Tracing Interrupts in Embedded Software

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```
$ echo 'int main() { printf ("Hello,
world\n"); }' | gcc -xc - -o out
```

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- **Interrupts => Complexity**
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- **Complexity => Nasty bugs**
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- **Nasty bugs require good debugging support**

Next Gen Debugging Support?

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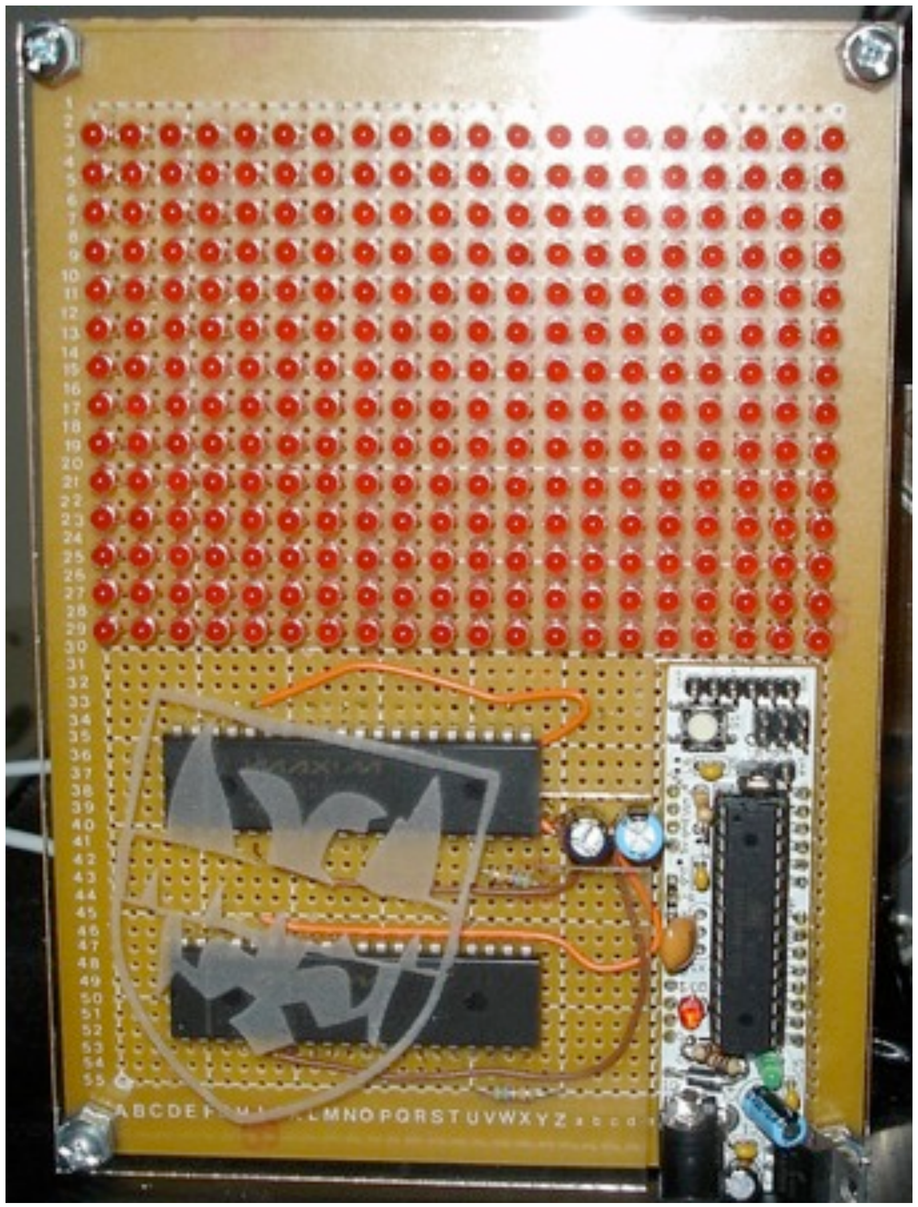

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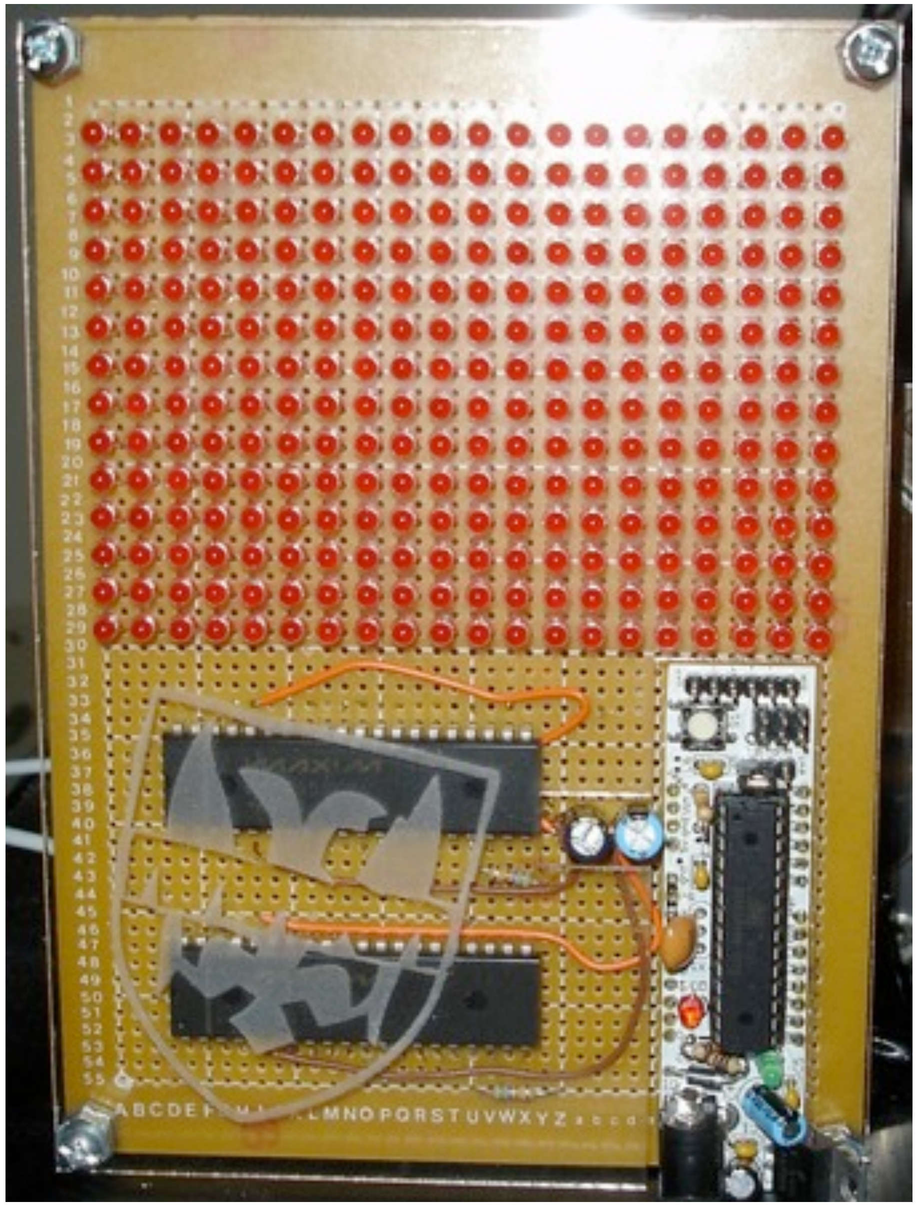

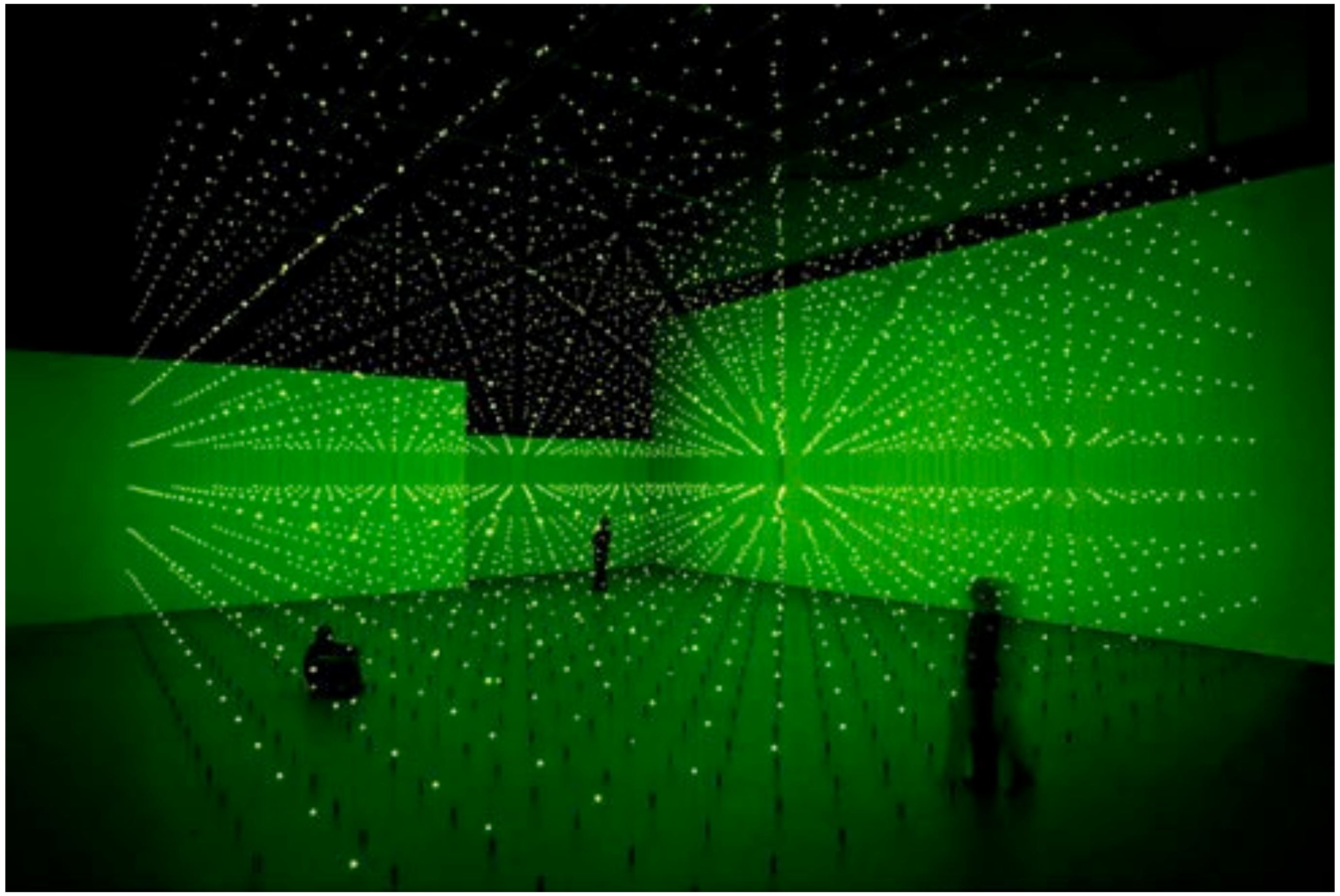

Replay Debugging

Recording at run time

Replay offline (sim)

