RELOAD+REFRESH: Abusing Cache Replacement Policies to Perform Stealthy Cache Attacks

Samira Briongos[1], Pedro Malagón Marzo[1], José M. Moya Fernández[1], Thomas Eisenbarth[2]

[1]Universidad Politécnica de Madrid, [2]University of Lübeck

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Motivation

- **Can we trust existing countermeasures against cache attacks?**
  - Hardware countermeasures
  - Preemptive countermeasures
  - Detection countermeasures

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  - Collect information from performance counters (cache misses, cache accesses…)
  - Compute behavioral models of the process

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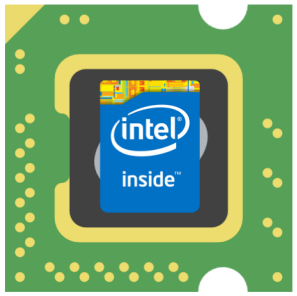
  - Preemptive countermeasures
  - **Detection countermeasures**
- **How do they detect cache attacks?**
  - Collect information from performance counters (cache misses, cache accesses…)
  - Compute behavioral models of the process
- **Could an attacker gain information without forcing misses?**
  - It is possible if the eviction order depends on the actual order utilization of the data

LLC Replacement policy

- The algorithm that decides which element has to be evicted from the cache in case of conflict.
- We focus on the L3 cache
  - Shared
  - Undocumented (Quad-Age LRU)



LLC Replacement policy

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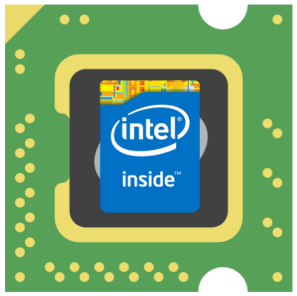
- **We focus on the L3 cache**
  - Shared
  - Undocumented
- **Idea:**
  - We know the location of each block of data in the cache
  - We can enforce the order of the accesses to the data in the cache
  - We can measure access times, i.e. cache hits and misses



LLC Replacement policy: Test

- Manually define a replacement policy to test.
- Generate two eviction sets.
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- Force a miss by accessing one element in the conflicting set.
- Check if the evicted block corresponds with the block predicted by the test policy.

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  - Apparently fixed Replacement Policy (6th ,7th and 8th generations).

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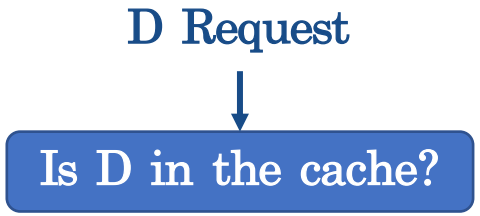
- **Only access to LLC update the ages of the blocks.**
- **Two different policies.**
  - Adaptive Replacement Policy (4th and 5th generations).
  - Apparently fixed Replacement Policy (6th ,7th and 8th generations).
- **The replacement policy is the same, evict blocks with age 3.**
  - Differ in the insertion age (2 or 3).

LLC Replacement policy



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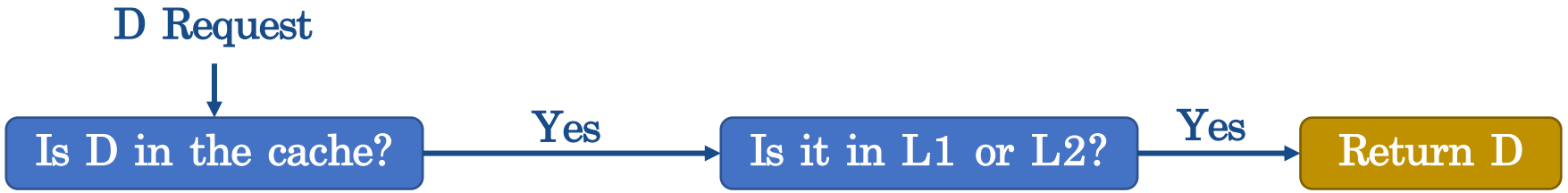

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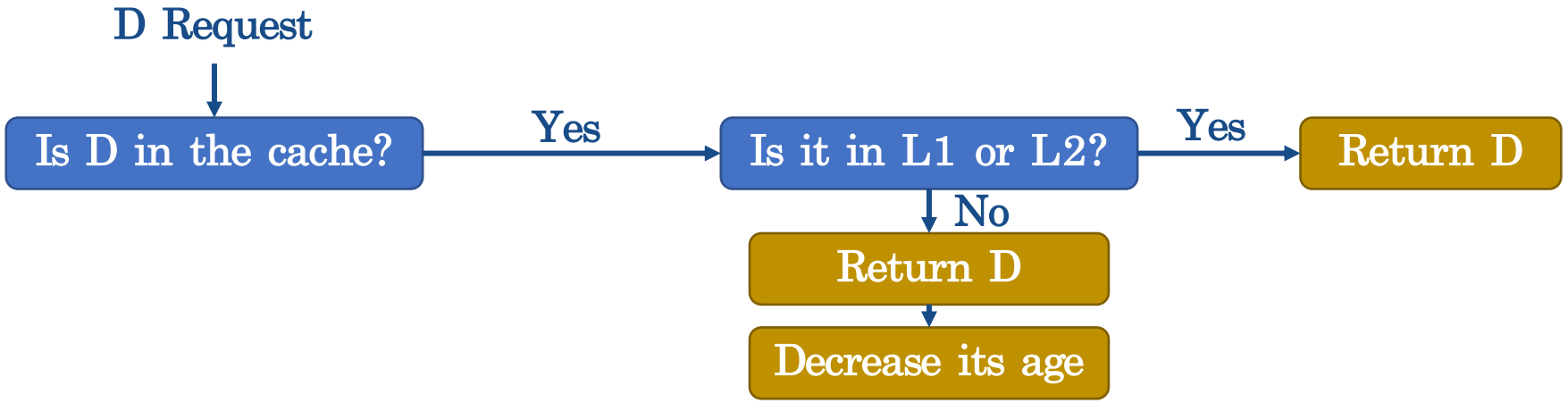

