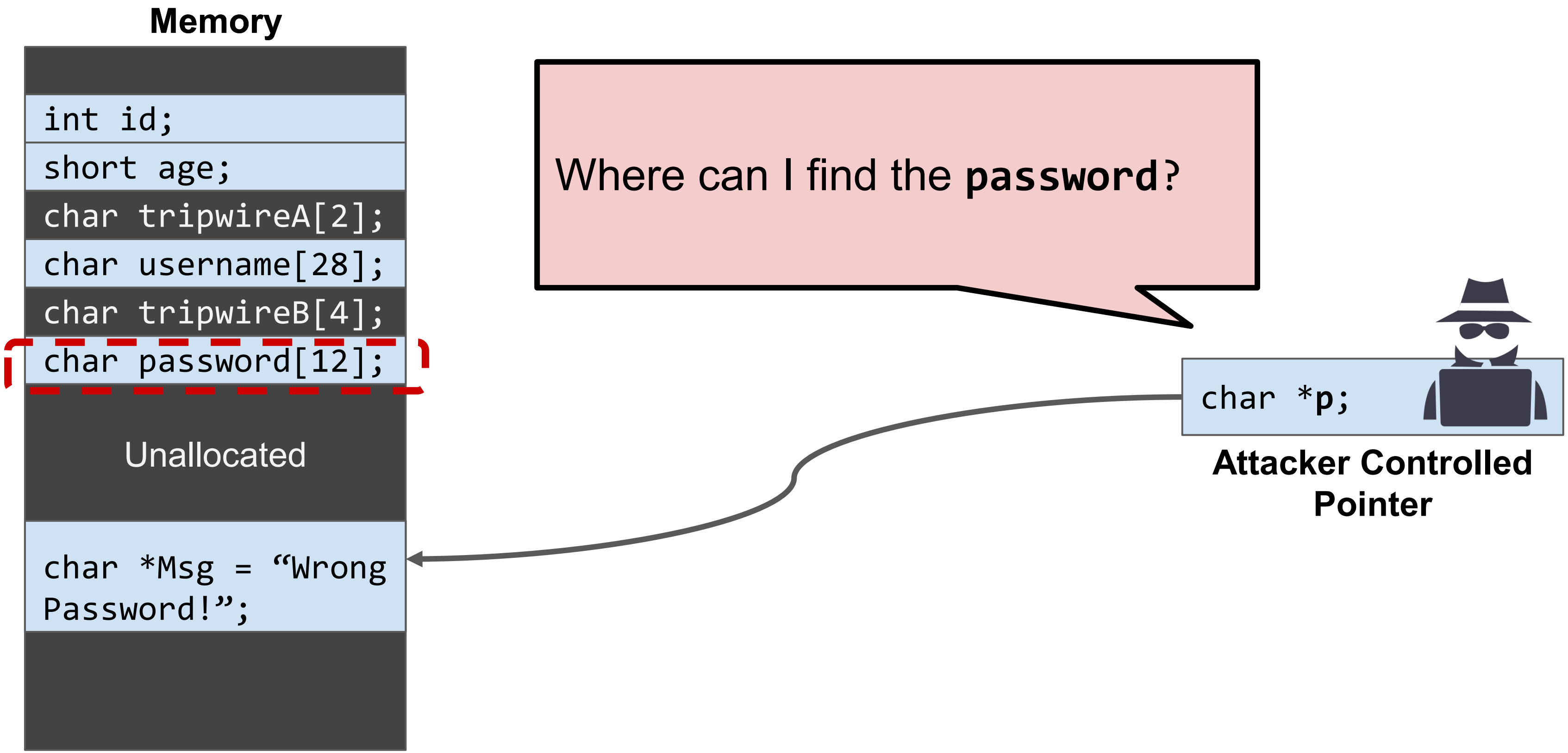
# MEMORY SCANNING ATTACK

**WITH** CALIFORMS

# EXAMPLE: MEMORY SCANNING ATTACK