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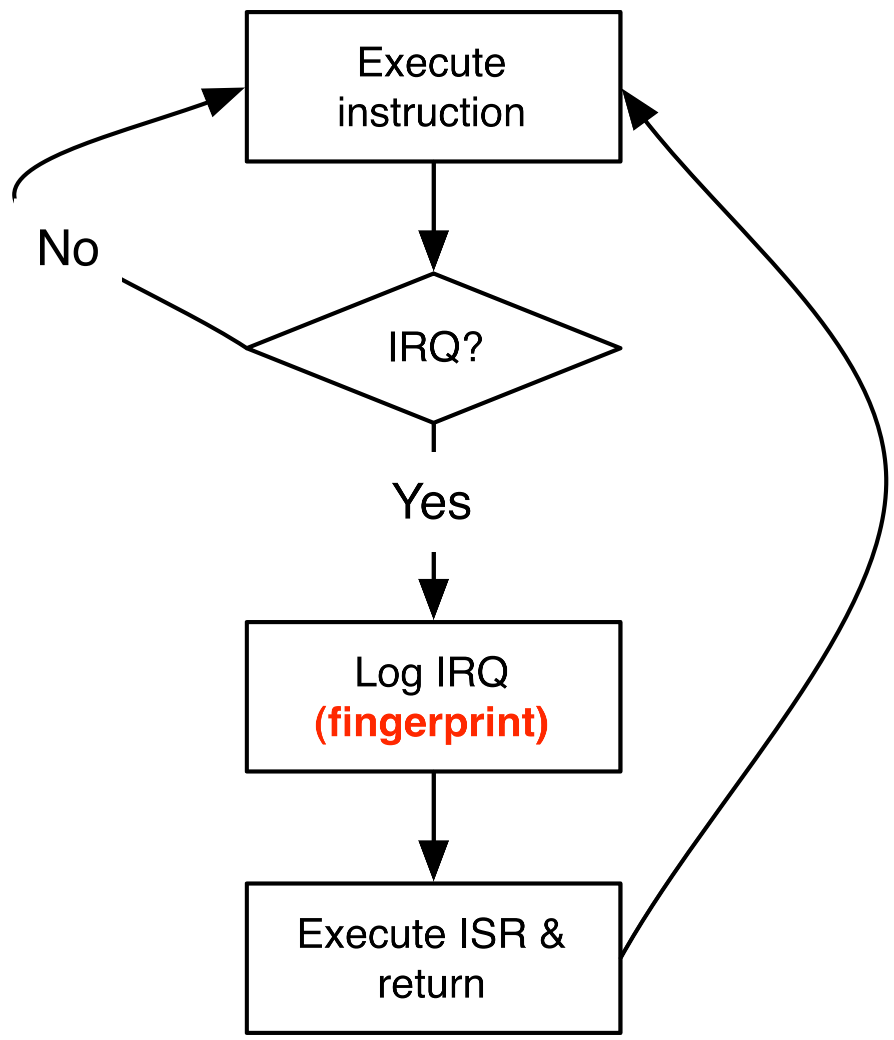

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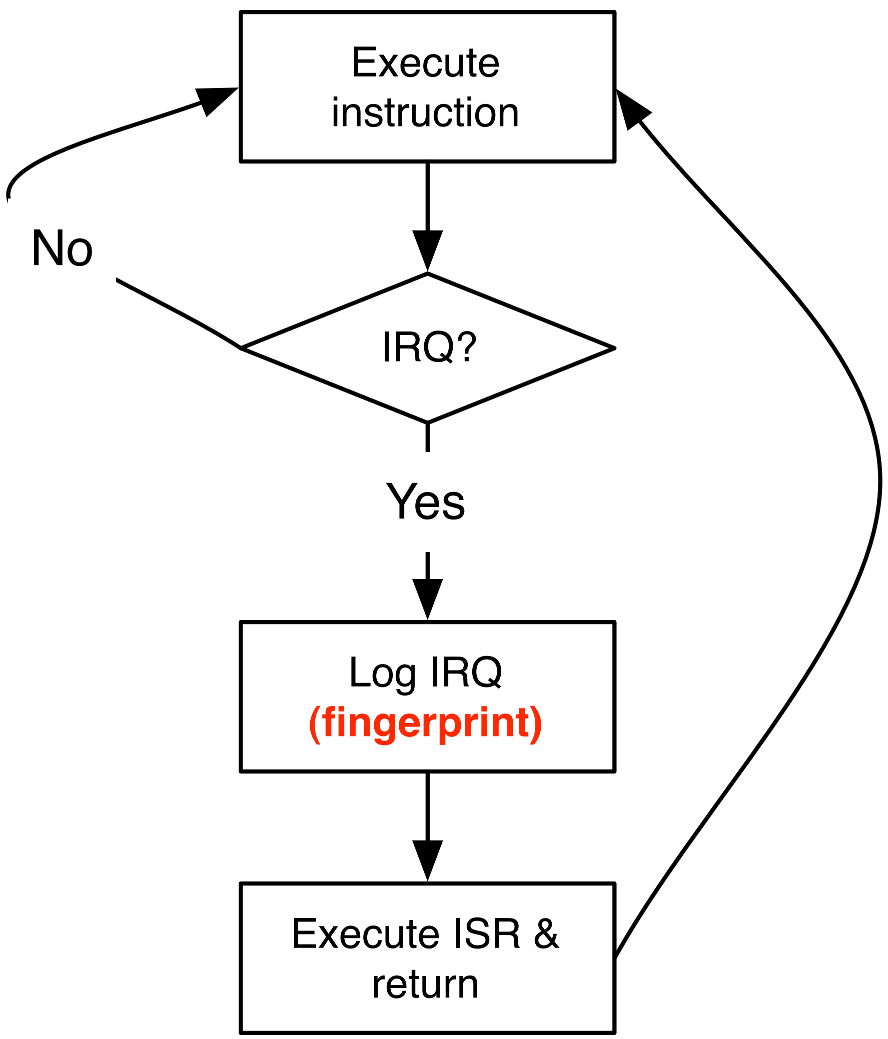

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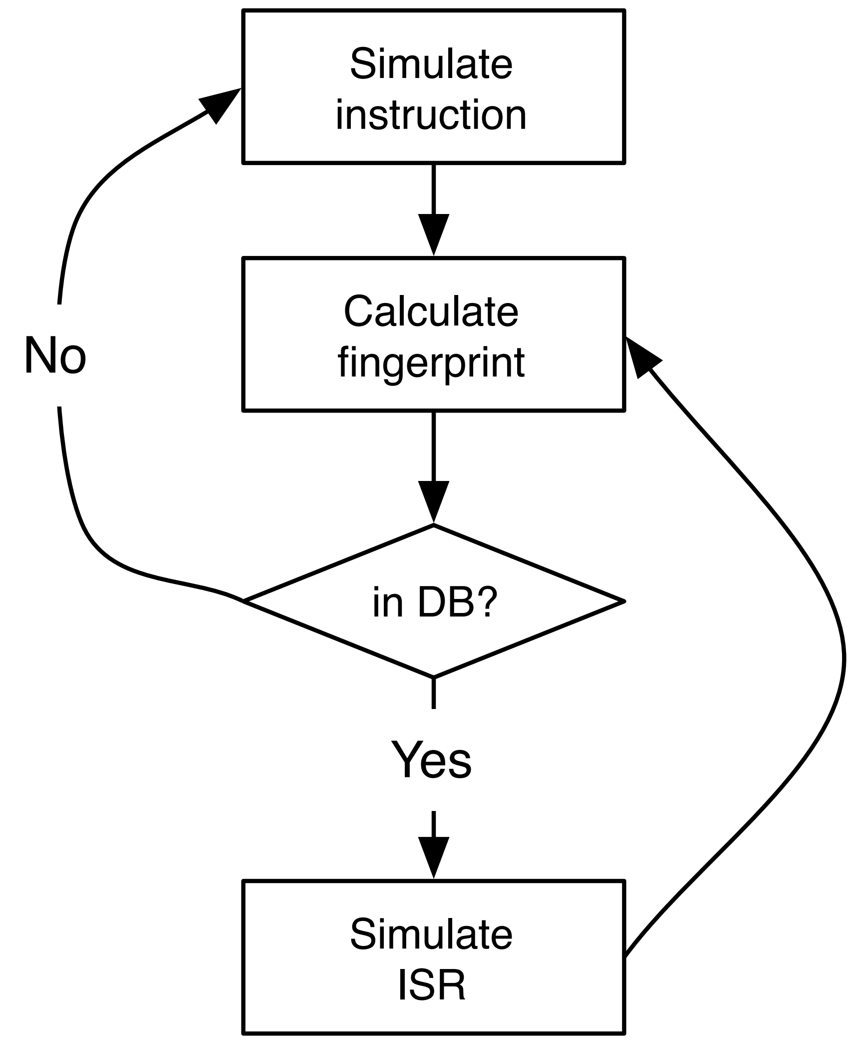

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✗ Non-determinism happens (e.g., interrupt)

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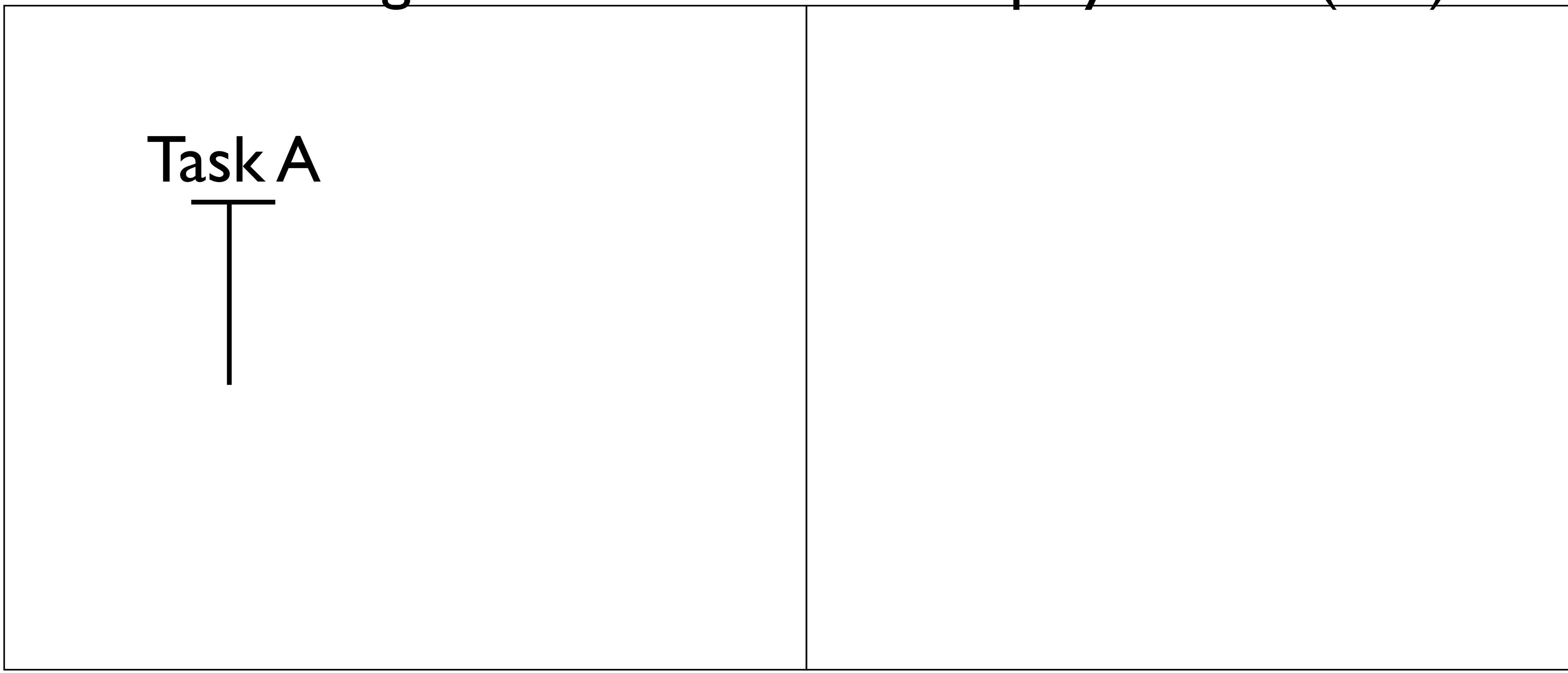

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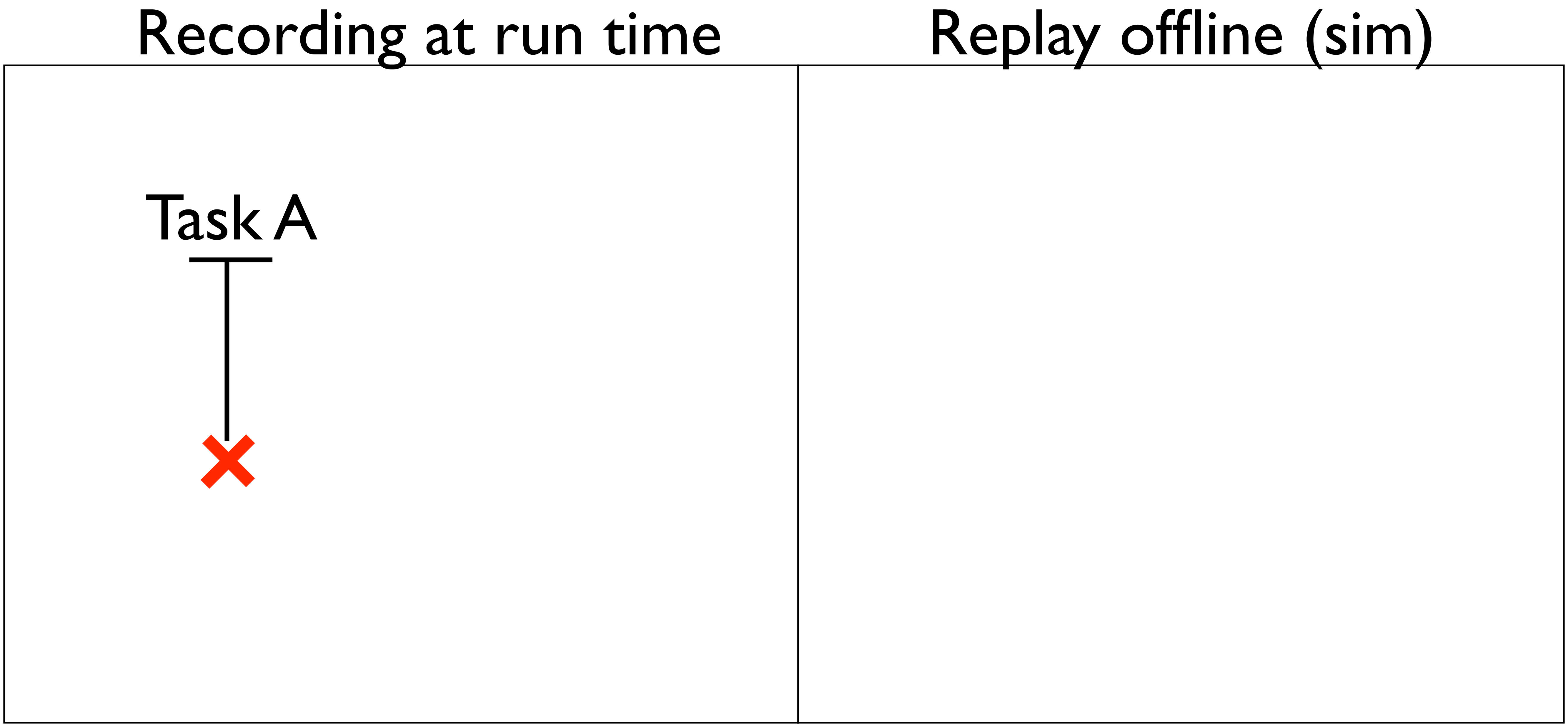

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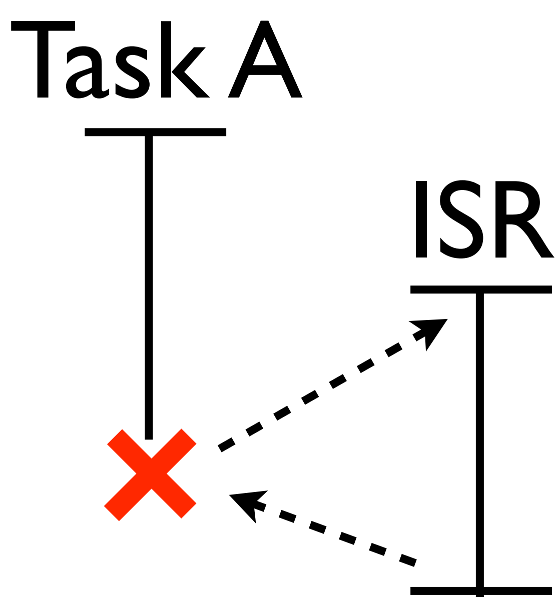

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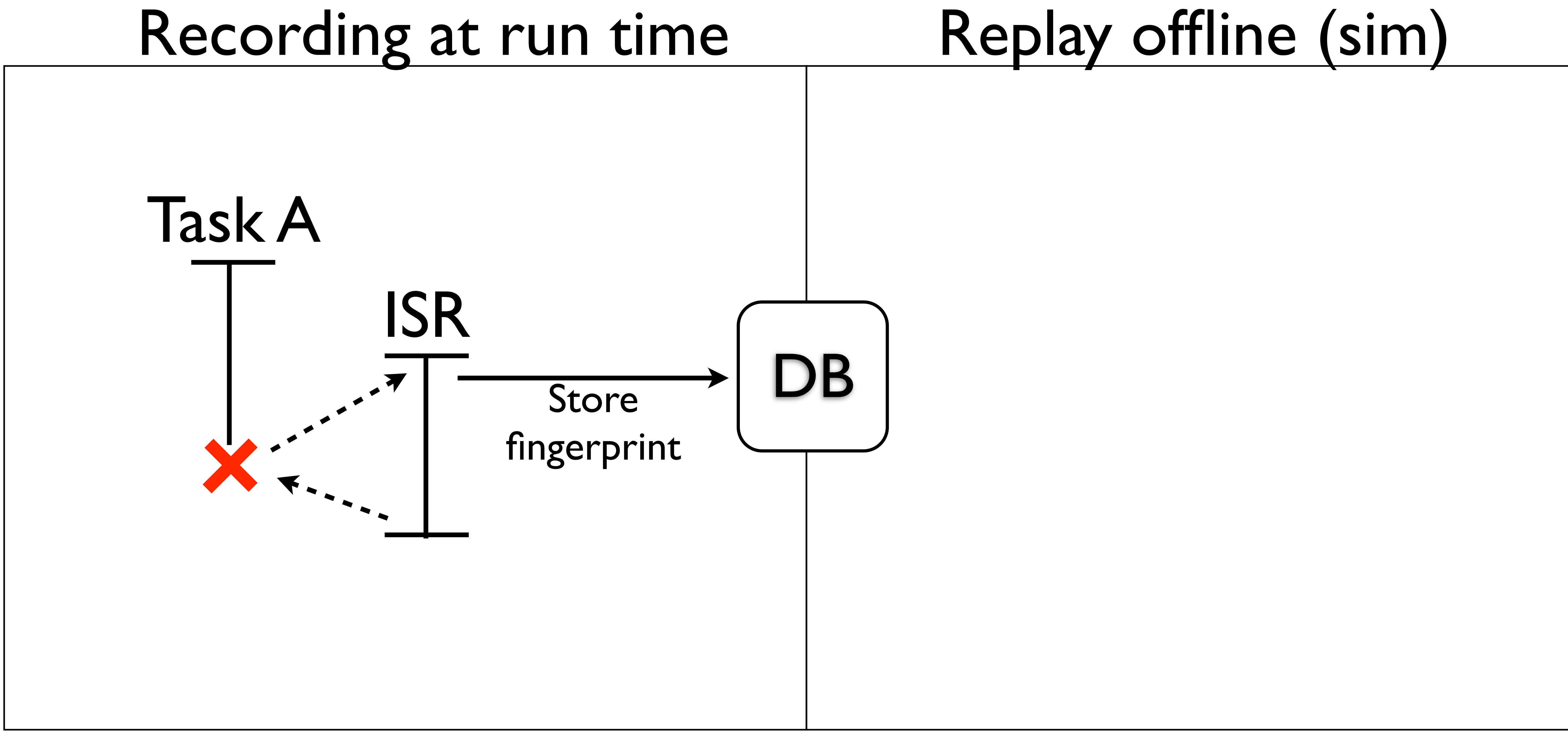