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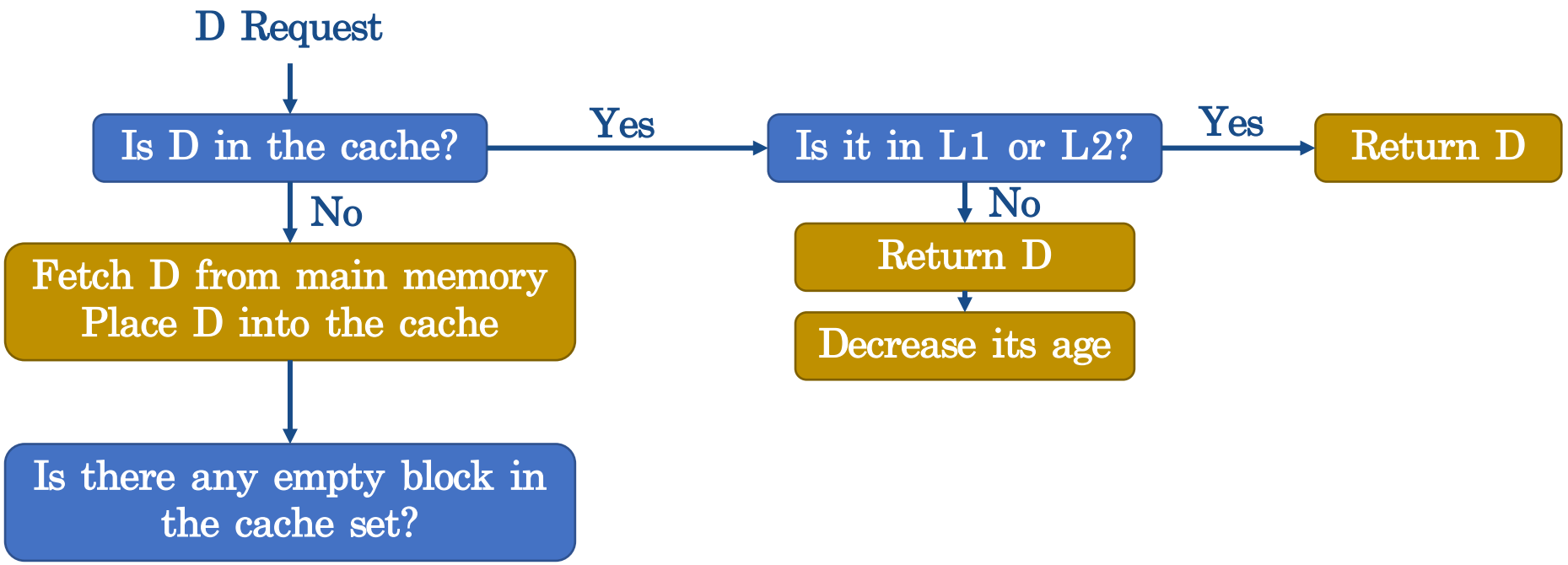