# EXAMPLE: MEMORY SCANNING ATTACK



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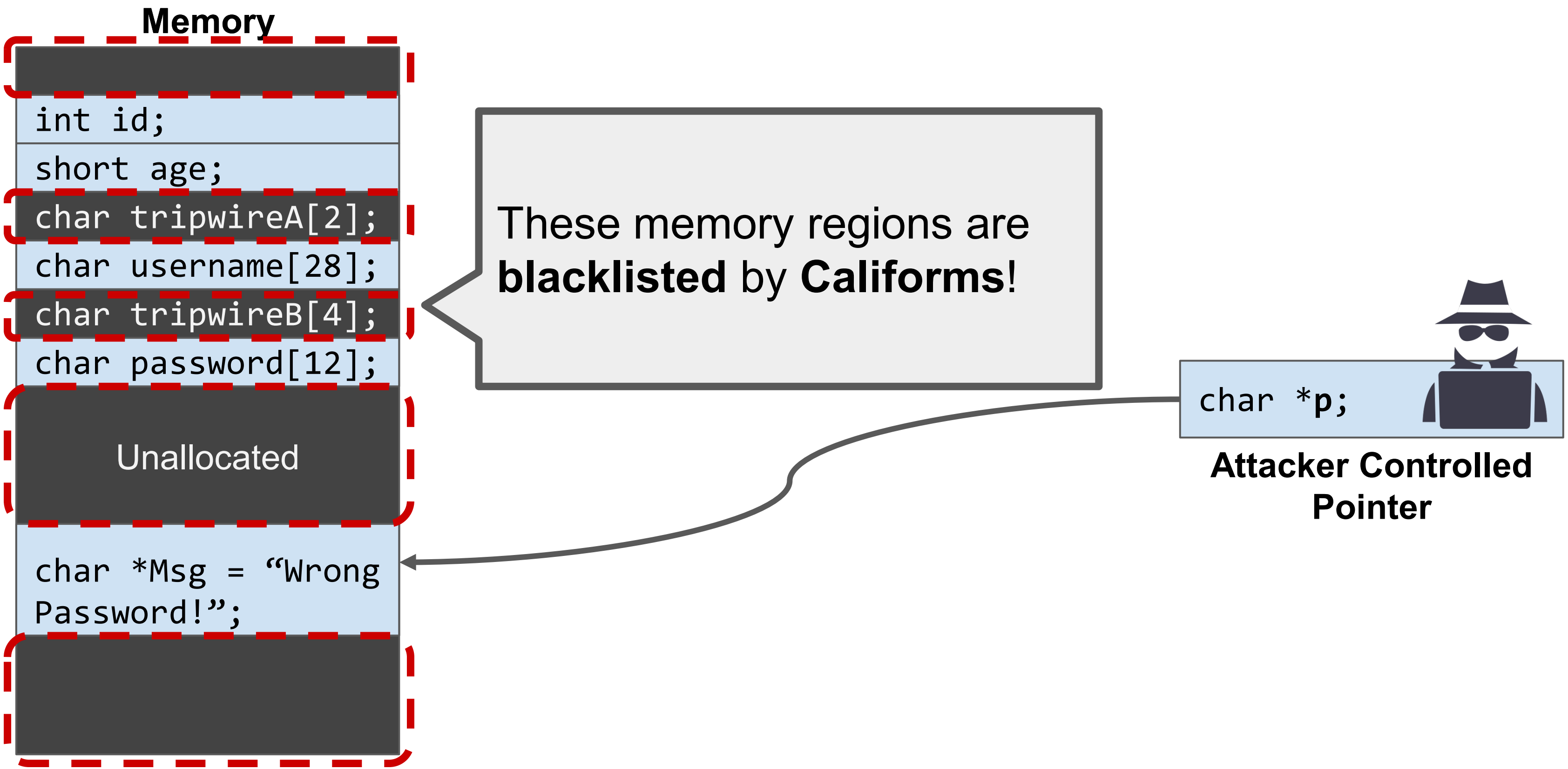