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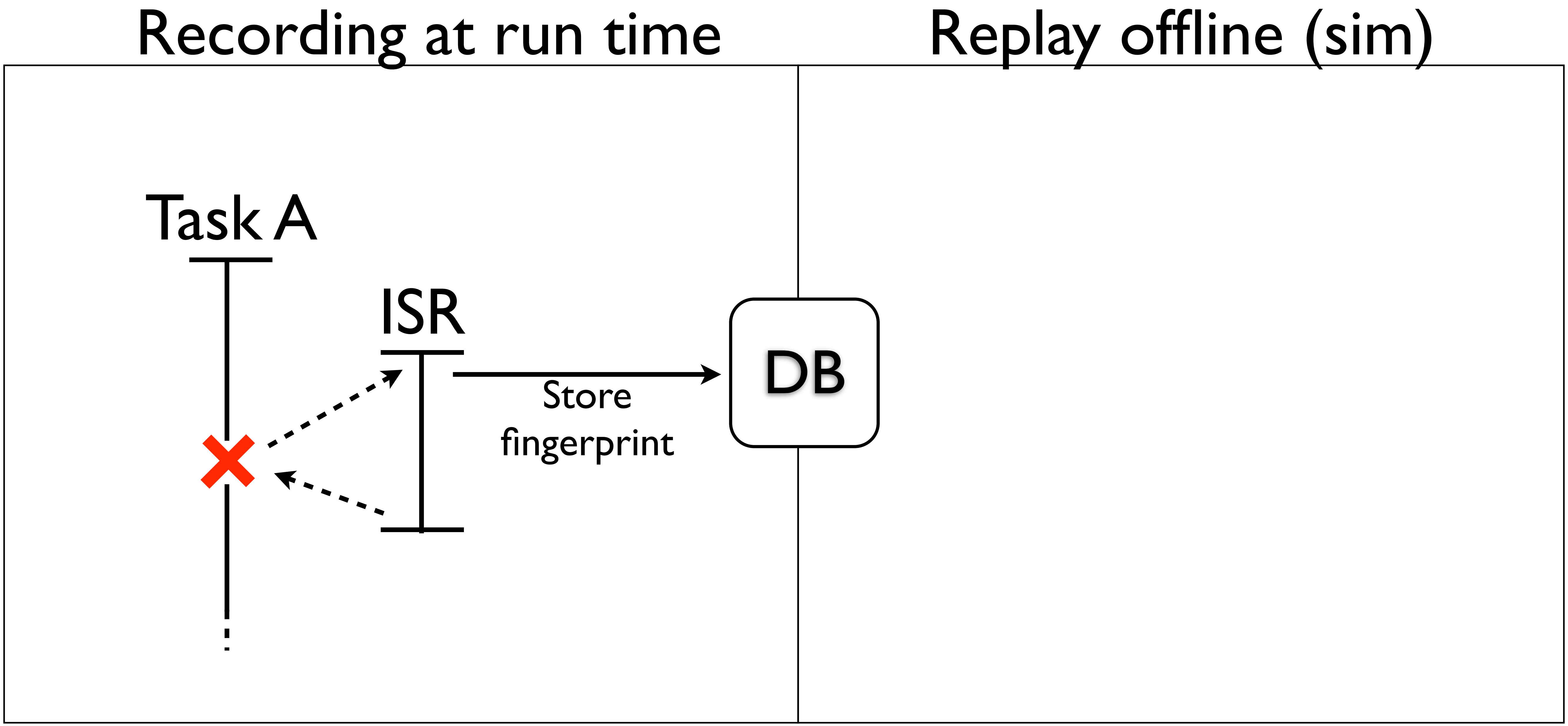

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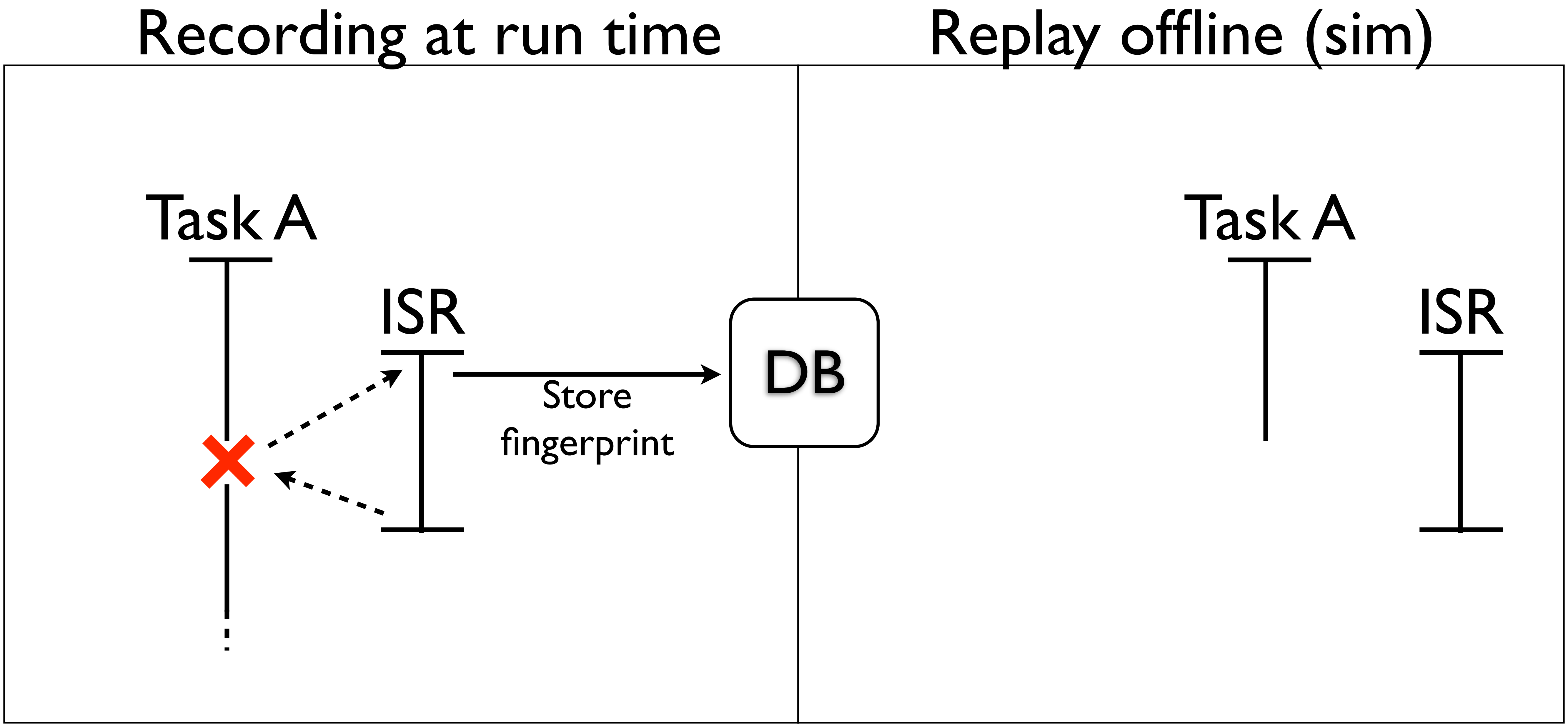

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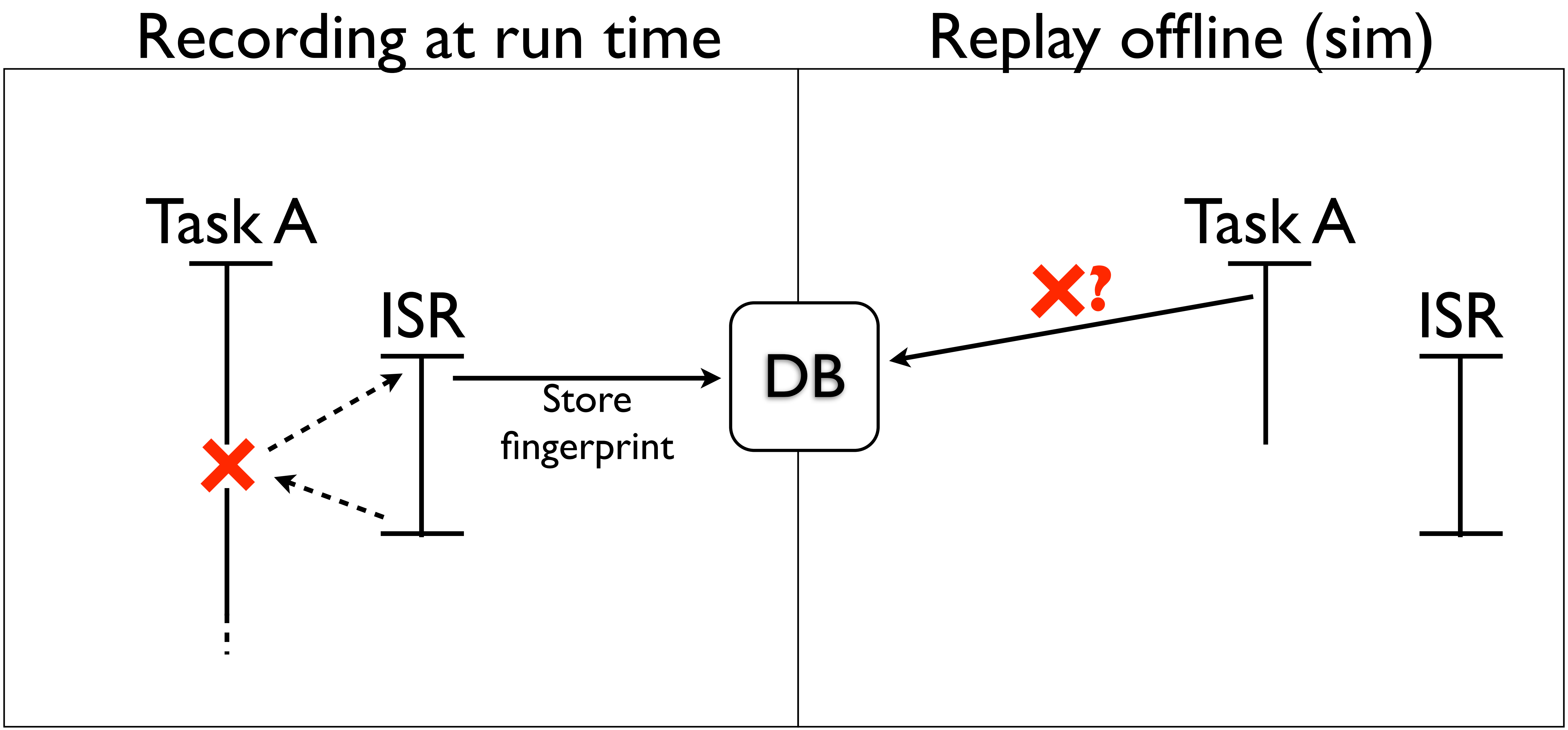

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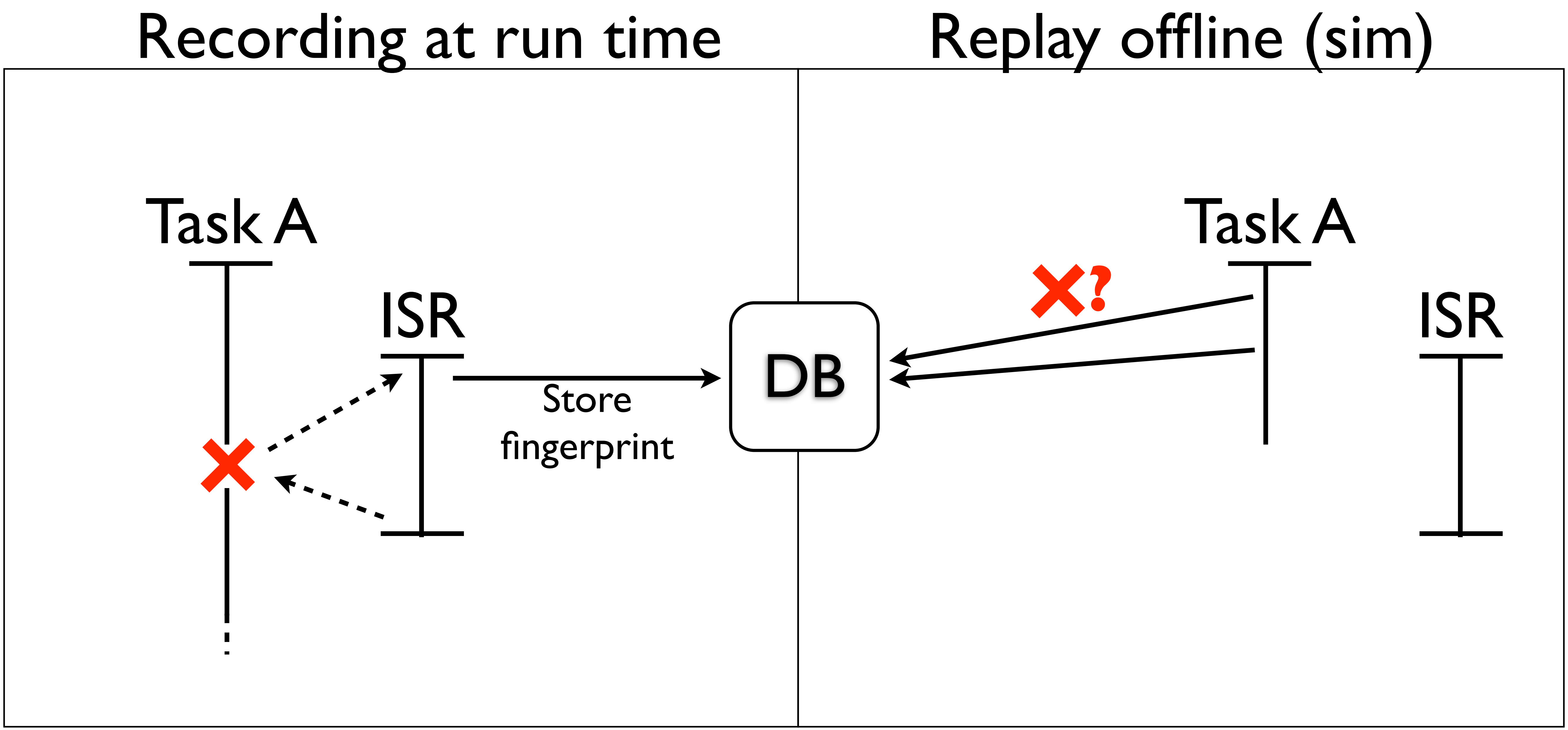

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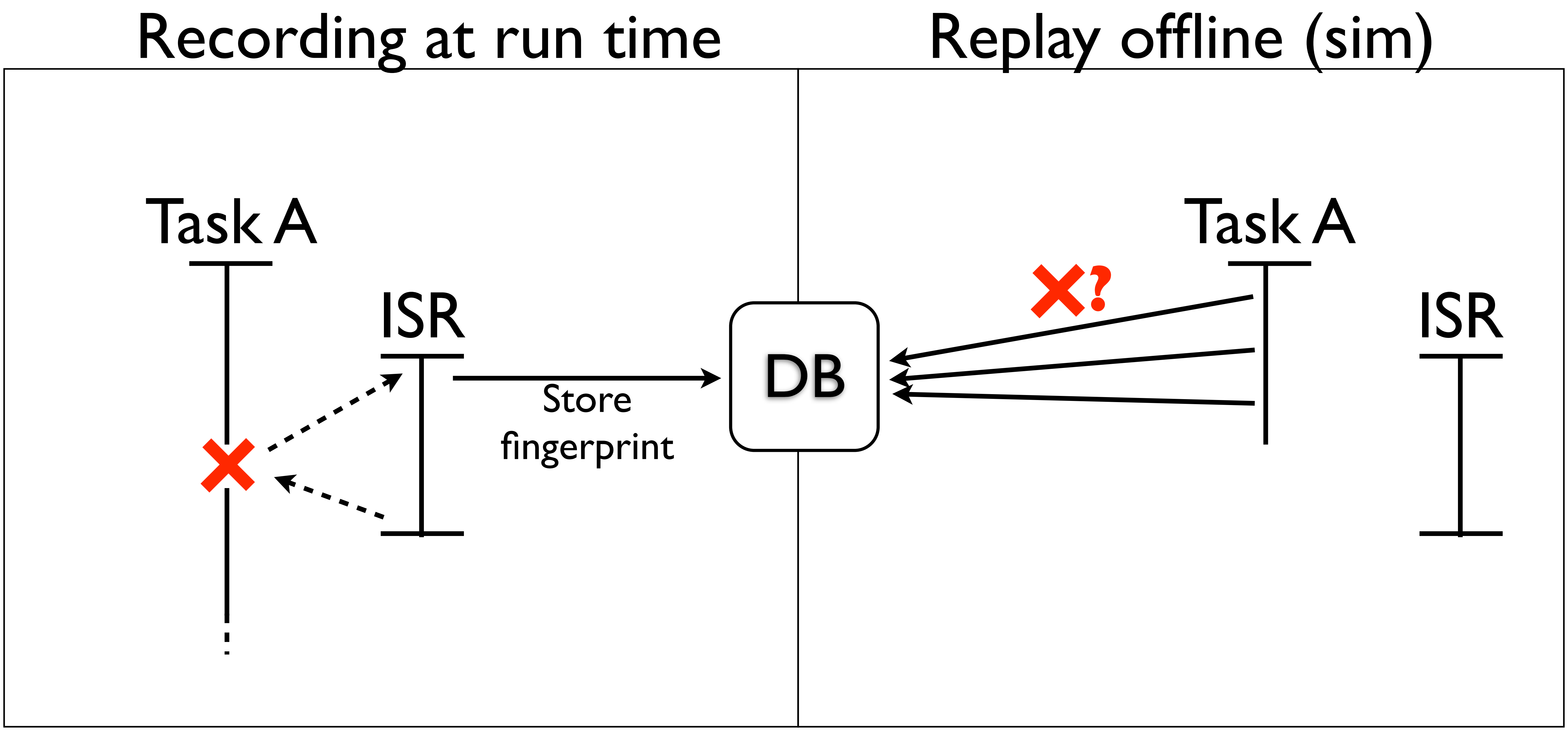

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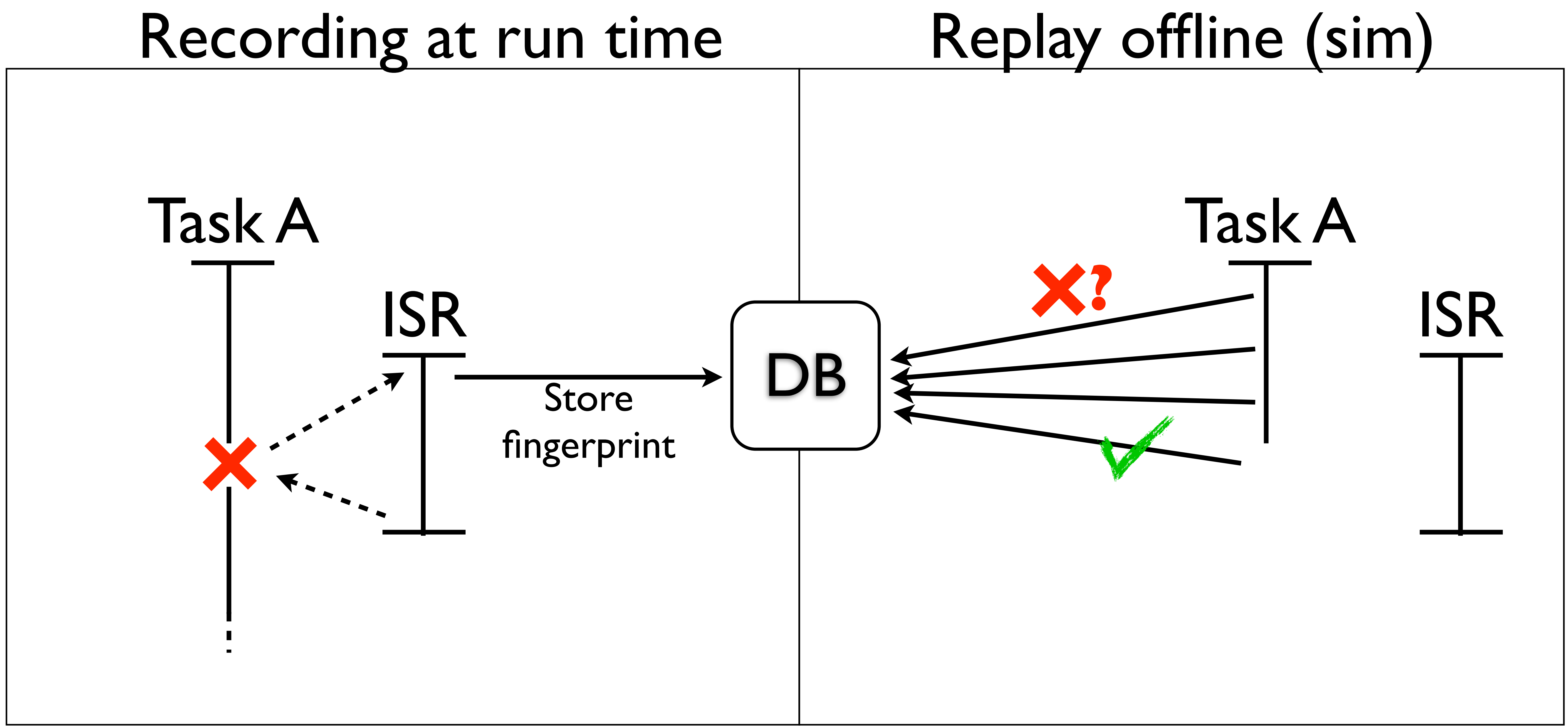

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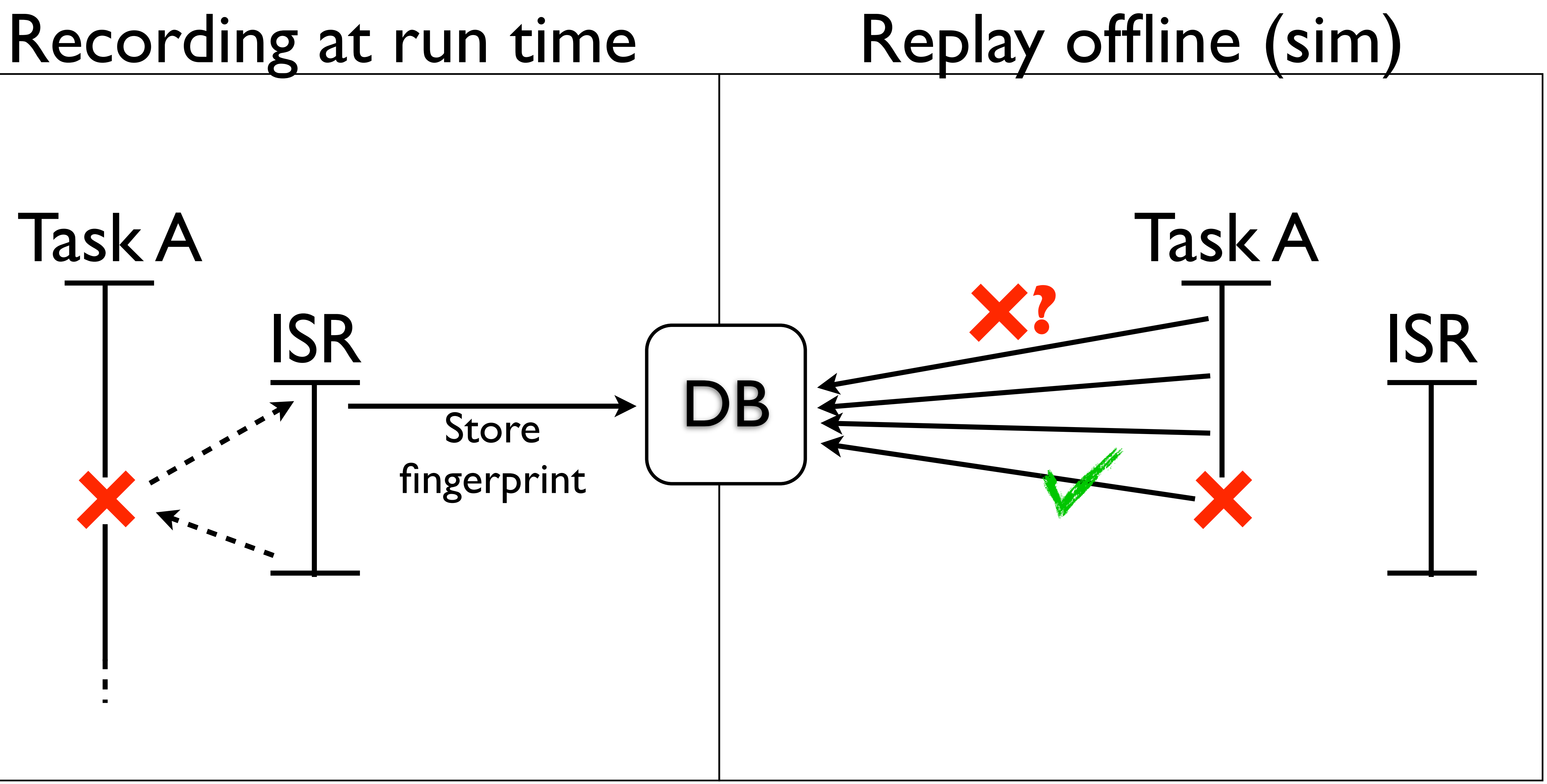

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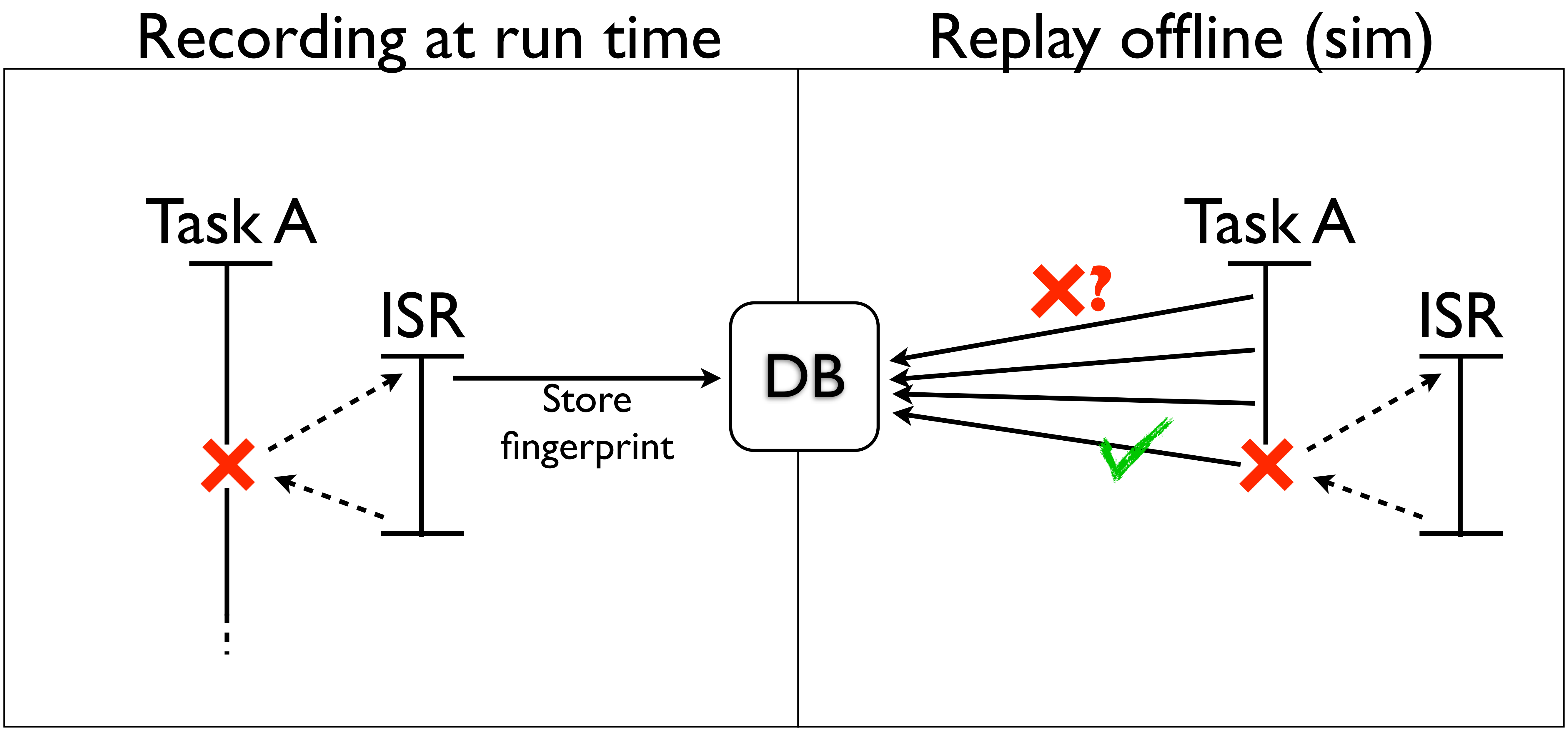

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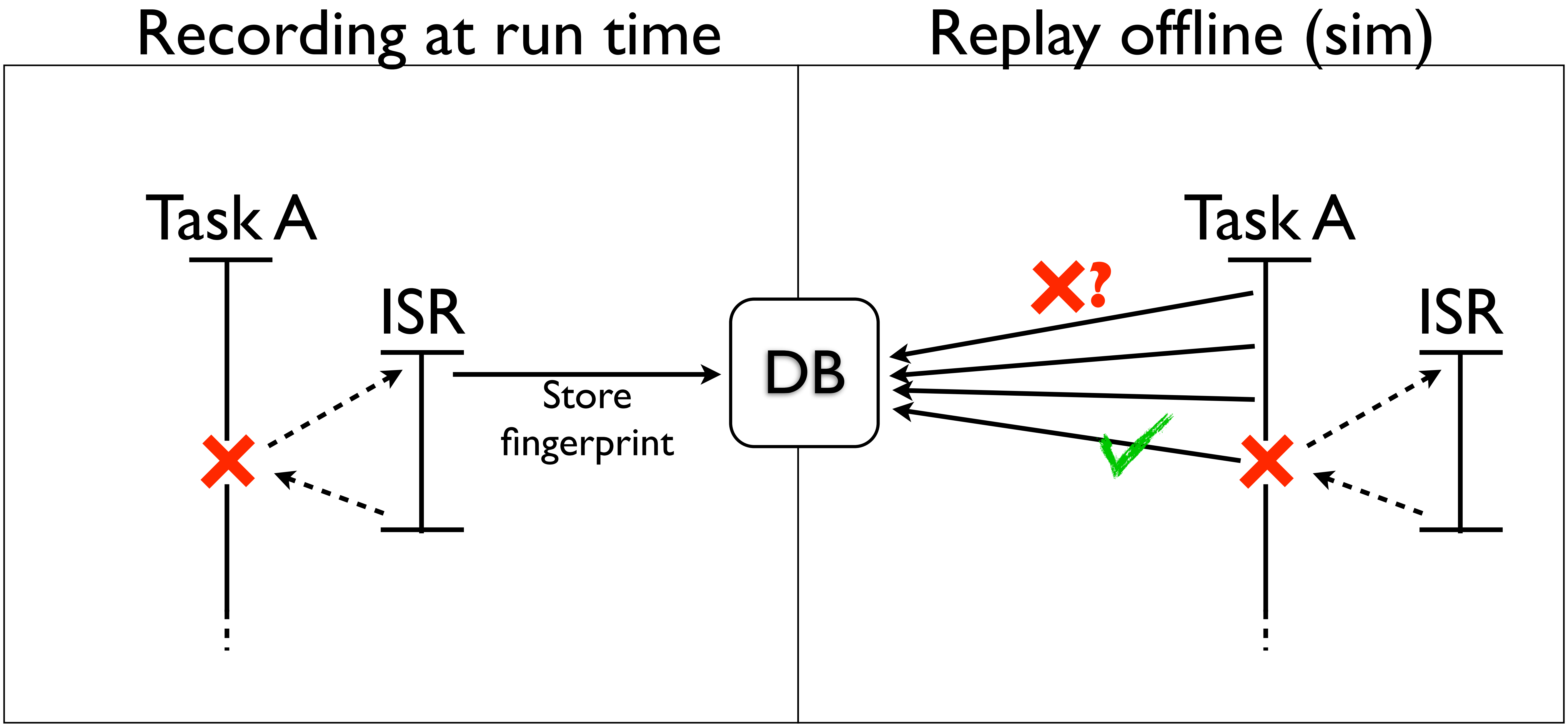