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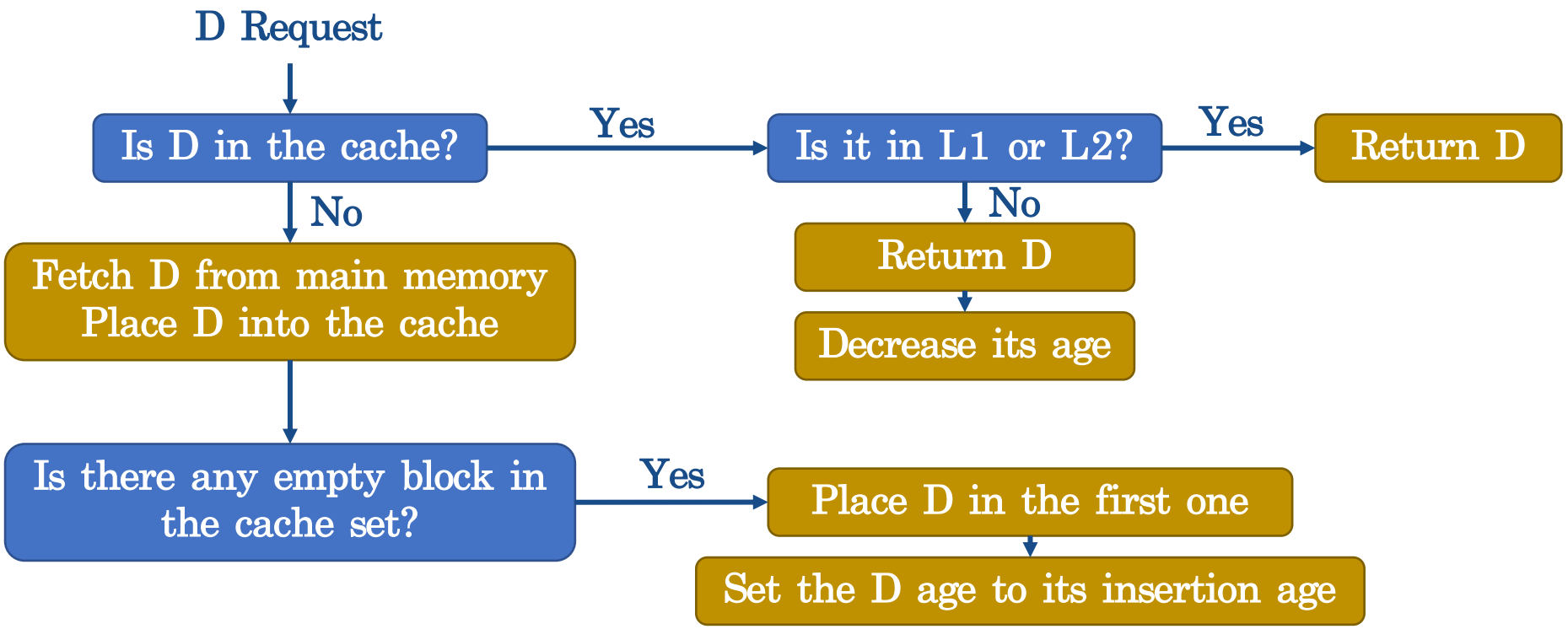

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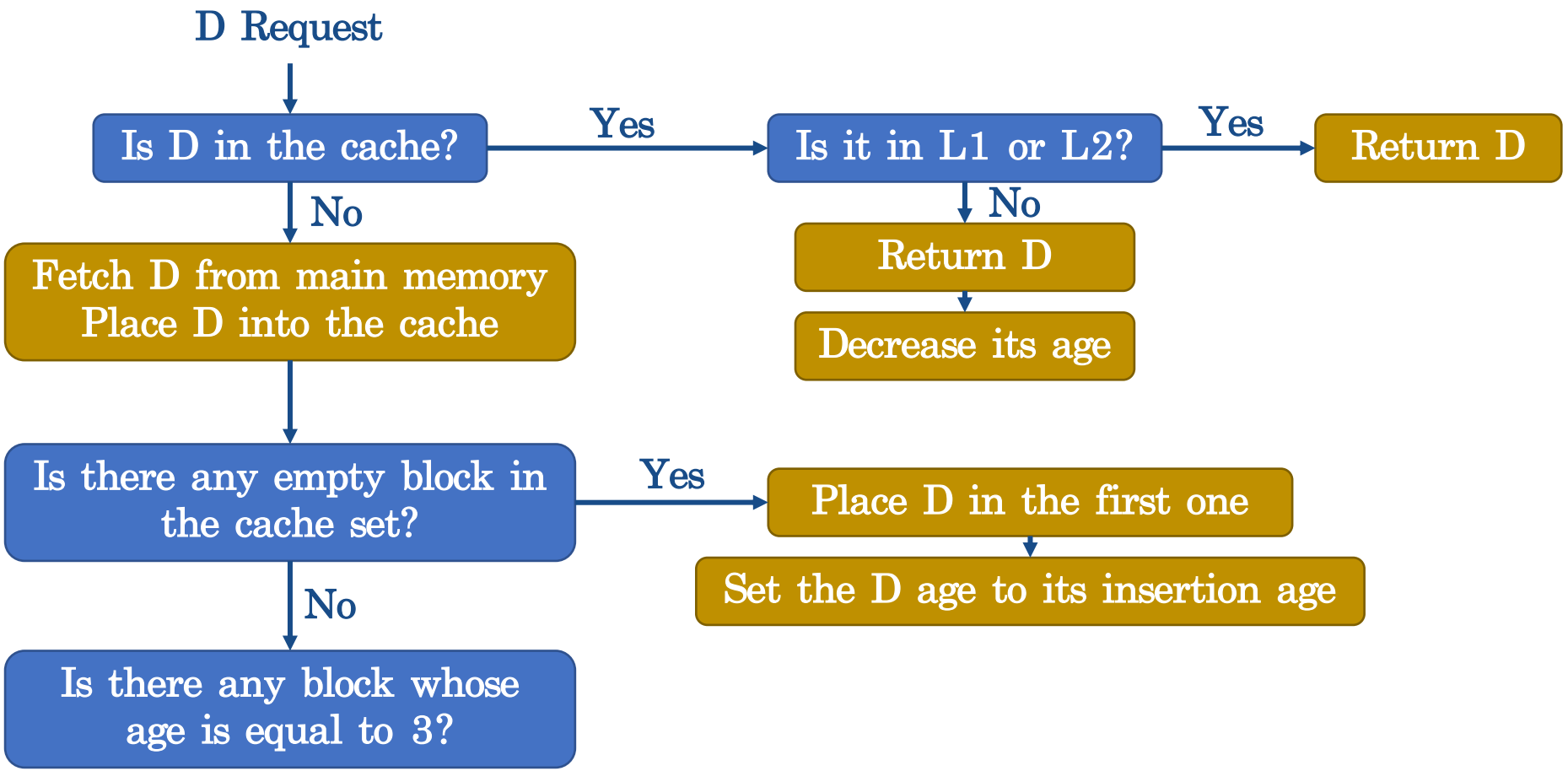