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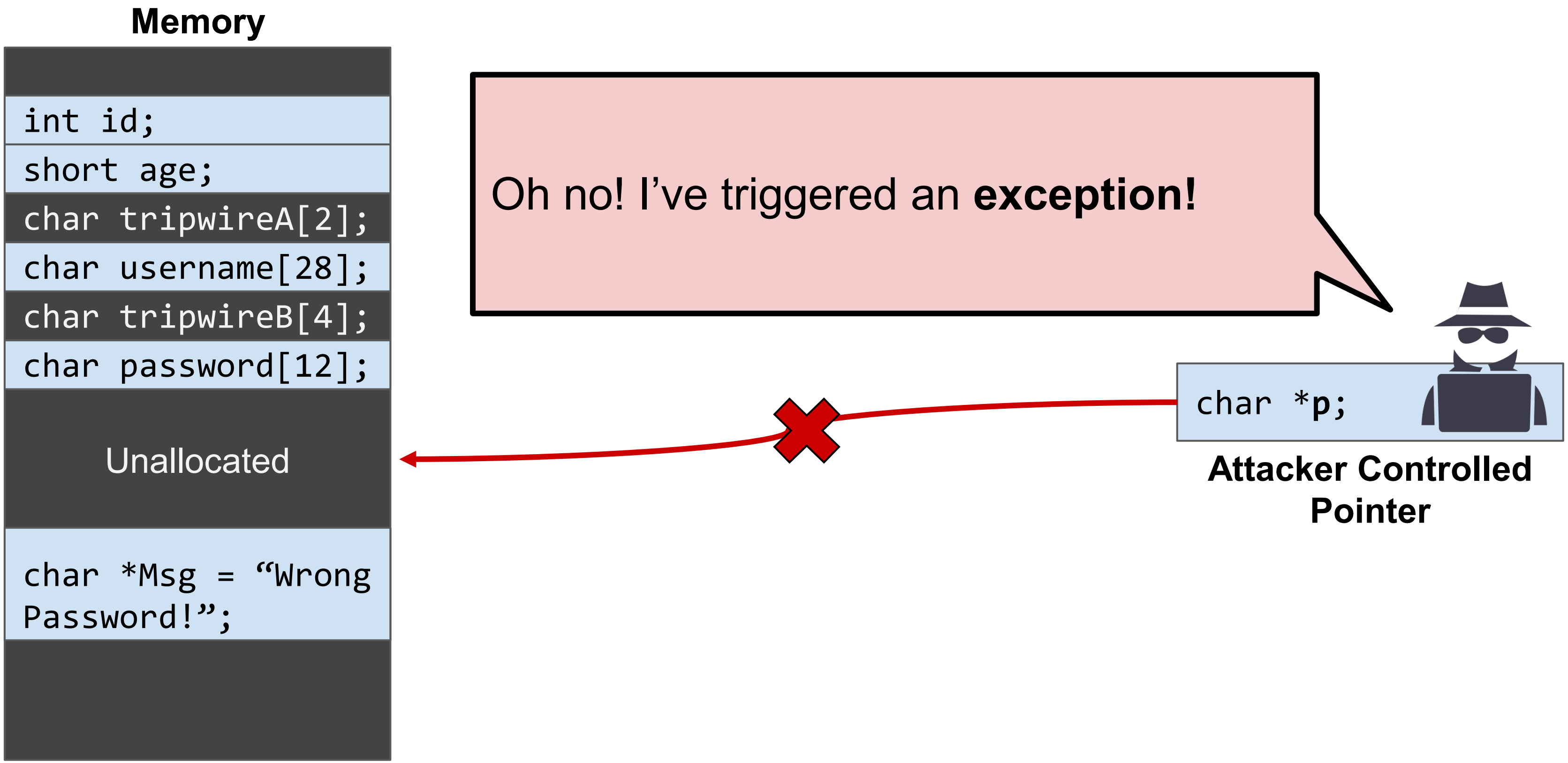