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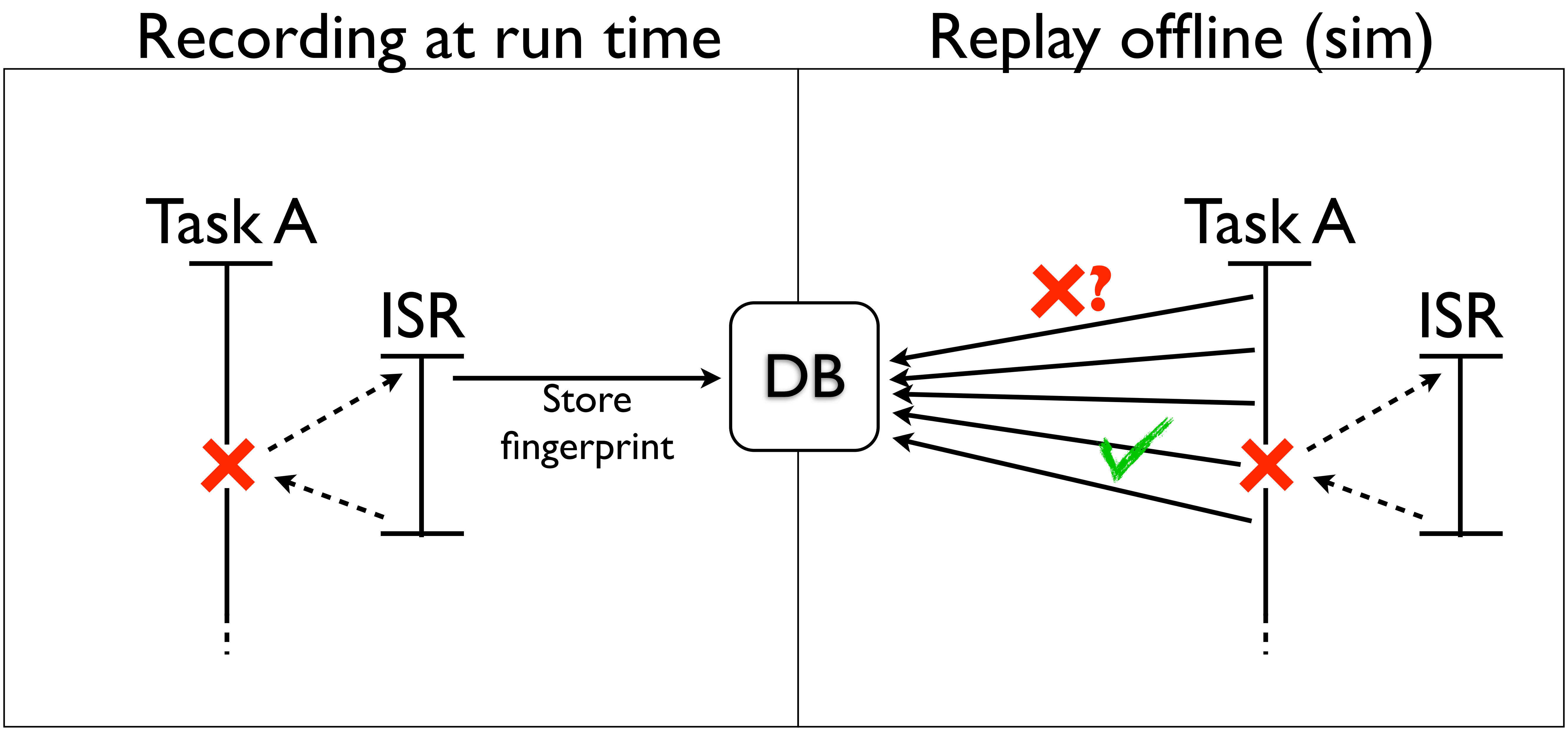

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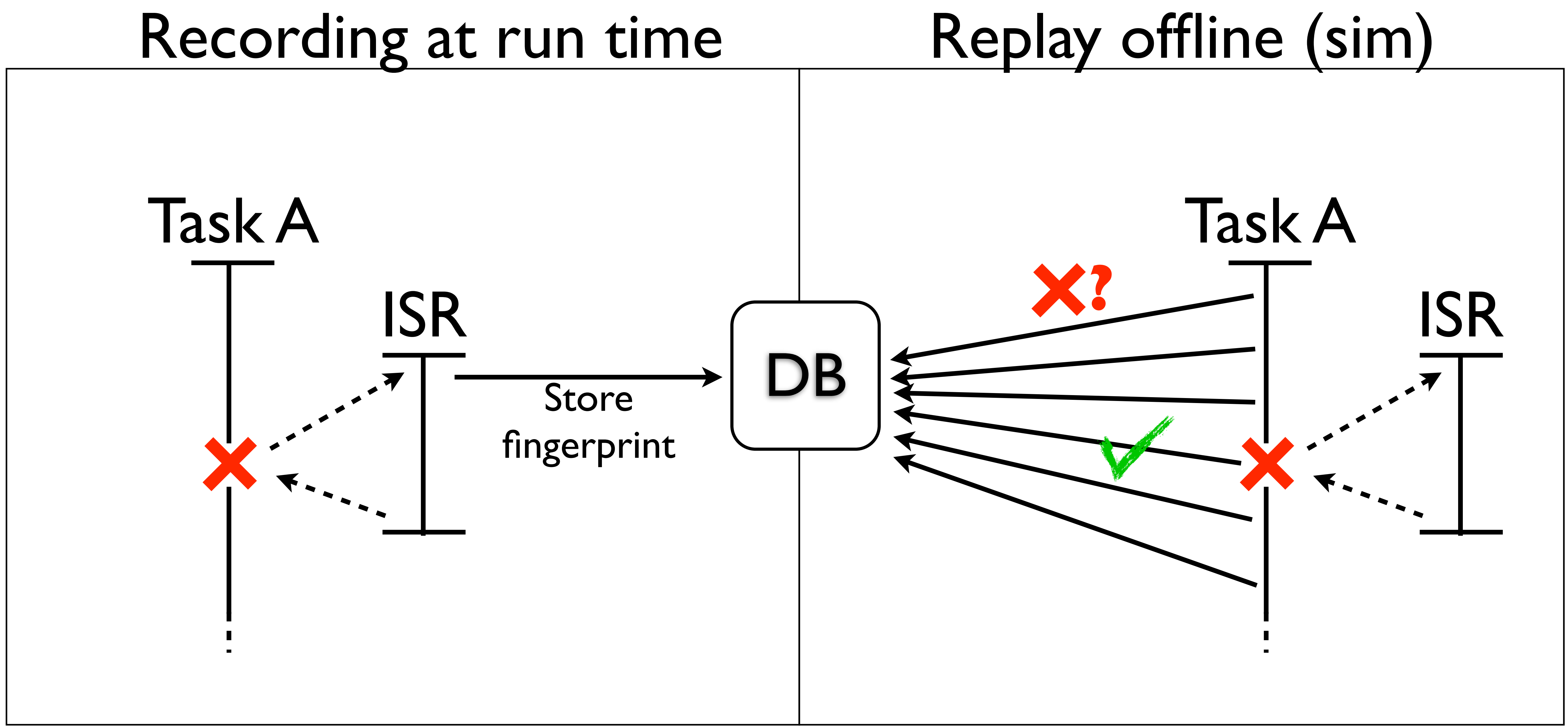

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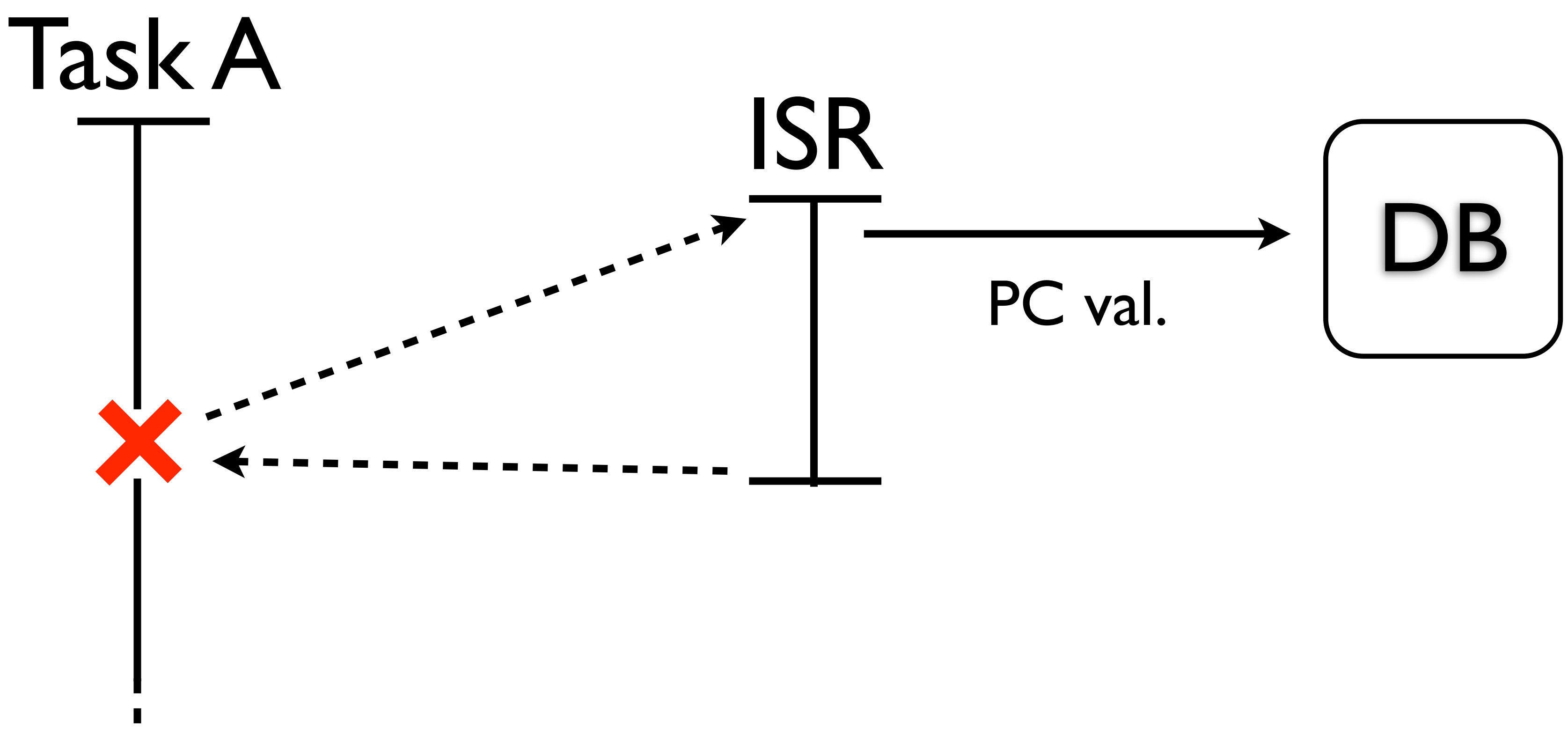
Replay Debugging

- Benefits
  - Communicate and document bugs
    (Show the trace)
  - Go forward and backwards in time
    (Thoroughly analyze how the bug happened)
  - Retest specific scenario for fixes
    (Exercise the system with the specific trace)

Recording Phase

First try: record program counter



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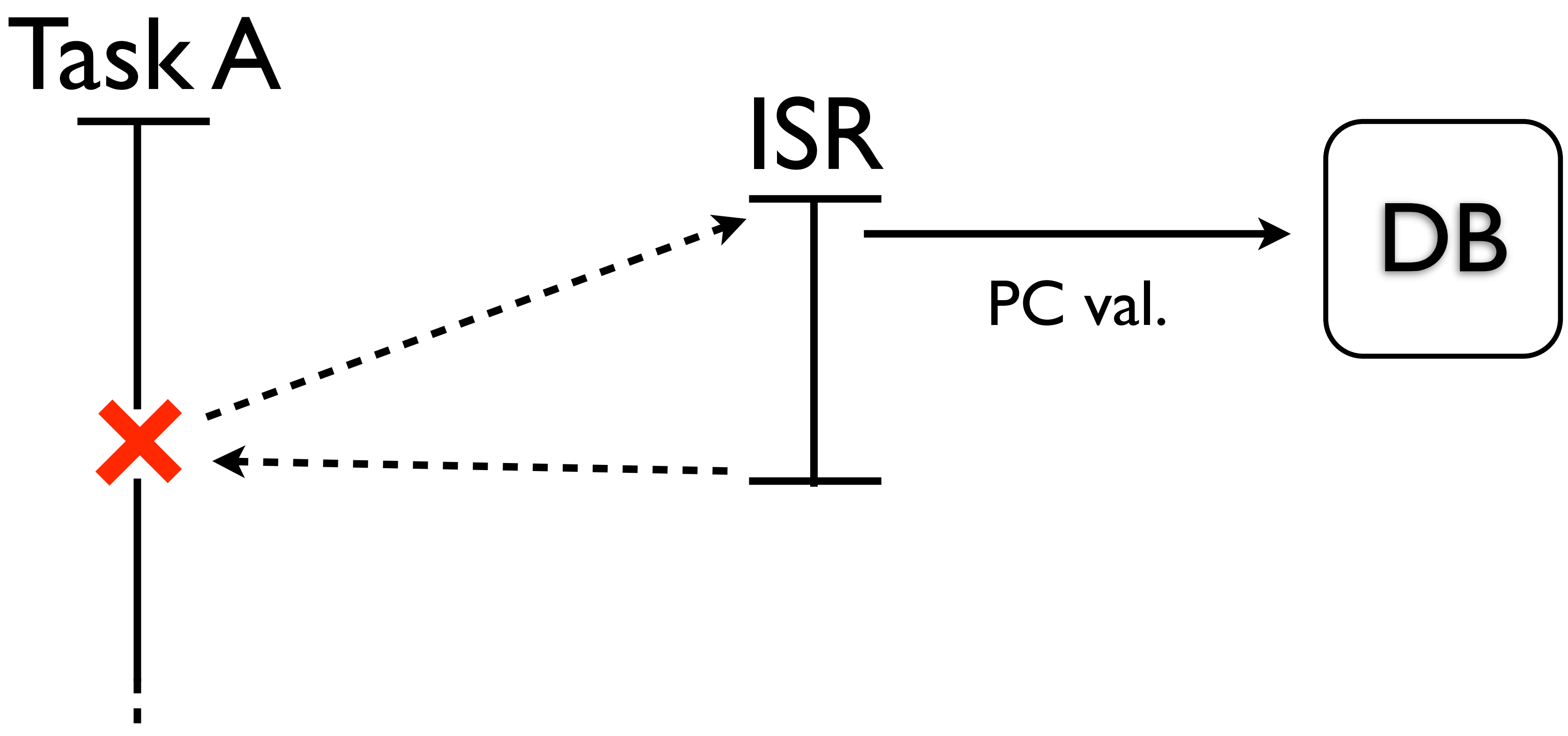