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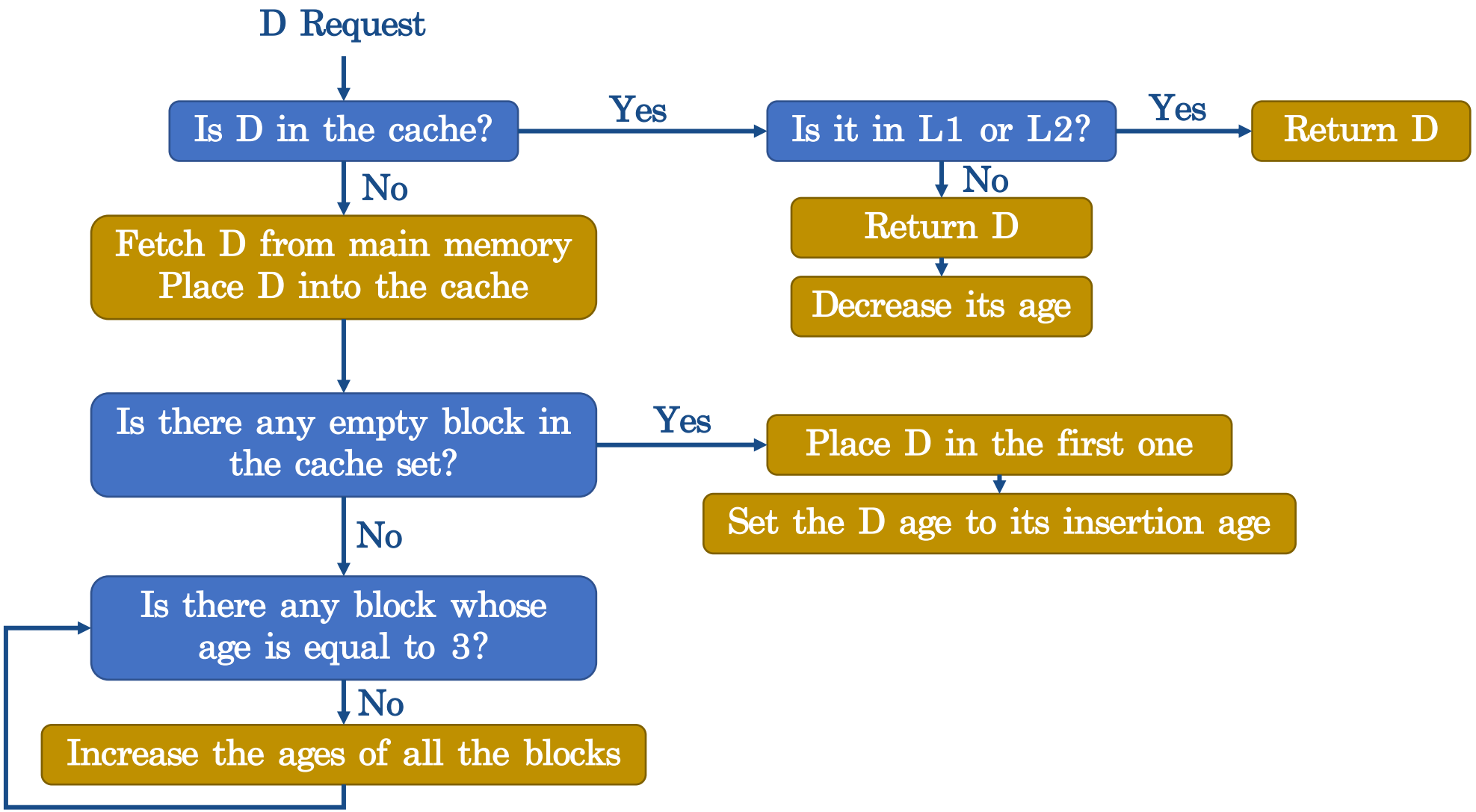