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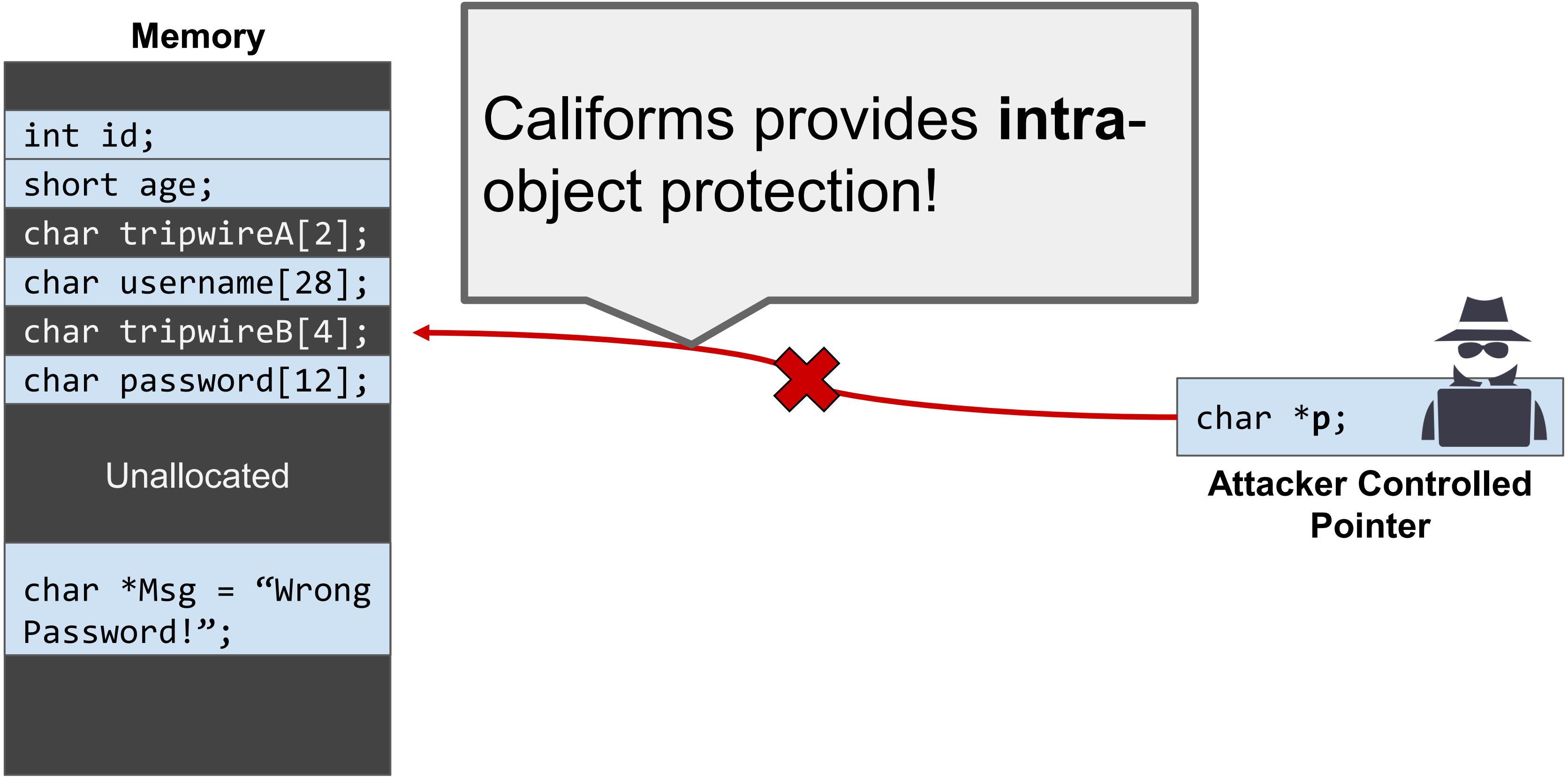