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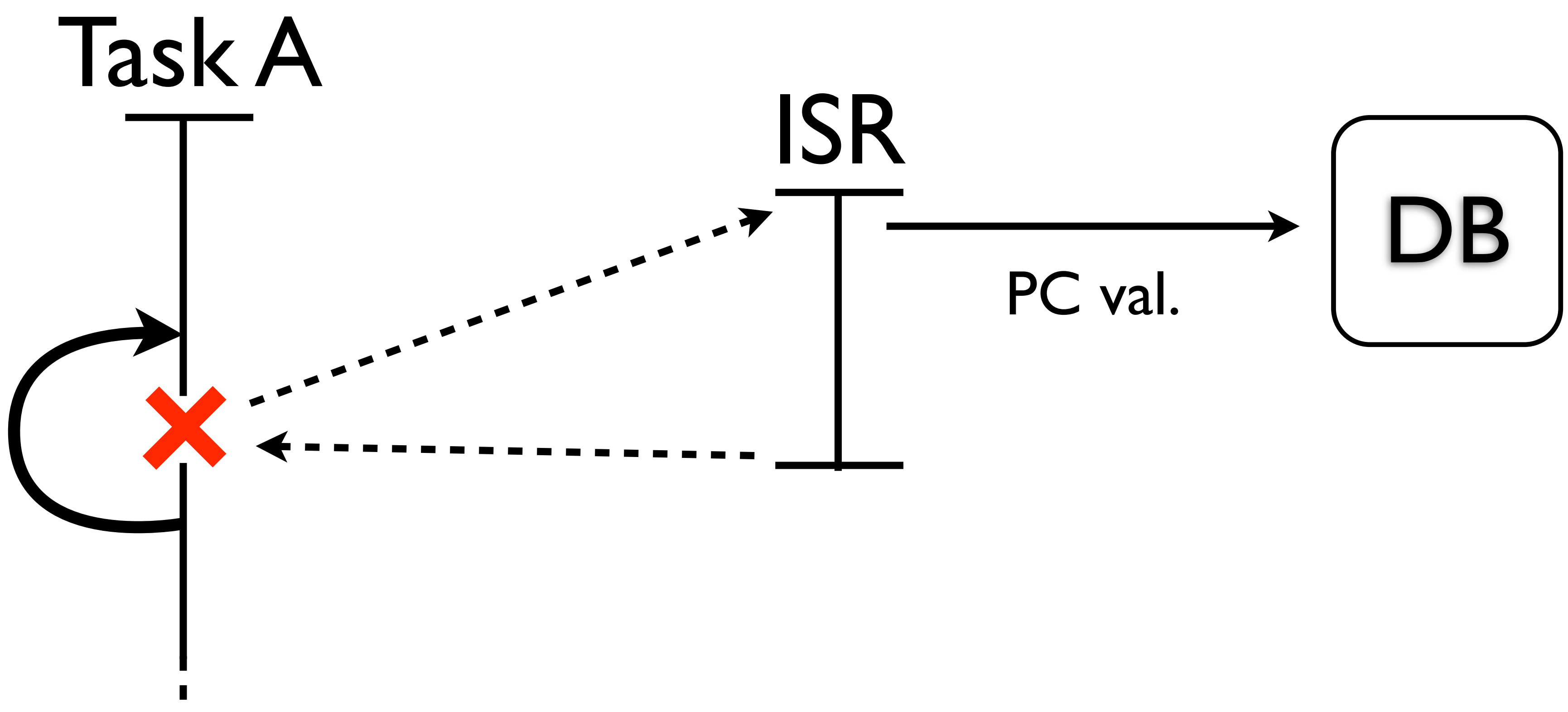

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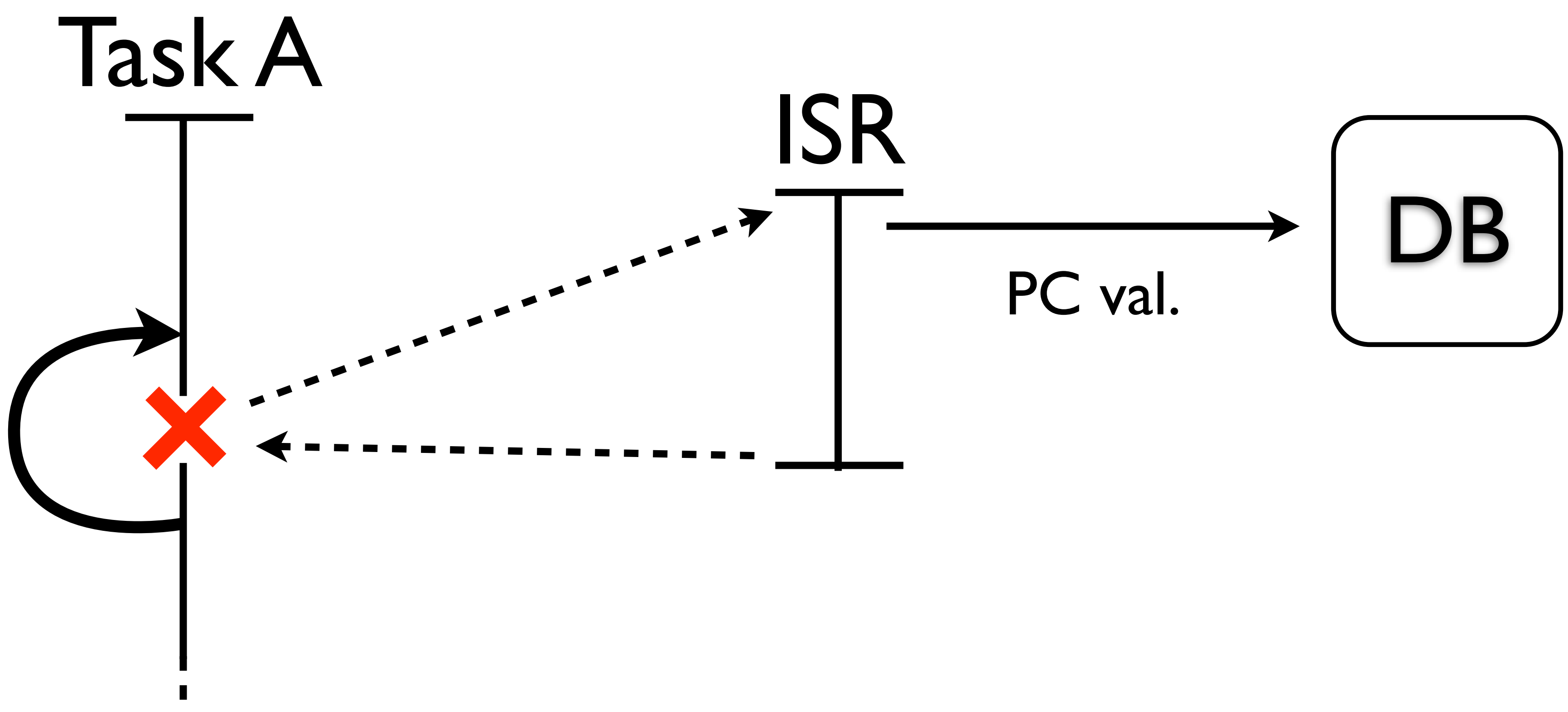

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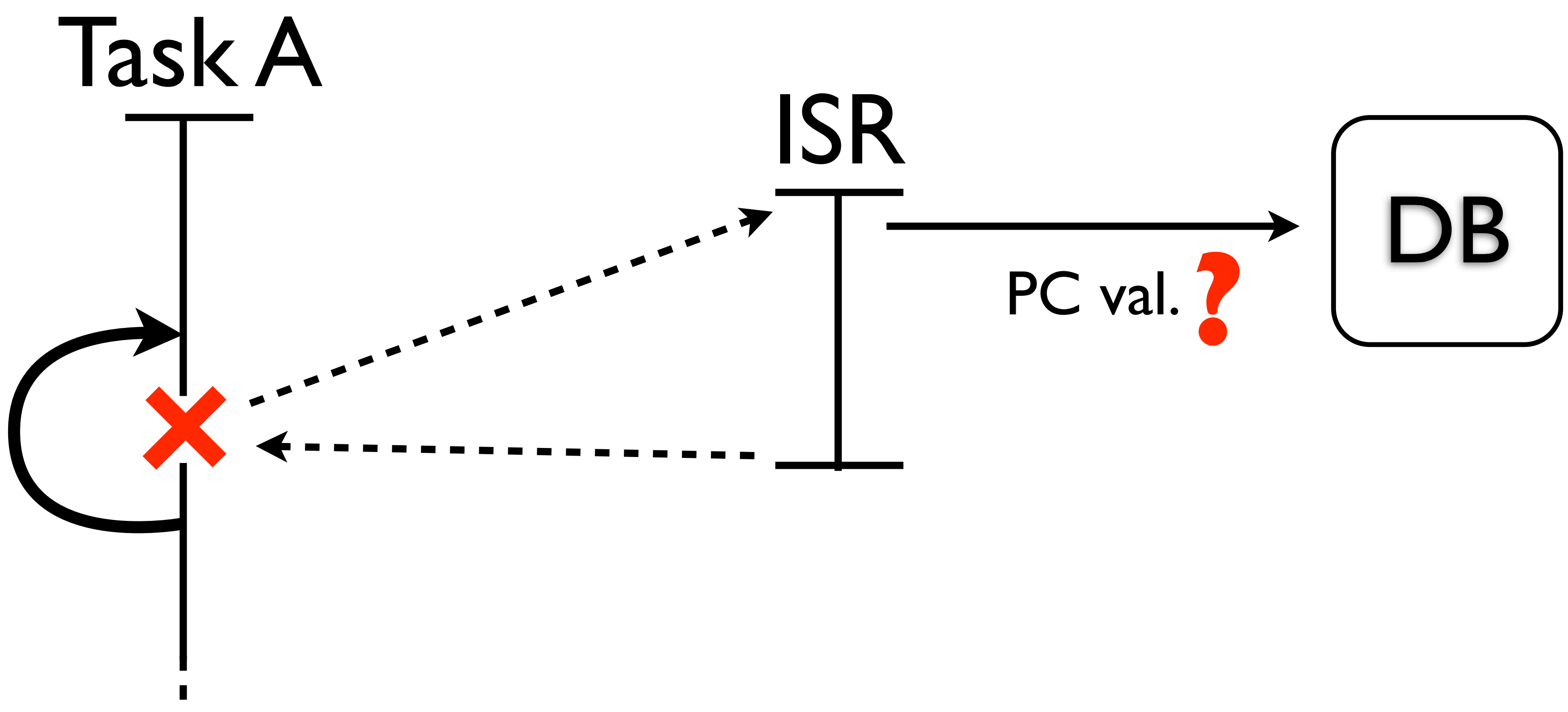

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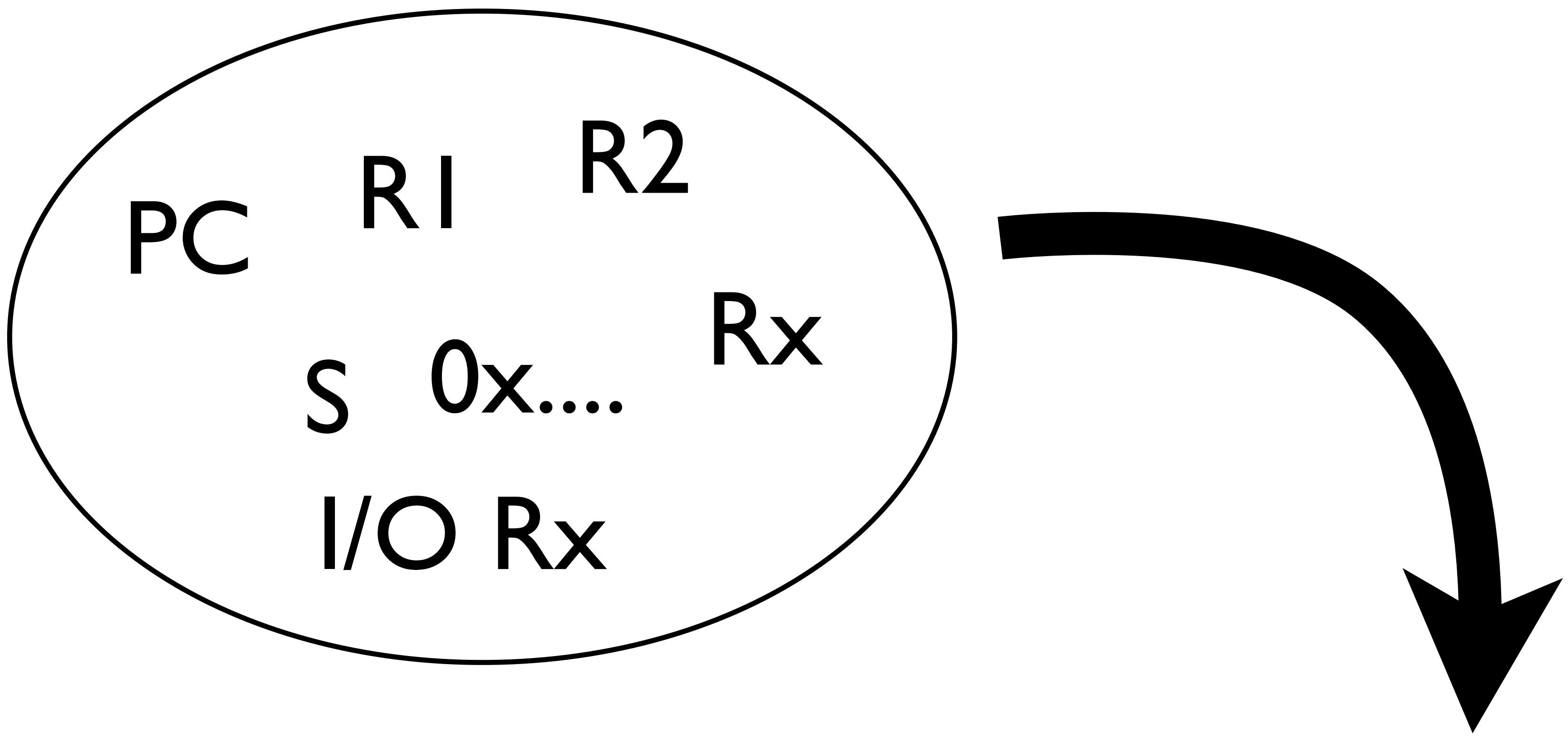
Fingerprinting

Compress system state

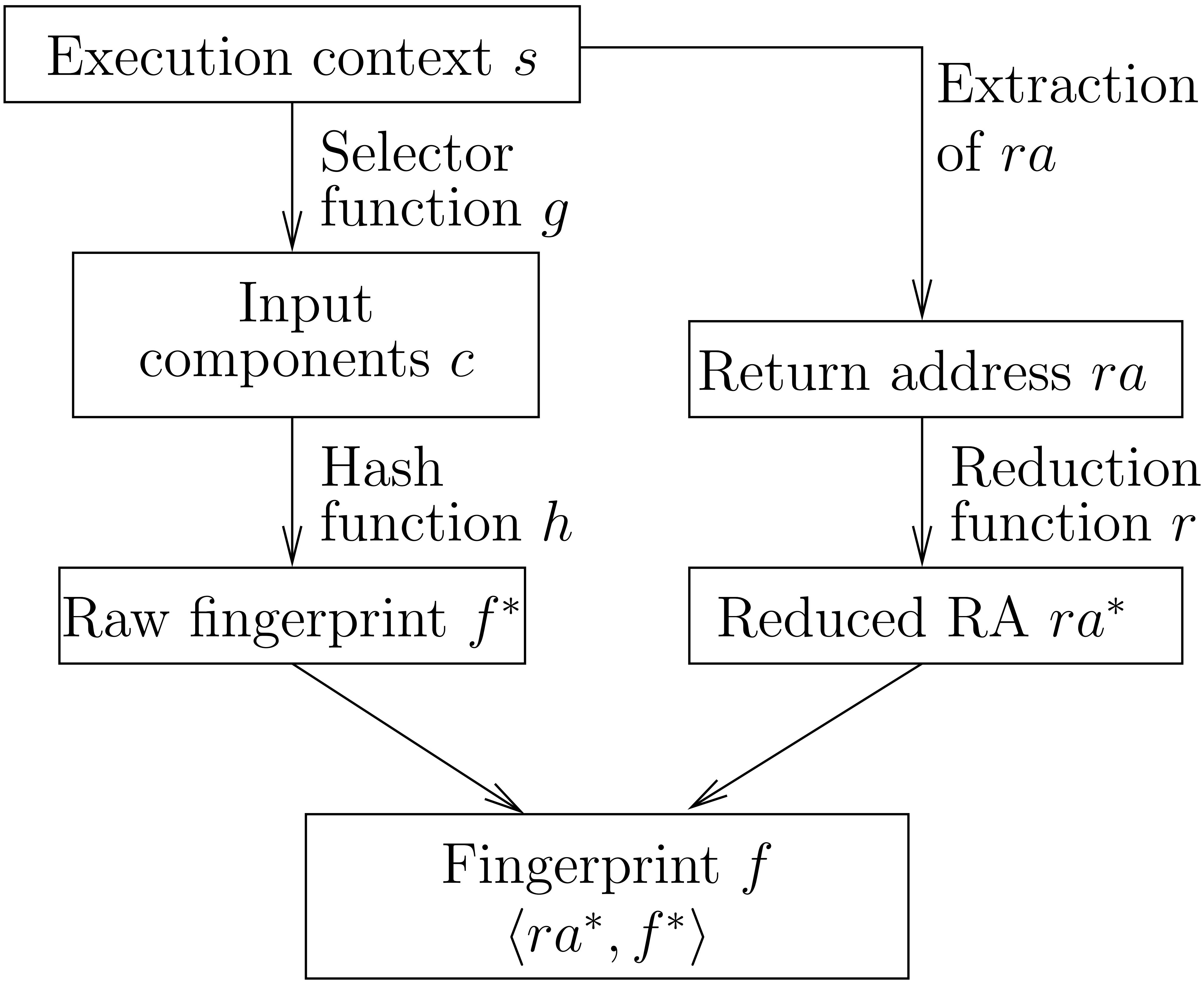
System state 512+ bits



Fingerprint <32 bits

01001000100100100101110

System Model



Caveats

- False input duplicates *(selected bad subset)*

$$s \neq s' \wedge g(s) = g(s')$$

- False loop positives *(falsely believe IRQ happened here)*

$$s \neq s' \wedge s.ra = s'.ra \text{ but also } (h \cdot g)(s) = (h \cdot g)(s')$$