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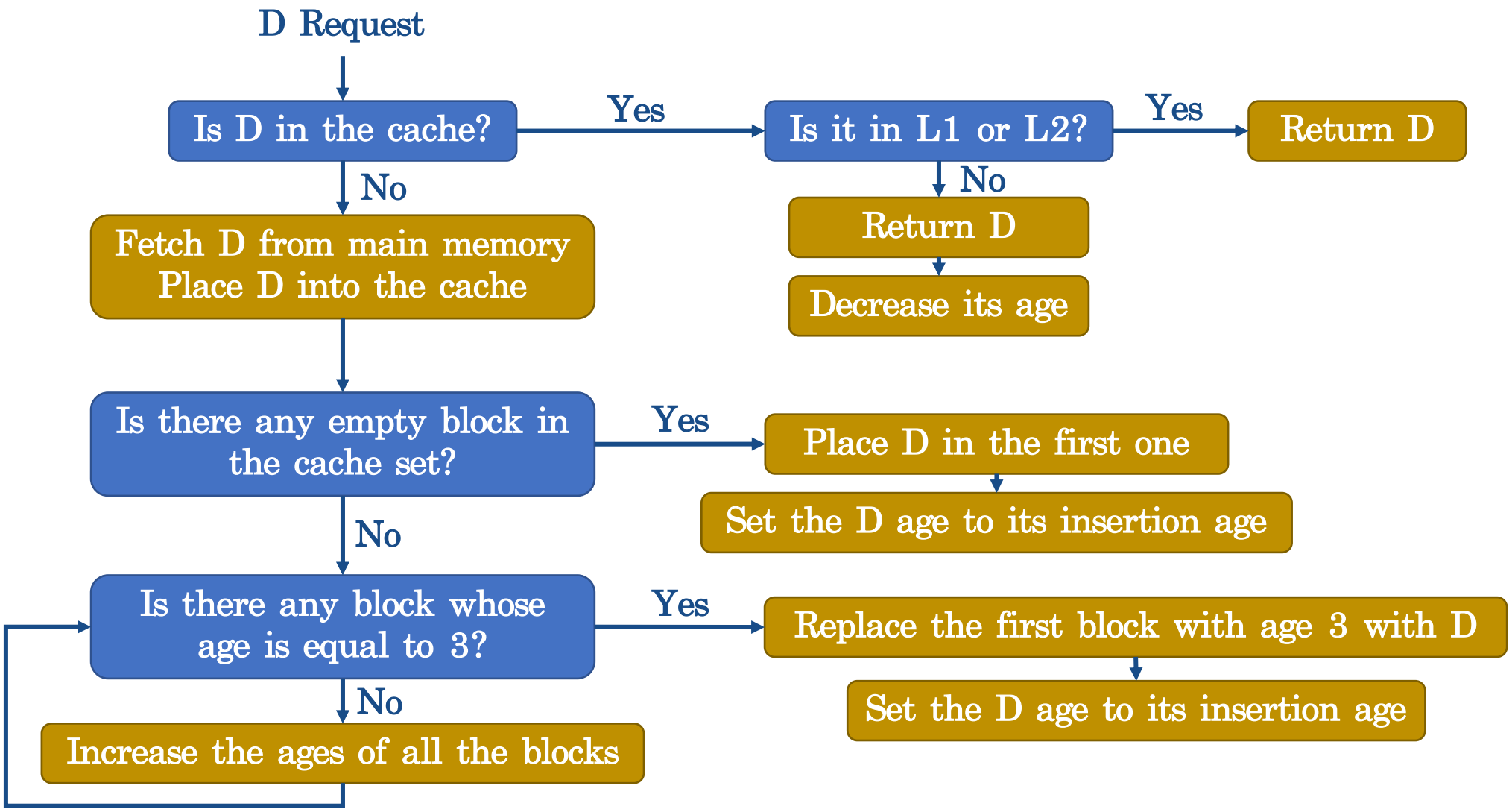

RELOAD+REFRESH

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- **Abuse the replacement policy:**
  - Place data in the L3 cache in the desired position and set its age
  - Observe changes in the eviction candidate.

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- **Abuse the replacement policy:**
  - Place data in the L3 cache in the desired position and set its age
  - Observe changes in the eviction candidate.
- **Assume:**
  - There is shared memory
  - The attacker can construct an eviction set
  - The attacker can ensure the order of the accesses