# RELATED WORK

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| --- | --- | --- |
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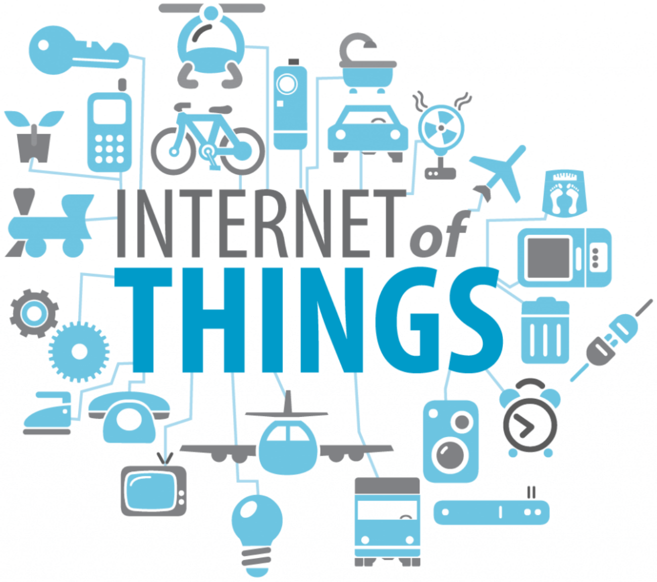
| Califorms | $\propto$ # blacklisted locations | $\propto$ # of blacklisting instructions |

# CONCLUSION

- Californs can be applied to **non 64-bit systems** (e.g IoT, CPS, etc).

- Califorms' blacklisting is an efficient solution to memory safety:
  - Is **easy to implement**.
  - Has **low overheads**.
  - Offers **robust security**.



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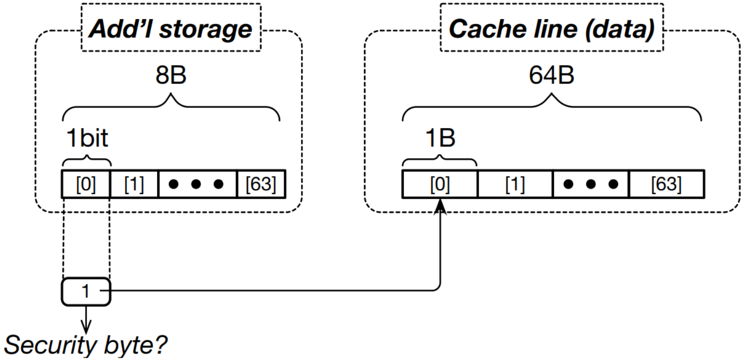
QUESTIONS?

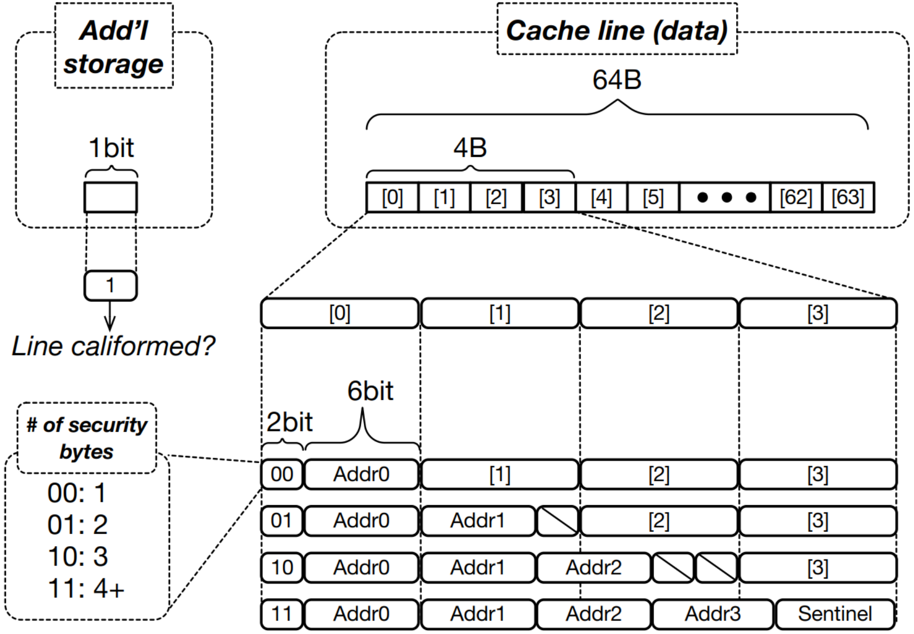
Stop by during the poster session to chat!
2:50-4:00pm