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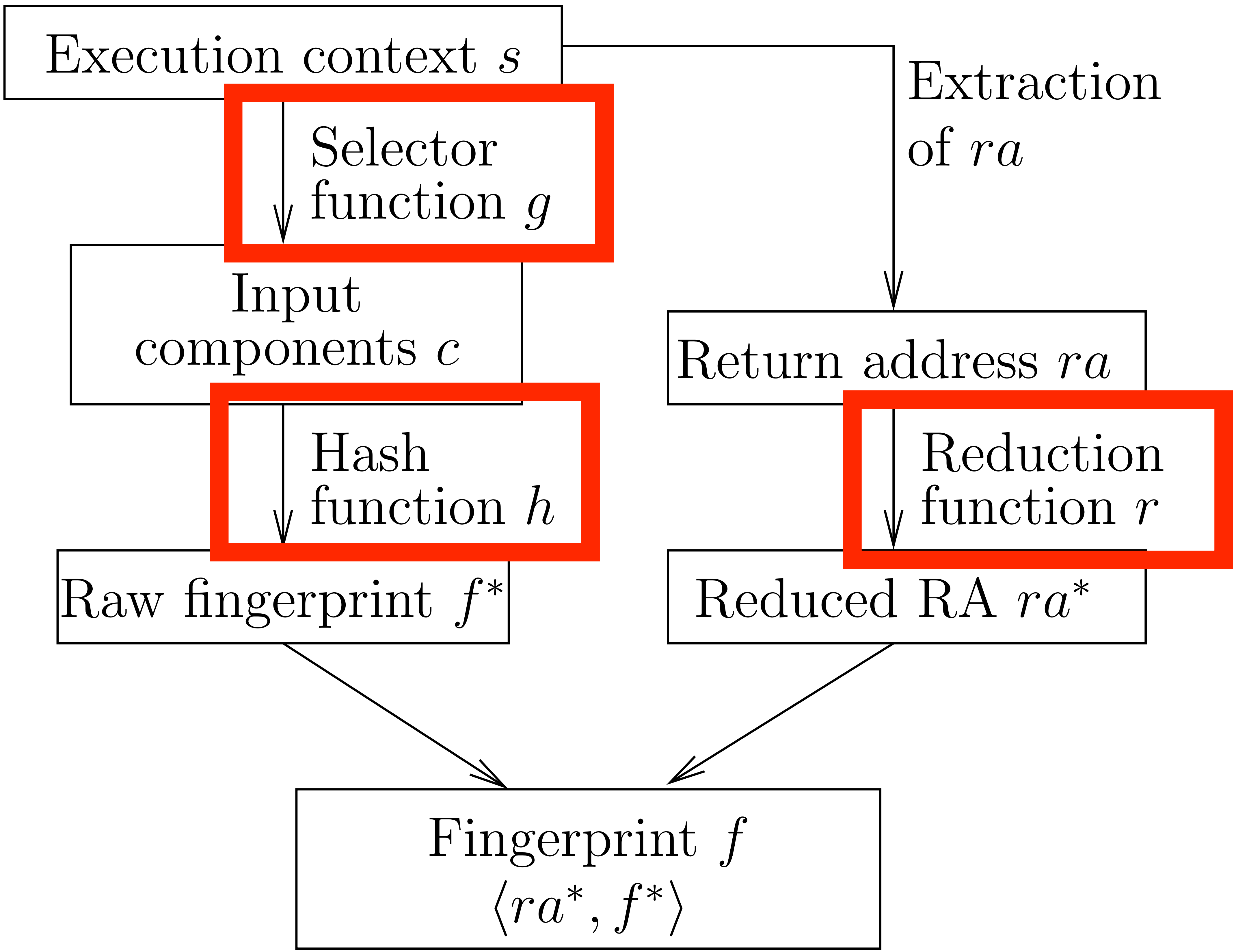
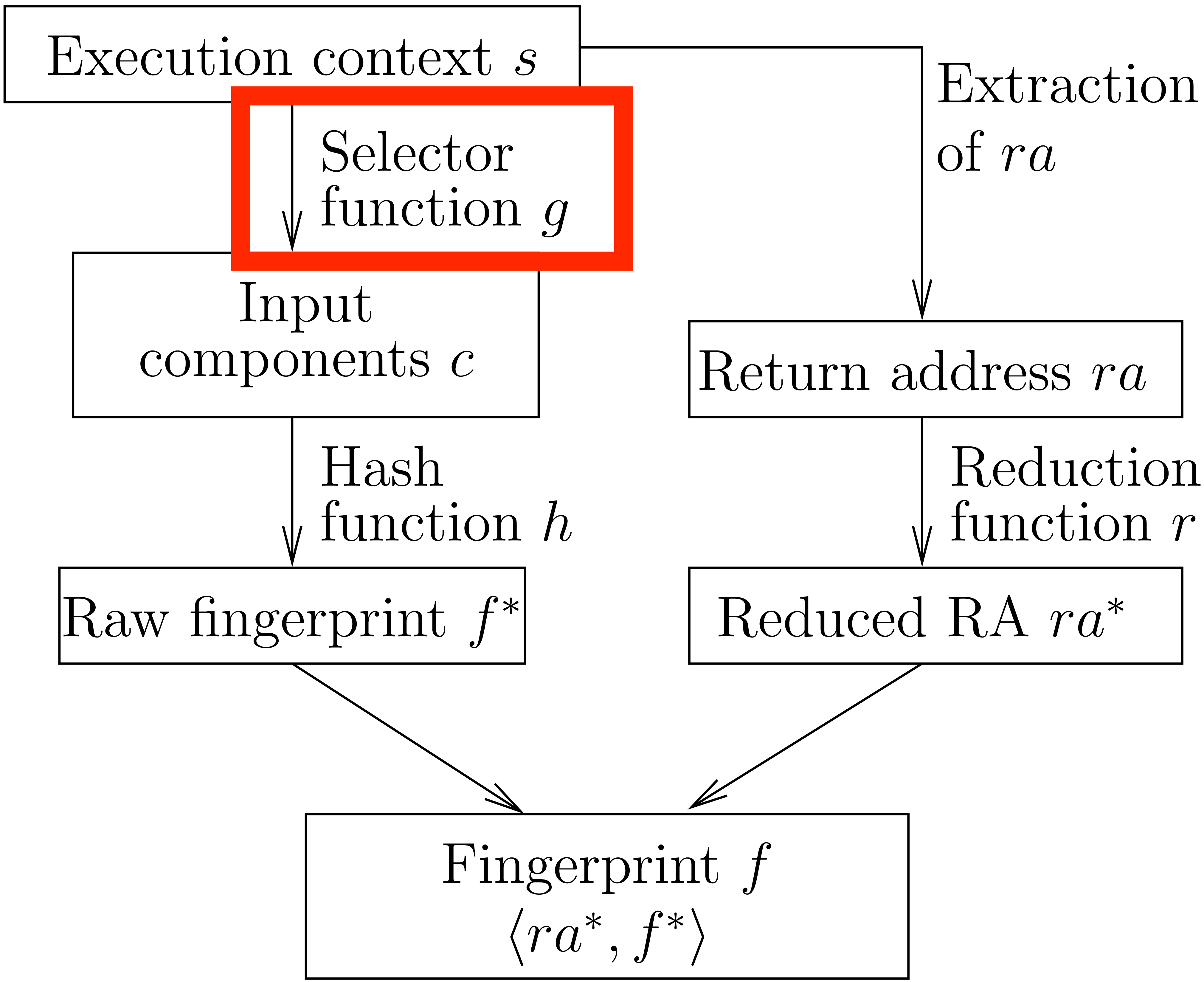
Calls for good design of fingerprint

Designing the Fingerprint




Execution context s
Selector function g
Extraction of ra
Input components c
Return address ra
Hash function h
Reduction function r
Raw fingerprint f^*
Reduced RA ra^*
Fingerprint f
$\langle ra^*, f^* \rangle$

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- **Can't take all:**
  - Too much computation overhead
  - Not all are used equally often

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Pick the most frequently used ones

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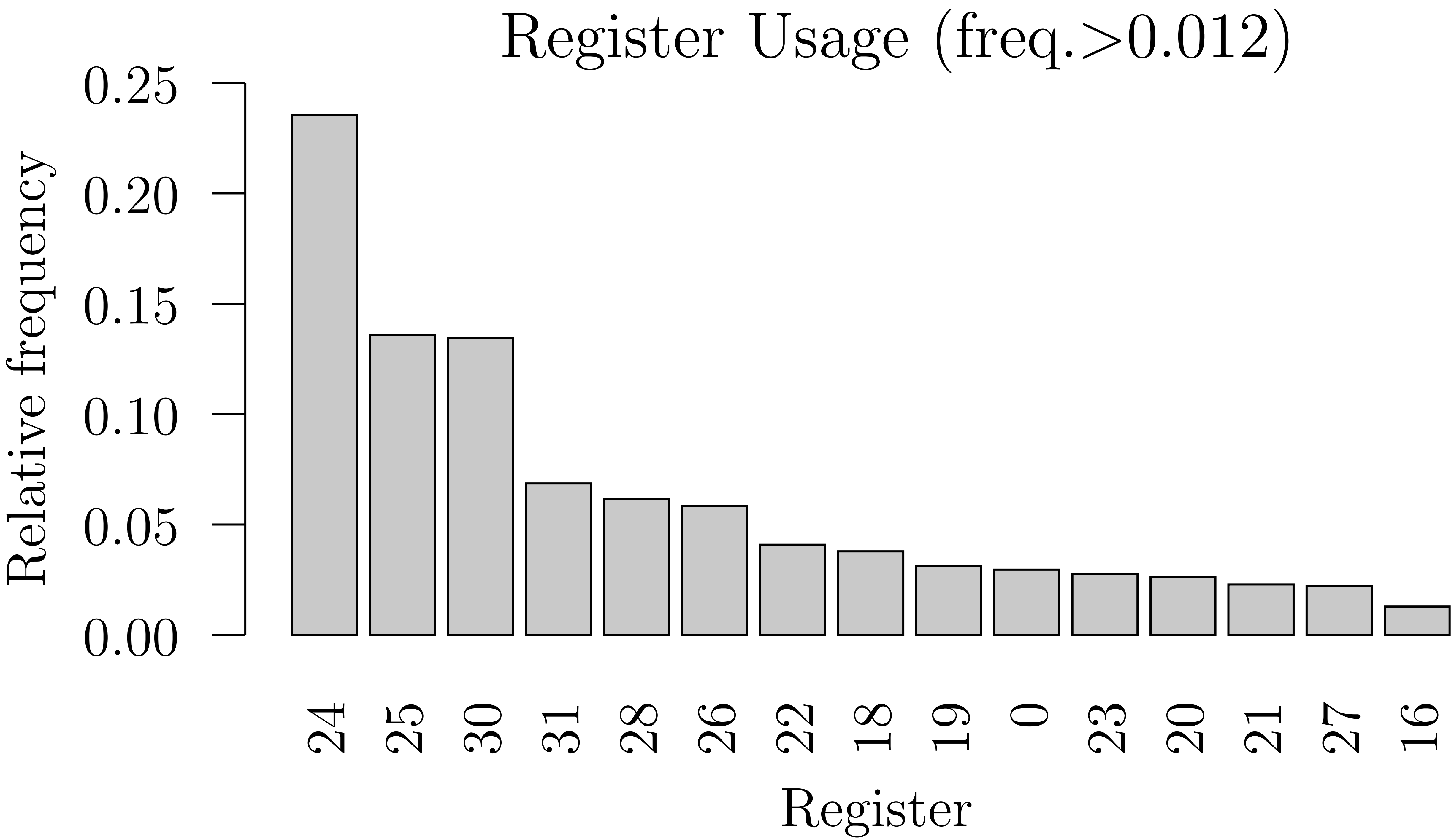
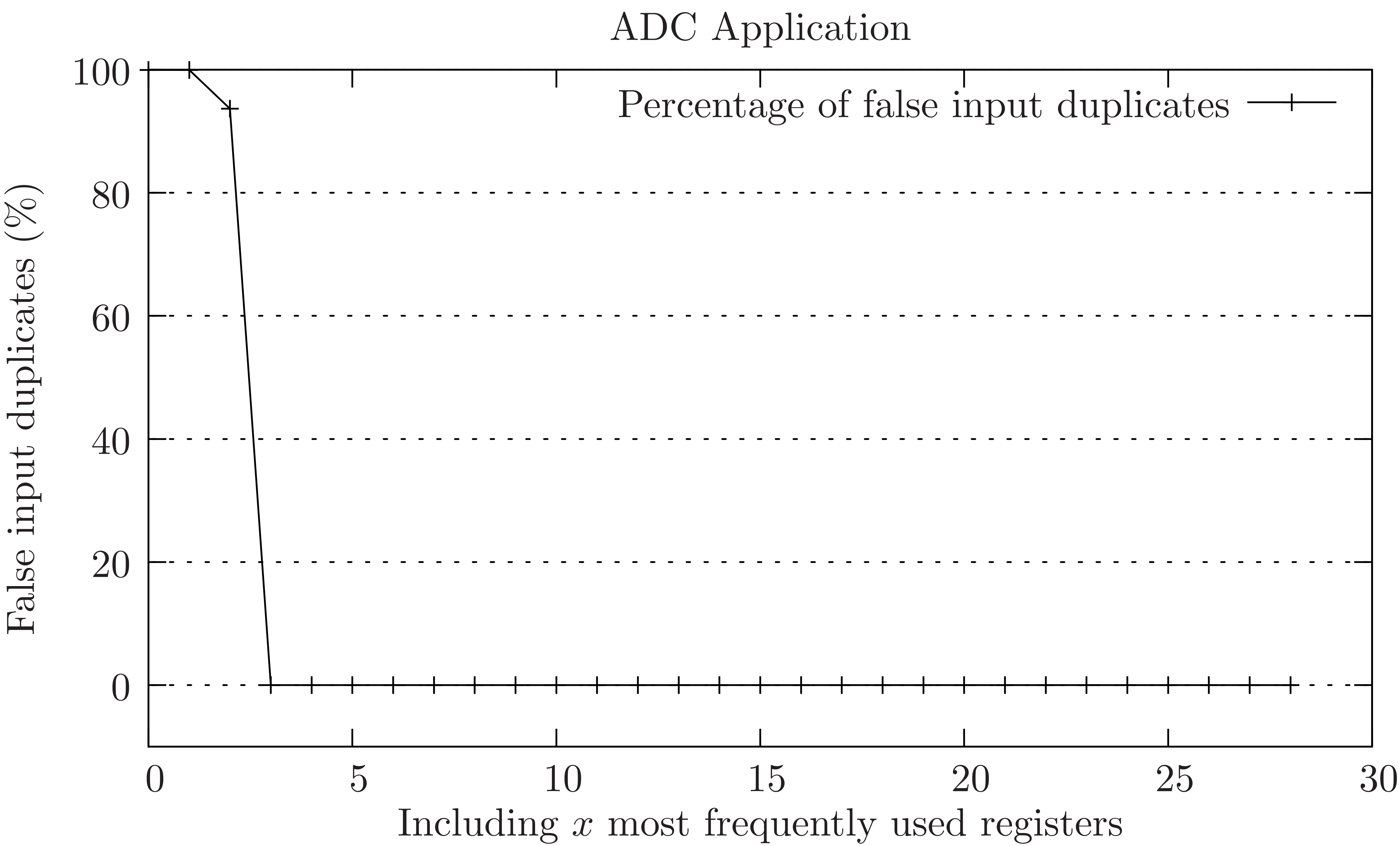


Does it work?

Yes, quite well.