RELOAD+REFRESH: stages

1. Prepare the cache

Candidate

Content	Target							
Age	2							

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1. Prepare the cache

Candidate

Content	Target	A	B	C	D	E	F	G
Age	2	2	2	2	2	2	2	2

RELOAD+REFRESH: stages

2. Wait for the victim to access the data

Candidate

Content	Target	A	B	C	D	E	F	G
Age	2	2	2	2	2	2	2	2

RELOAD+REFRESH: stages

2. Wait for the victim to access the data

Candidate

Content	Target	A	B	C	D	E	F	G
Age	1	2	2	2	2	2	2	2

ACCESS

RELOAD+REFRESH: stages

2. Wait for the victim to access the data

Candidate

Content	Target	A	B	C	D	E	F	G
Age	1	2	2	2	2	2	2	2

ACCESS

RELOAD+REFRESH: stages

2. Wait for the victim to access the data

Candidate

Content	Target	A	B	C	D	E	F	G
Age	1	2	2	2	2	2	2	2

ACCESS

Candidate

Content	Target	A	B	C	D	E	F	G
Age	2	2	2	2	2	2	2	2

NO ACCESS

RELOAD+REFRESH: stages

3. Retrieve the information (Force miss + Reload)

Candidate

Content	Target	A	B	C	D	E	F	G
Age	1	2	2	2	2	2	2	2

ACCESS

Candidate

Content	Target	A	B	C	D	E	F	G
Age	2	2	2	2	2	2	2	2

NO ACCESS

RELOAD+REFRESH: stages

3. Retrieve the information (Force miss + Reload)

Candidate

Content	Target	A	B	C	D	E	F	G	ACCESS
Age	2	3	3	3	3	3	3	3	

Candidate

Content	Target	A	B	C	D	E	F	G	NO ACCESS
Age	3	3	3	3	3	3	3	3	

RELOAD+REFRESH: stages

3. Retrieve the information (Force miss + Reload)

Candidate

Content	Target	H	B	C	D	E	F	G	ACCESS
Age	2	2	3	3	3	3	3	3	

Candidate

Content	H	A	B	C	D	E	F	G	NO ACCESS
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RELOAD+REFRESH: stages

4. Refresh the cache set state

Candidate

Content	Target	H	B	C	D	E	F	G
Age	1	2	3	3	3	3	3	3

ACCESS

Candidate

Content	H	Target	B	C	D	E	F	G
Age	2	2	3	3	3	3	3	3

NO ACCESS

RELOAD+REFRESH: stages

4. Refresh the cache set state

Candidate

Content			B	C	D	E	F	G	ACCESS
Age			3	3	3	3	3	3	

Candidate

Content			B	C	D	E	F	G	NO ACCESS
Age			3	3	3	3	3	3	

RELOAD+REFRESH: stages

4. Refresh the cache set state

Candidate

Content	Target		B	C	D	E	F	G	ACCESS
Age	2		3	3	3	3	3	3	

Candidate

Content	Target		B	C	D	E	F	G	NO ACCESS
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RELOAD+REFRESH: stages

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Content	Target	A	B	C	D	E	F	G
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Content	Target	A	B	C	D	E	F	G
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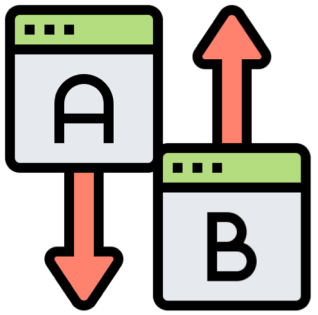
NO ACCESS

RELOAD+REFRESH: Evaluation

- **Covert channel**
  - Similar performance to existing approaches.
  - Slightly lower resolution



F-Score for the different approaches: Reload+Refresh(R+R), Flush+Reload(F+R) and Prime+Probe (P+P).

	Window length (ns)					
	50000	10000	1000	750	500	250
R+R	0.988	0.975	0.925	0.684	-	-
F+R	0.999	0.995	0.996	0.991	0.989	0.981
P+P	0.934	0.934	0873	0.716	0.548	-

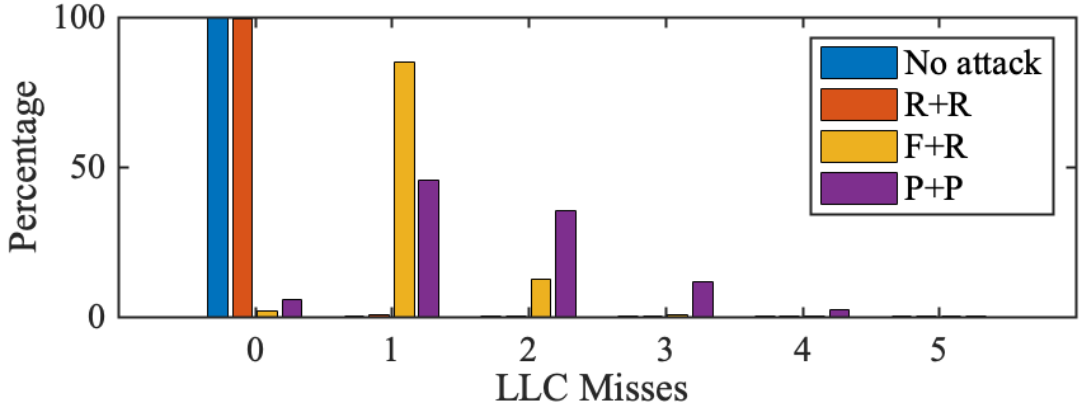
RELOAD+REFRESH: Evaluation

- AES
  - Retrieve the secret key

Attack	R+R	F+R	P+P
Samples	3800	3500	3900
F-Score	0.98	0.99	0.97

Reload+Refresh (R+R)
Flush+Reload (F+R)
Prime+Probe (P+P)