# BACKUPS

# CALIFORMS: ENCODING SCHEMES

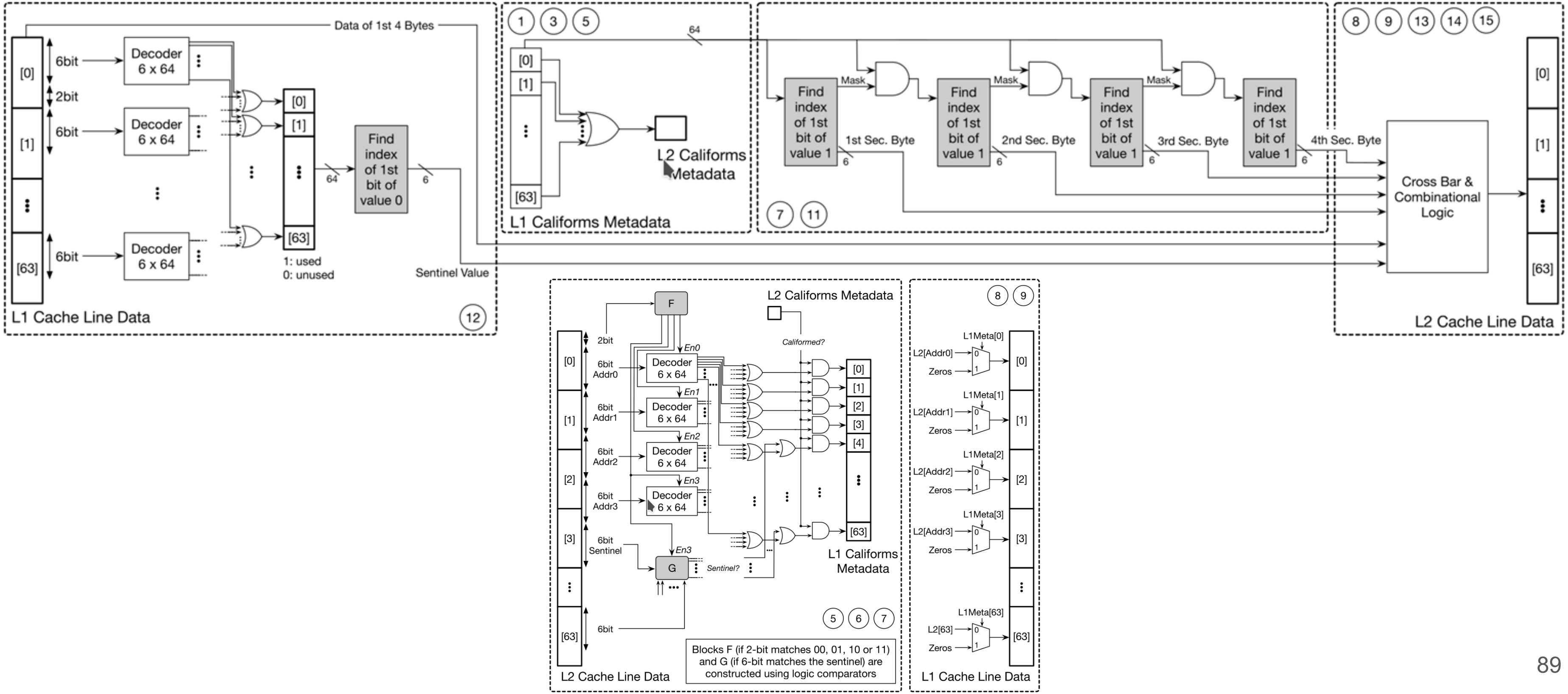



**califorms-bitvector**




**califorms-sentinel**

# CALIFORMS: HARDWARE DIAGRAM



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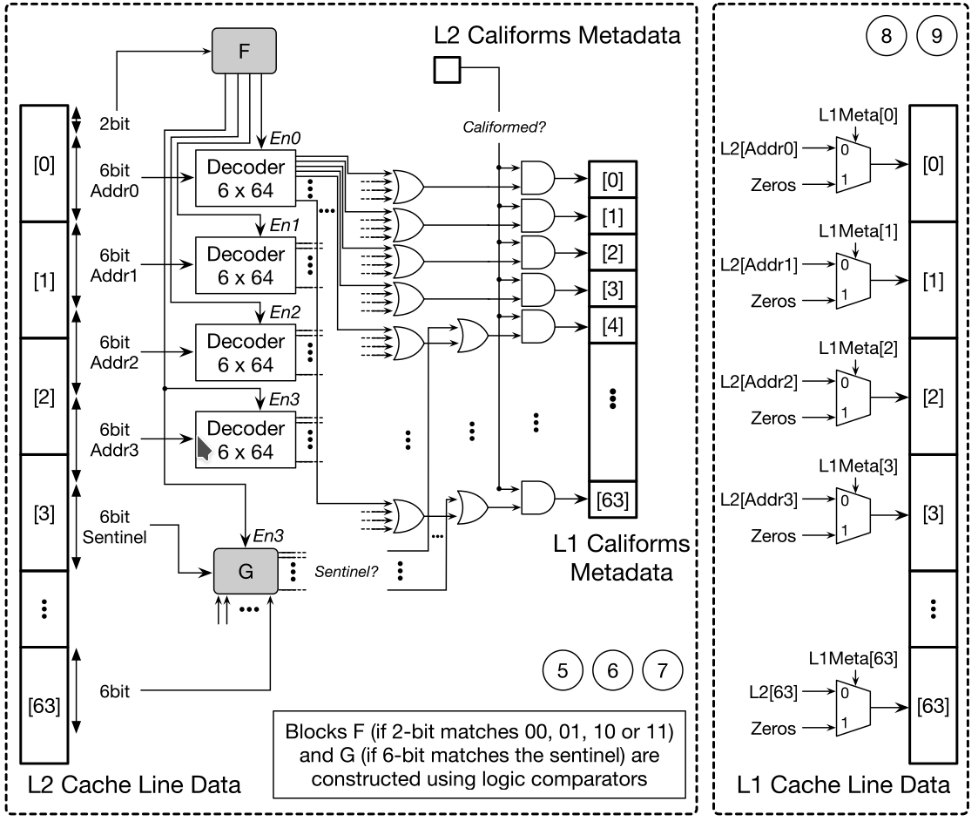
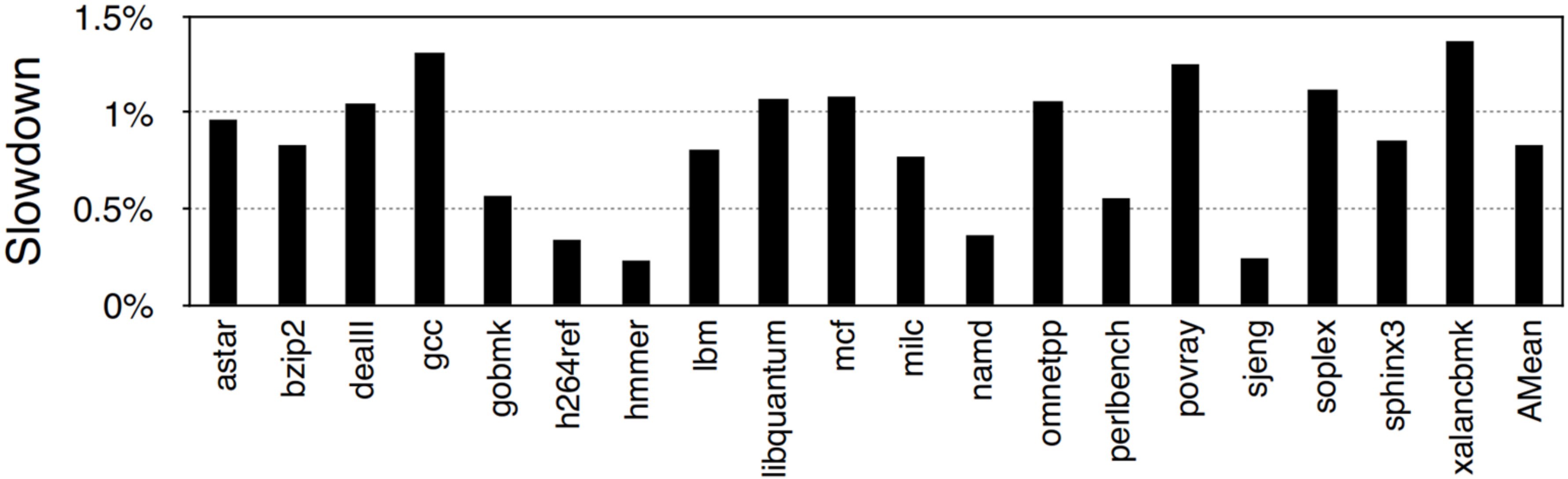