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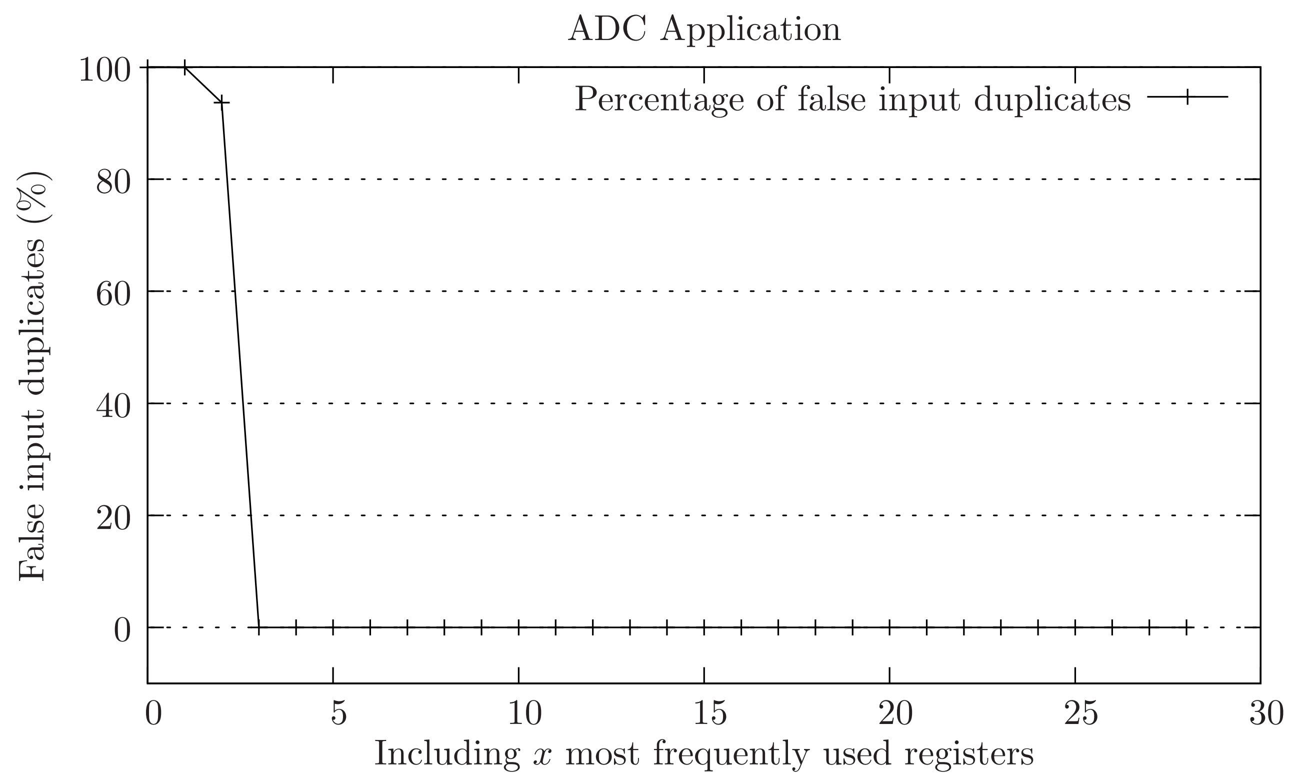
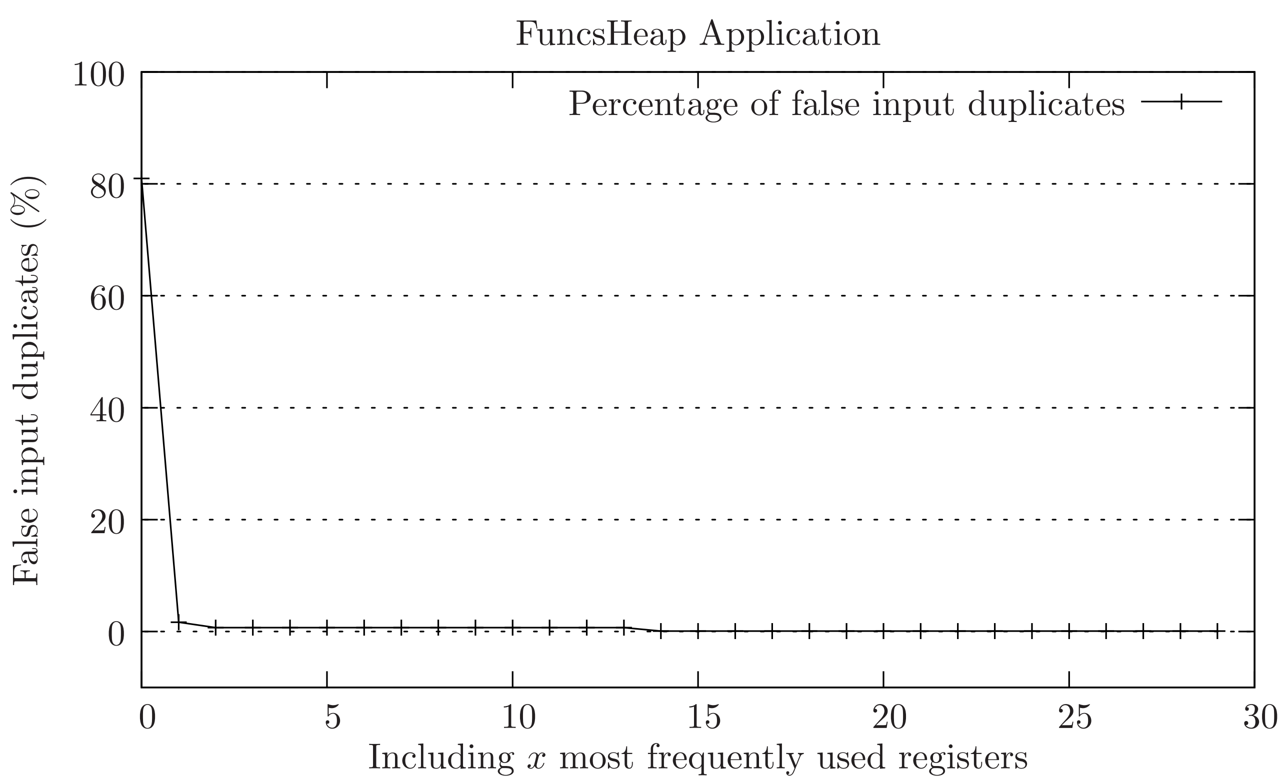

ADC Application
Percentage of false input duplicates
False input duplicates (%)
Including x most frequently used registers
0
20
40
60
80
100
0
5
10
15
20
25
30


FuncsHeap Application
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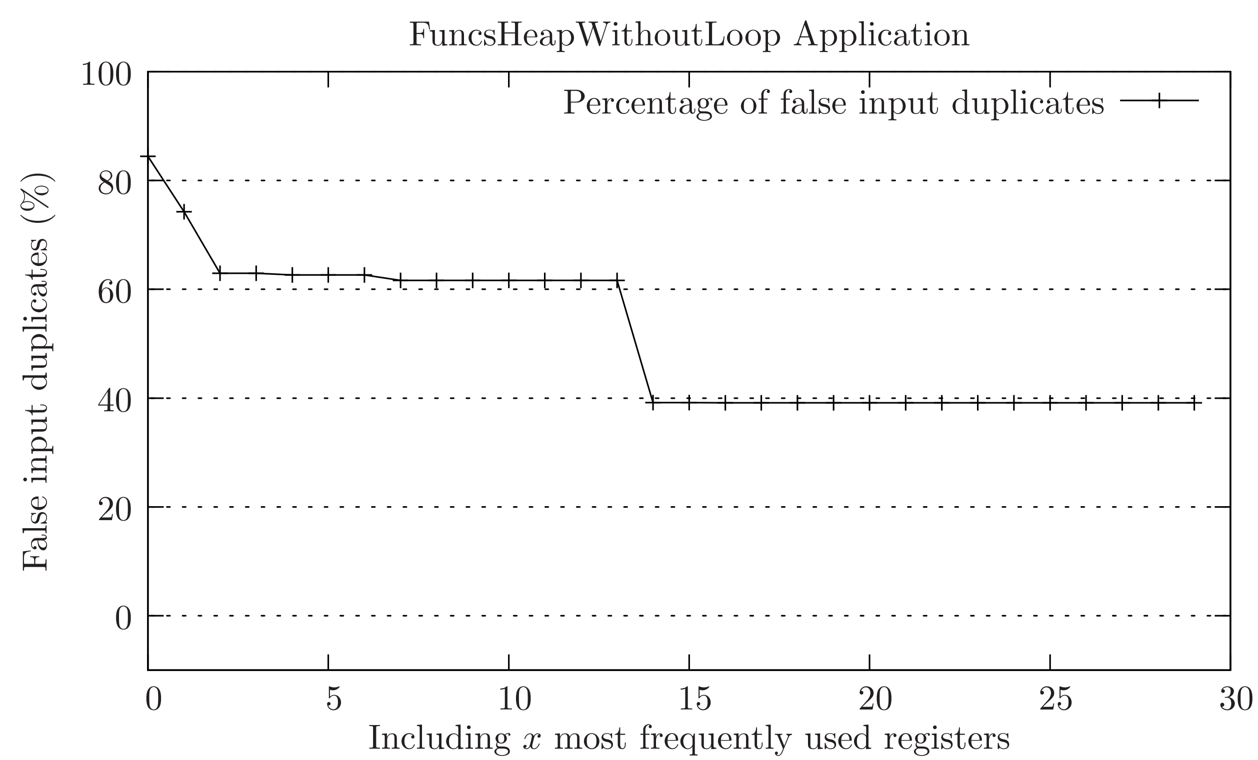
FuncsHeapWithoutLoop Application
Percentage of false input duplicates
False input duplicates (%)
Including x most frequently used registers
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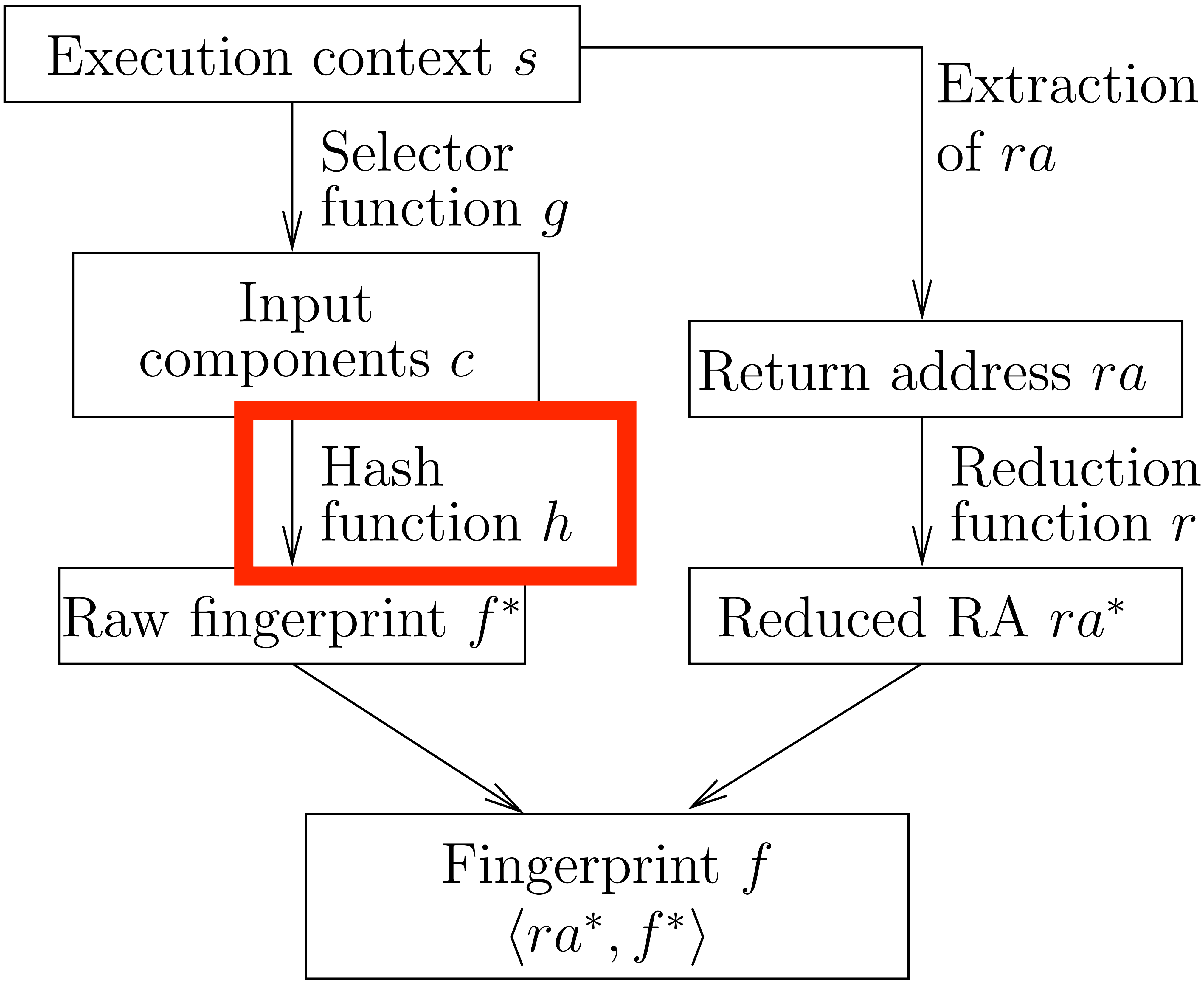
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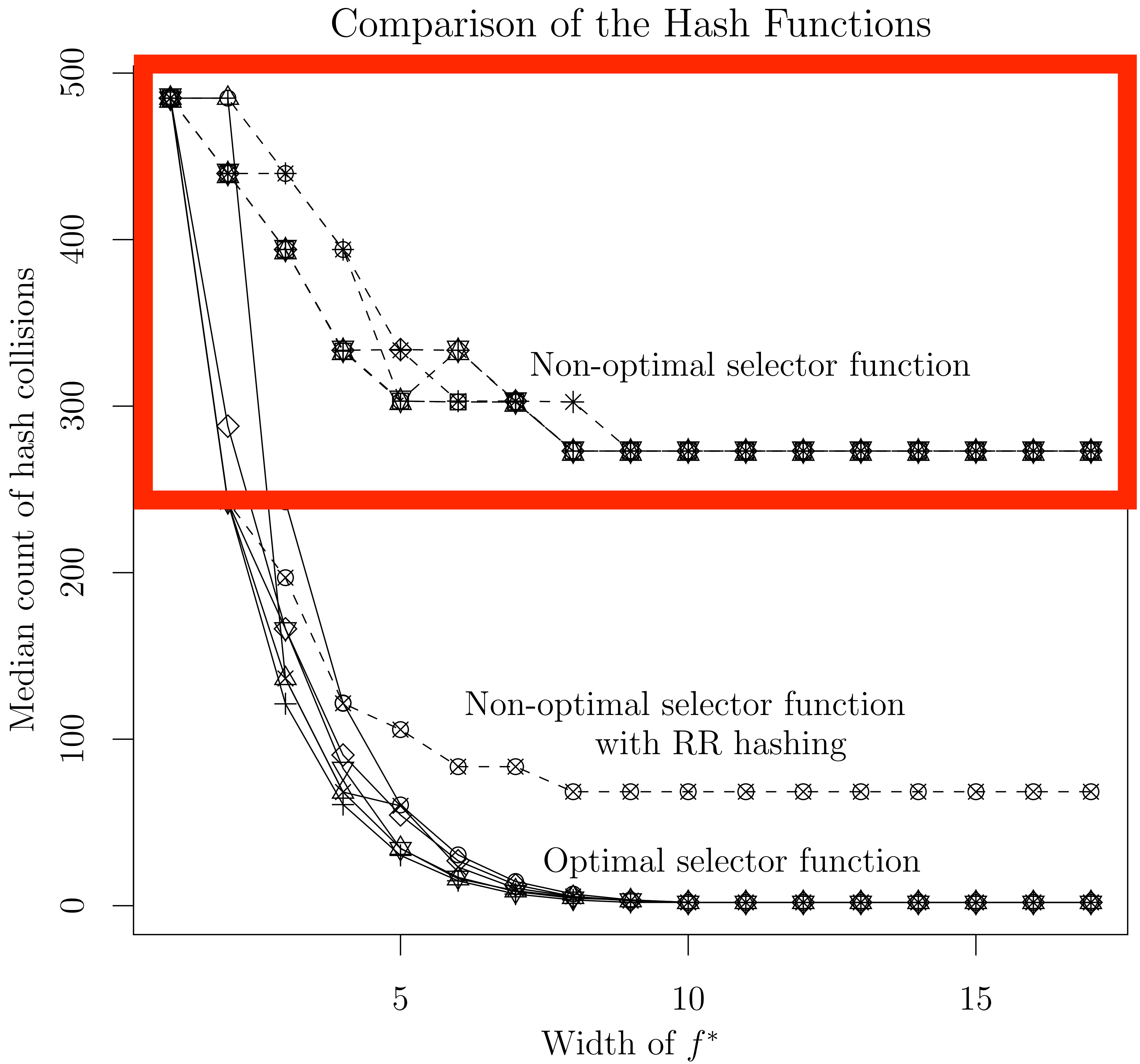