  - No cache misses



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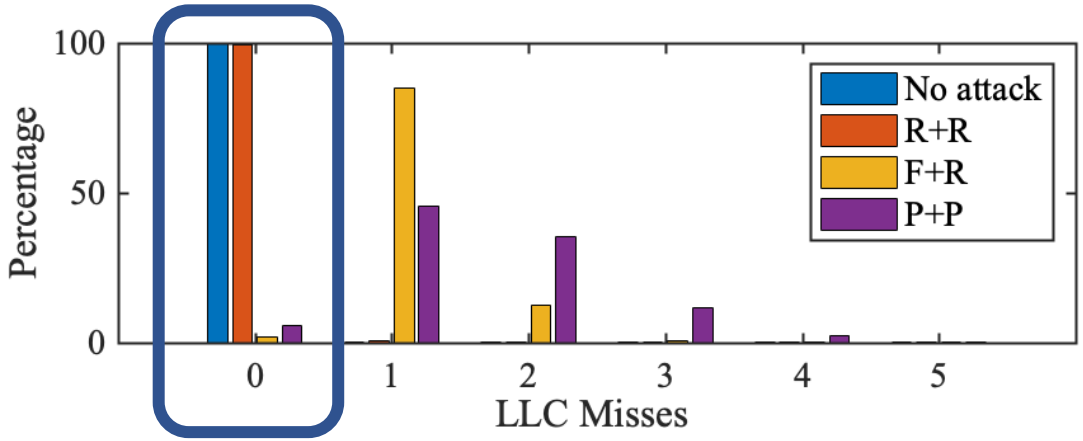