# CALIFORMS: CONSERVATIVE ANALYSIS



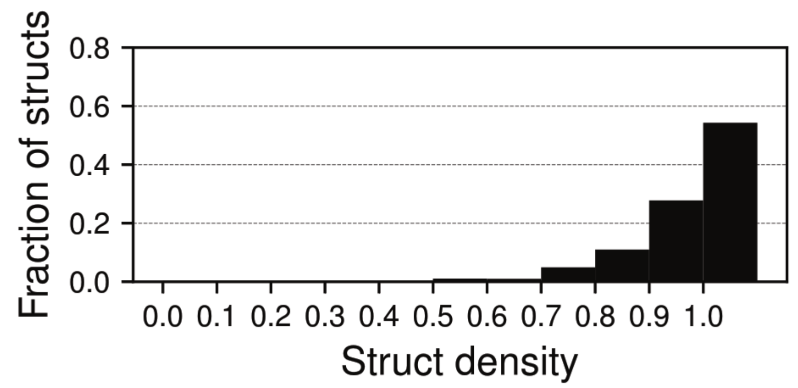

*Slowdown with additional one-cycle access latency for both L2 and L3 caches.*

# CALIFORMS: HARDWARE PERFORMANCE

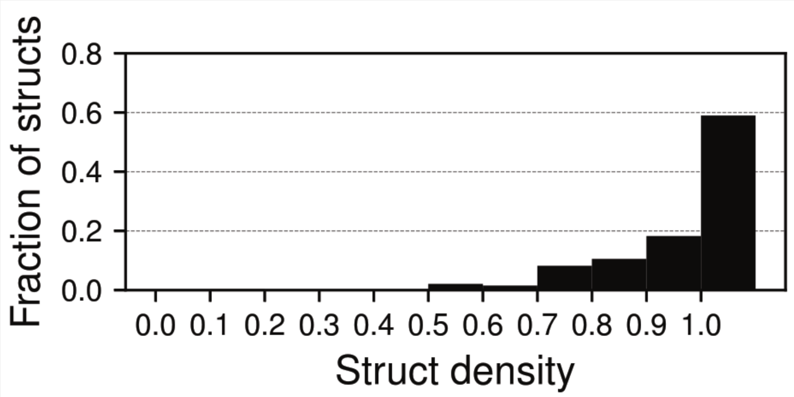
| **L1 Califorms** | **Area (GE)** | **Delay (*ns*)** | **Power (*mW*)** |
|---|---|---|---|
| L1 Overheads | [+18.69%] 412,263.87 | [+1.85%] 1.65 | [+2.12%] 16.17 |
| Fill Module | 8,957.16 | 1.43 | 0.18 |
| Spill Module | 34,561.80 | 5.50 | 0.52 |

# CALIFORMS: OPPORTUNISTIC POLICY

**Normally Occurring Dead Bytes**




*SPEC CPU2006 C and C++ Benchmarks*




*V8 JavaScript Engine*

**Struct density** = $\sum_i^{\#fields}(\texttt{sizeof}(\texttt{field}_i))/\texttt{sizeof}(\texttt{struct})$