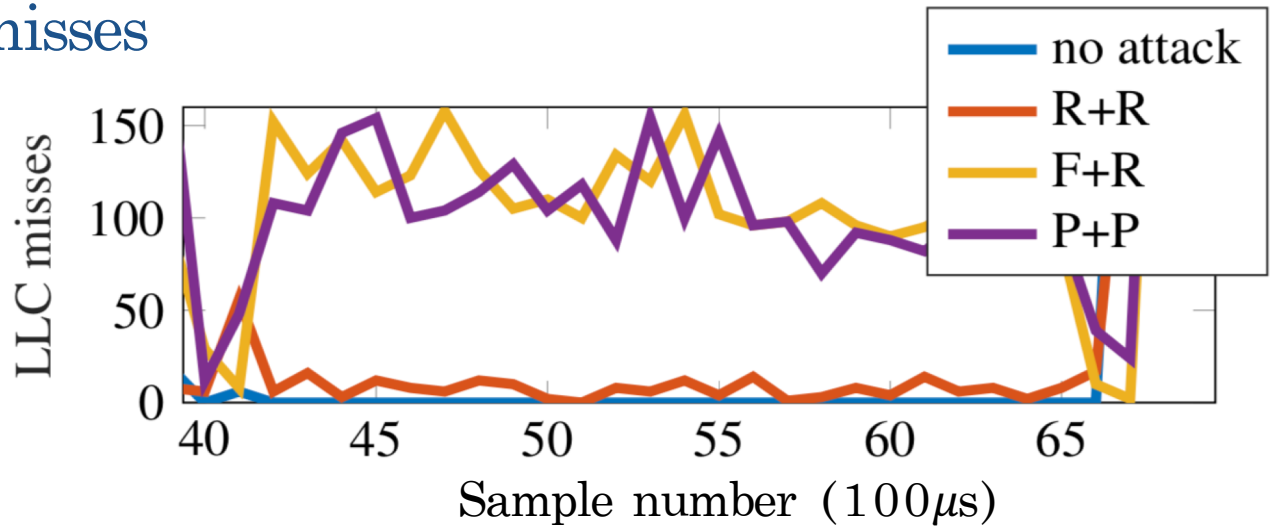
RELOAD+REFRESH: Evaluation

- RSA
  - Multiply operations

Attack	R+R	F+R	P+P
Accuracy	96.1%	98.6%	95.4%
F-Score	0.952	0.99	0.945

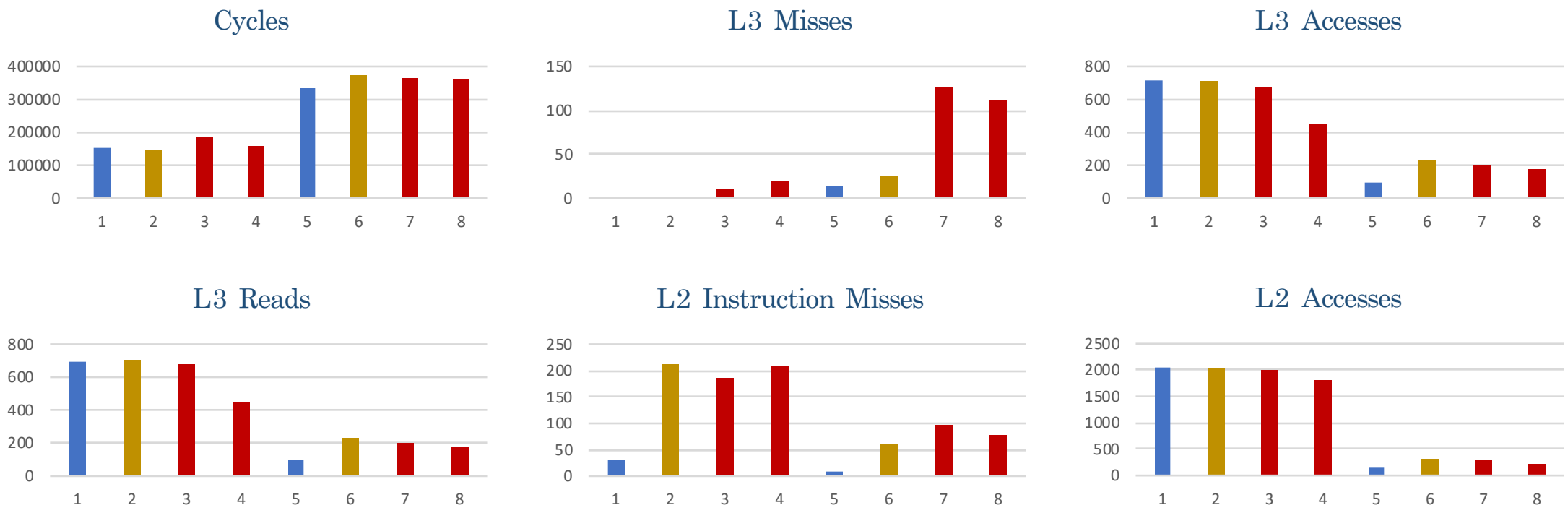
Reload+Refresh (R+R)
Flush+Reload (F+R)
Prime+Probe (P+P)

  - No cache misses



RELOAD+REFRESH: Detection

- Results of monitoring different performance counters



1-AES Normal 2-AES R+R 3-AES F+R 4-AES P+P 5-RSA Normal 6-RSA R+R 7-RSA F+R 8-RSA P+P

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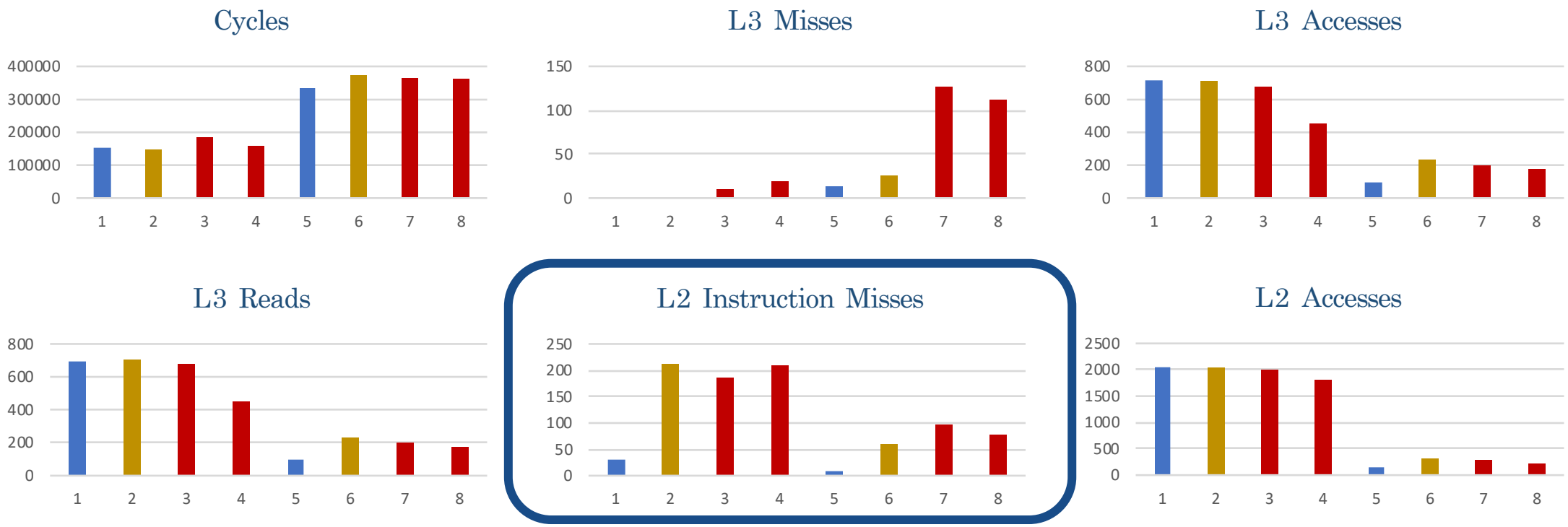

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Conclusions

- **Show an important limitation in detection algorithms**
  - The number of counters is limited
  - RELOAD+REFRESH hides misses from the monitor
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- **Show an important limitation in detection algorithms**
  - The number of counters is limited
  - RELOAD+REFRESH hides misses from the monitor
  - Cat and mouse game
- **Provide further insights into the cache architecture**
  - Reverse-engineer the replacement policy
  - Other cache attacks could benefit from this knowledge

Thank you for your attention

Q&A

Contact information: samirabriongos@die.upm.es
Sample code: https://github.com/greenlsi/reload_refresh