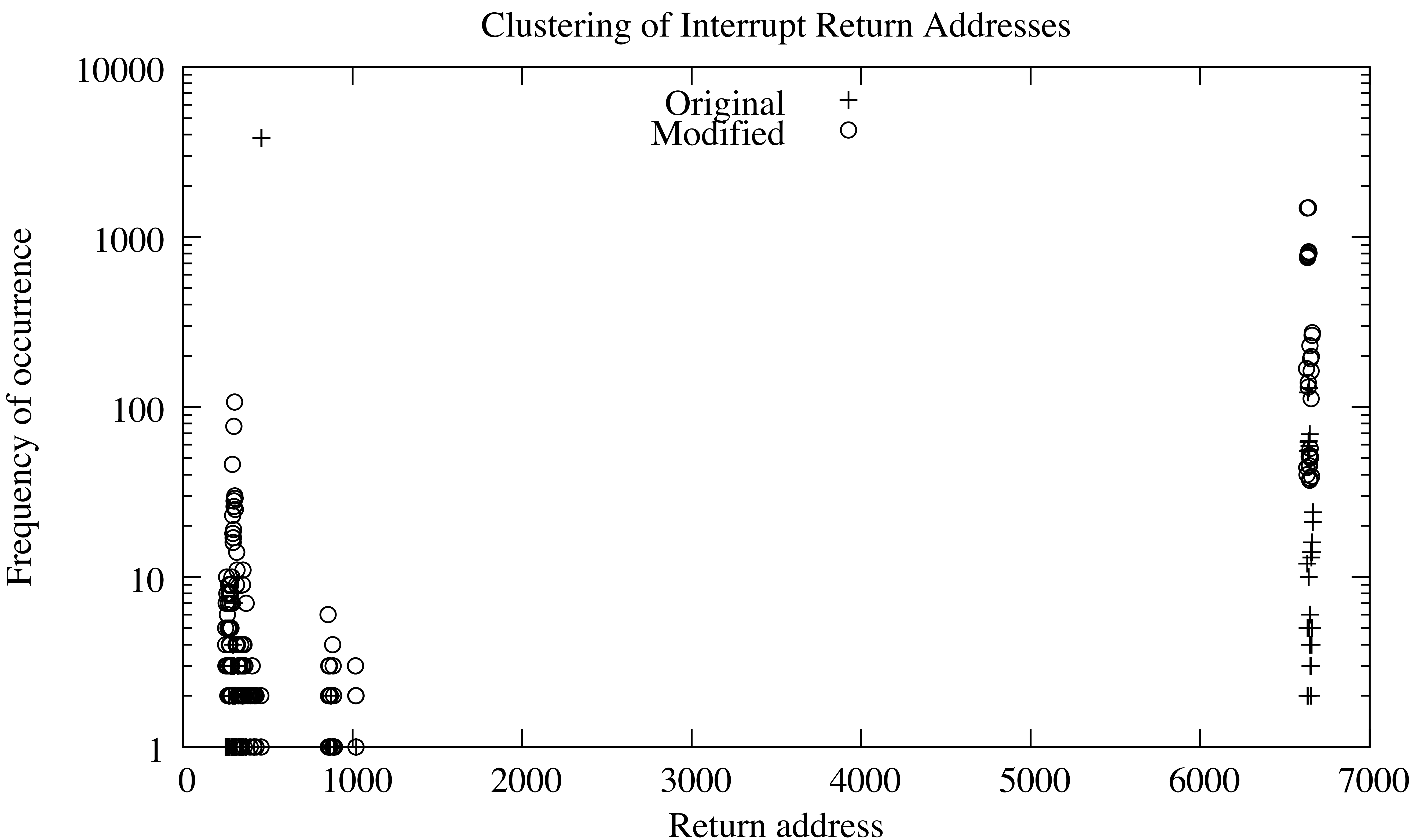
All Perform Equally Badly



Observation

Return addresses tend to cluster



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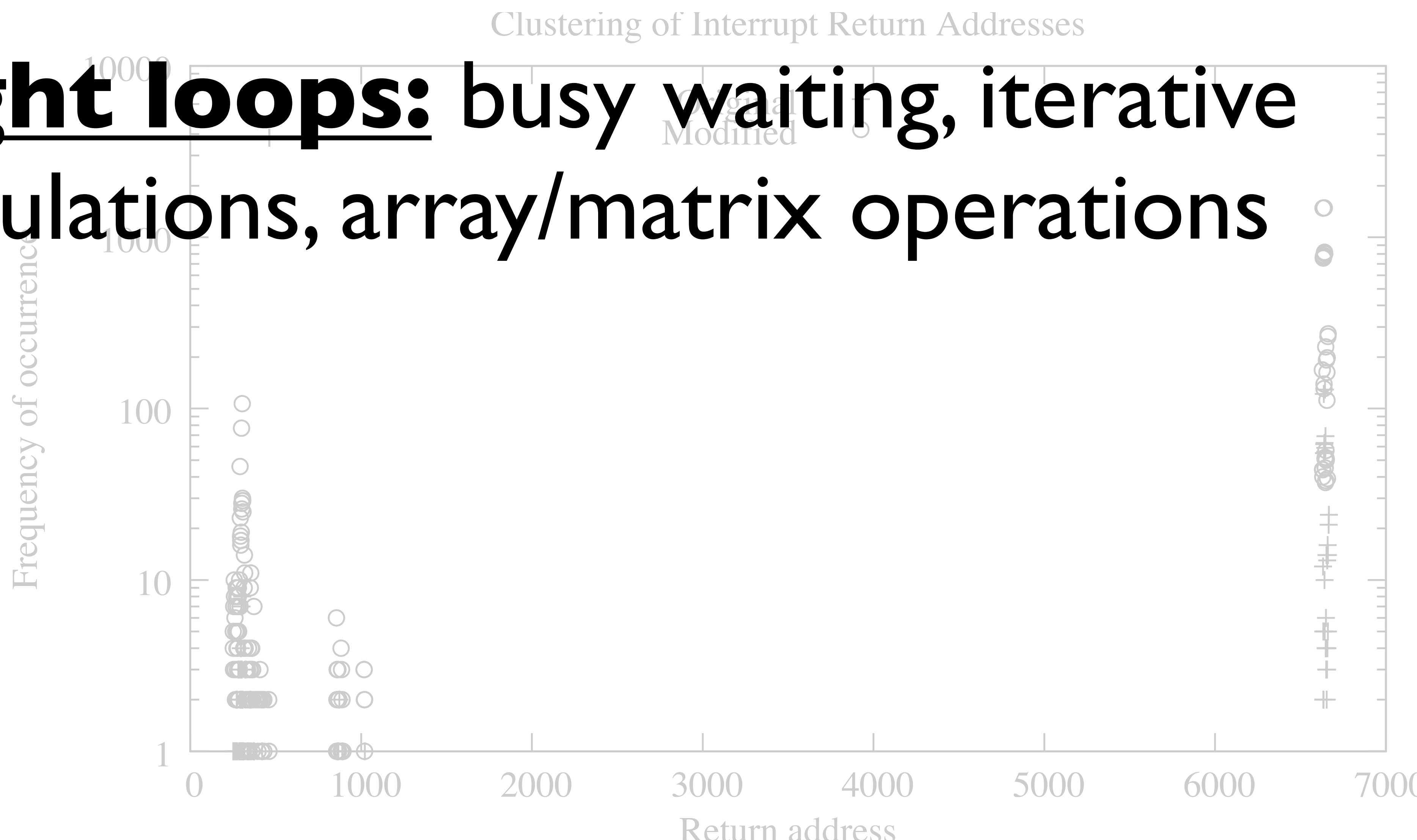

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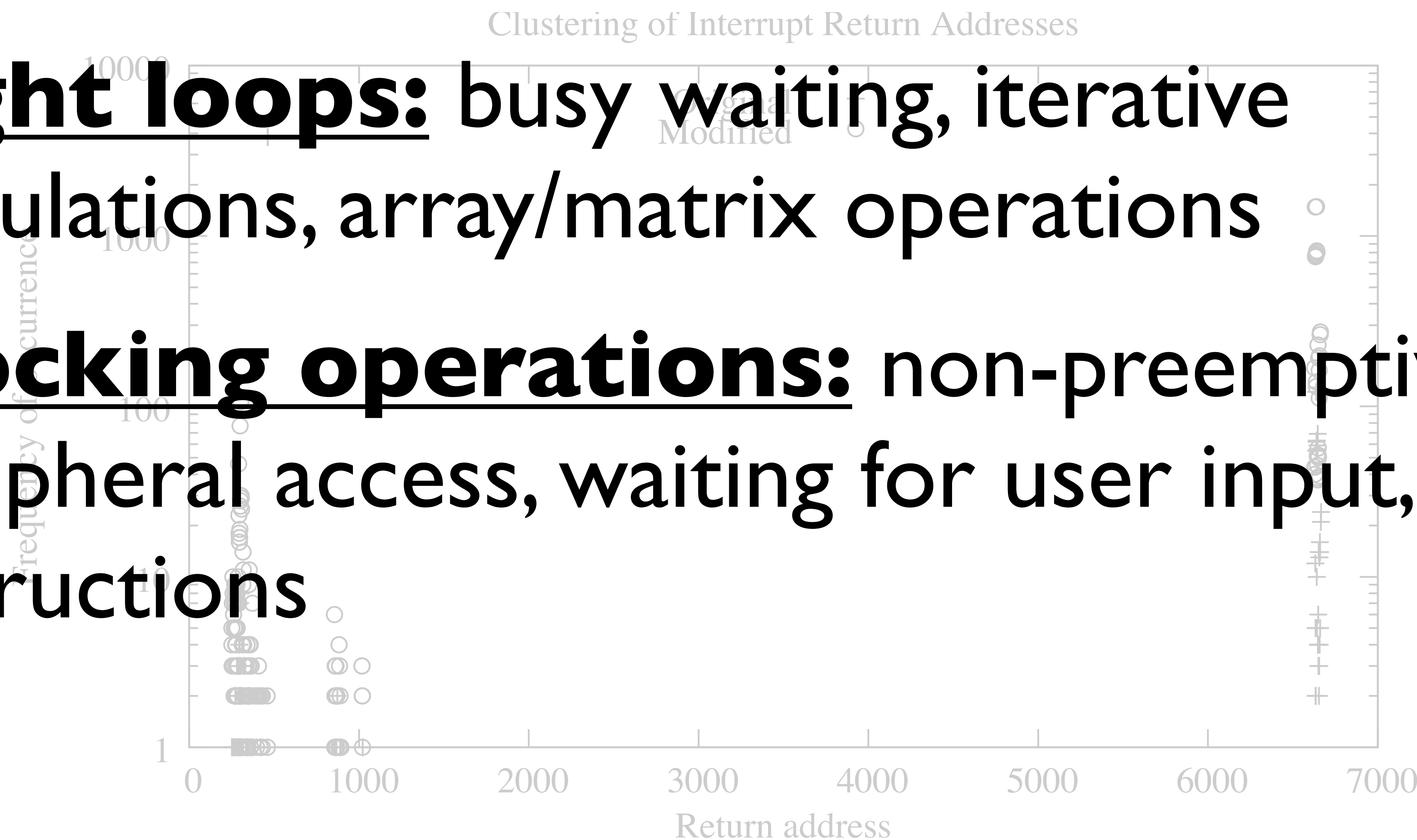

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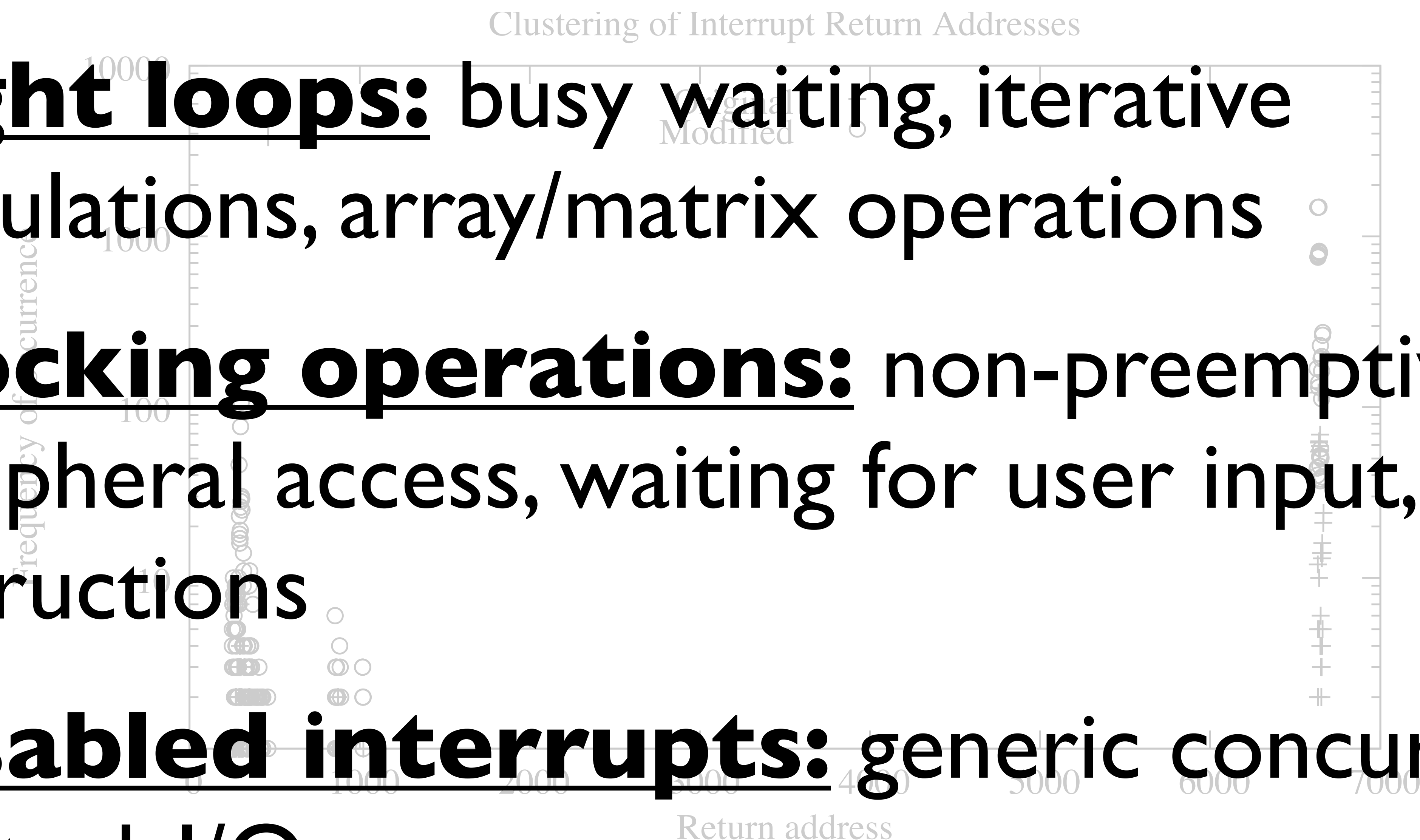

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Context specific hashing => RR hashing

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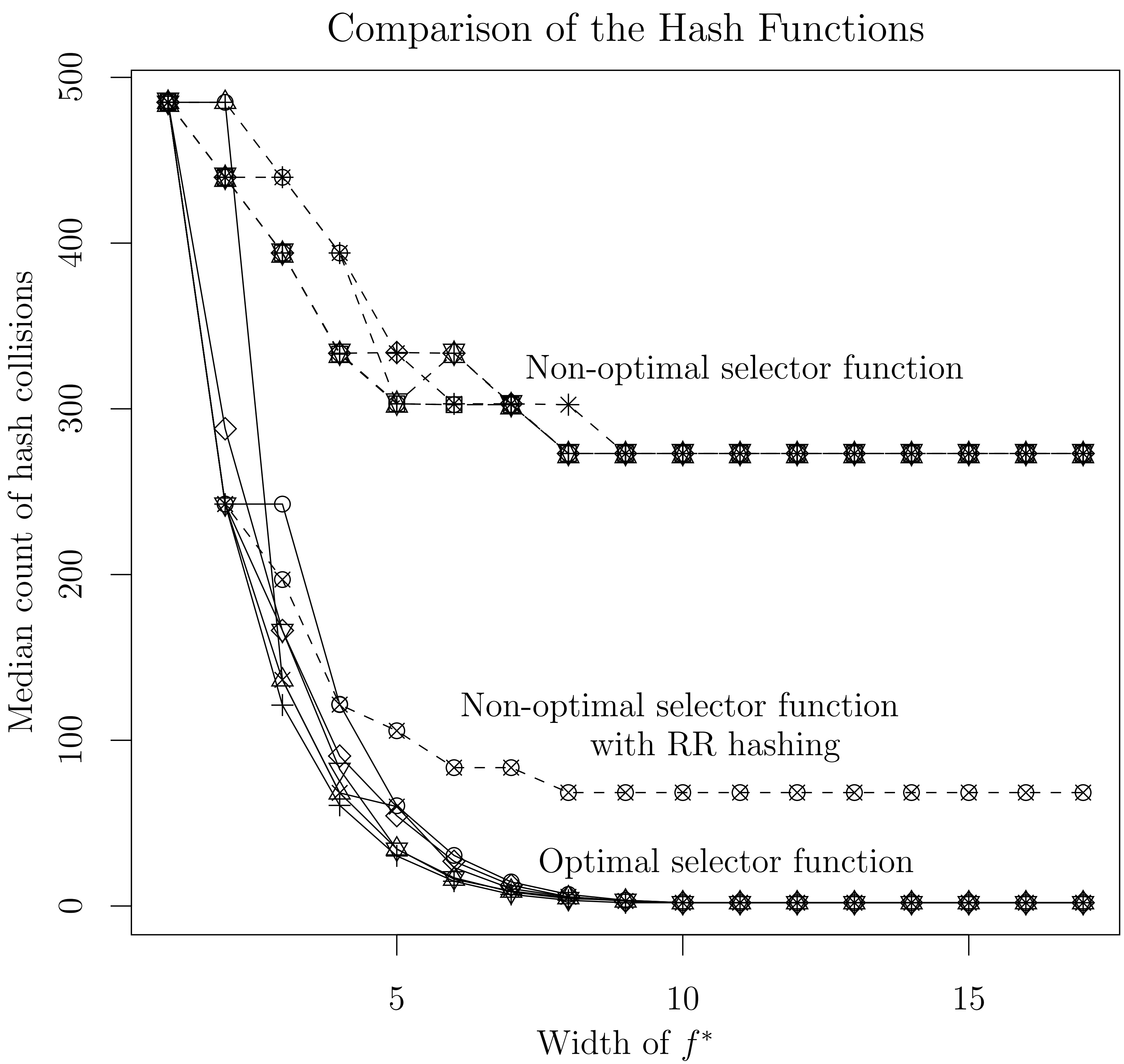
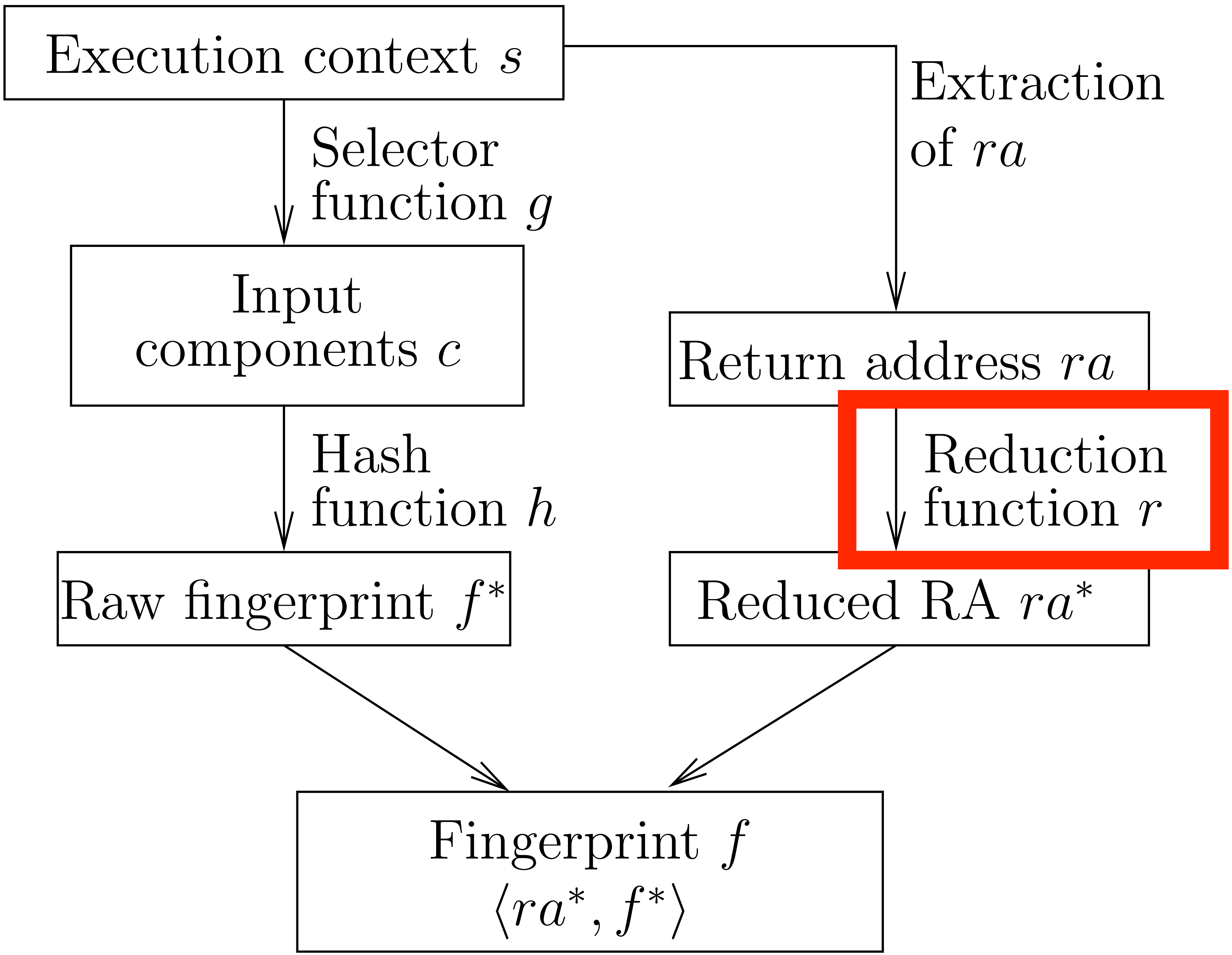
- In the replay use the correct hash function for according to the marker

Does it work?

RR hashing works surprisingly well

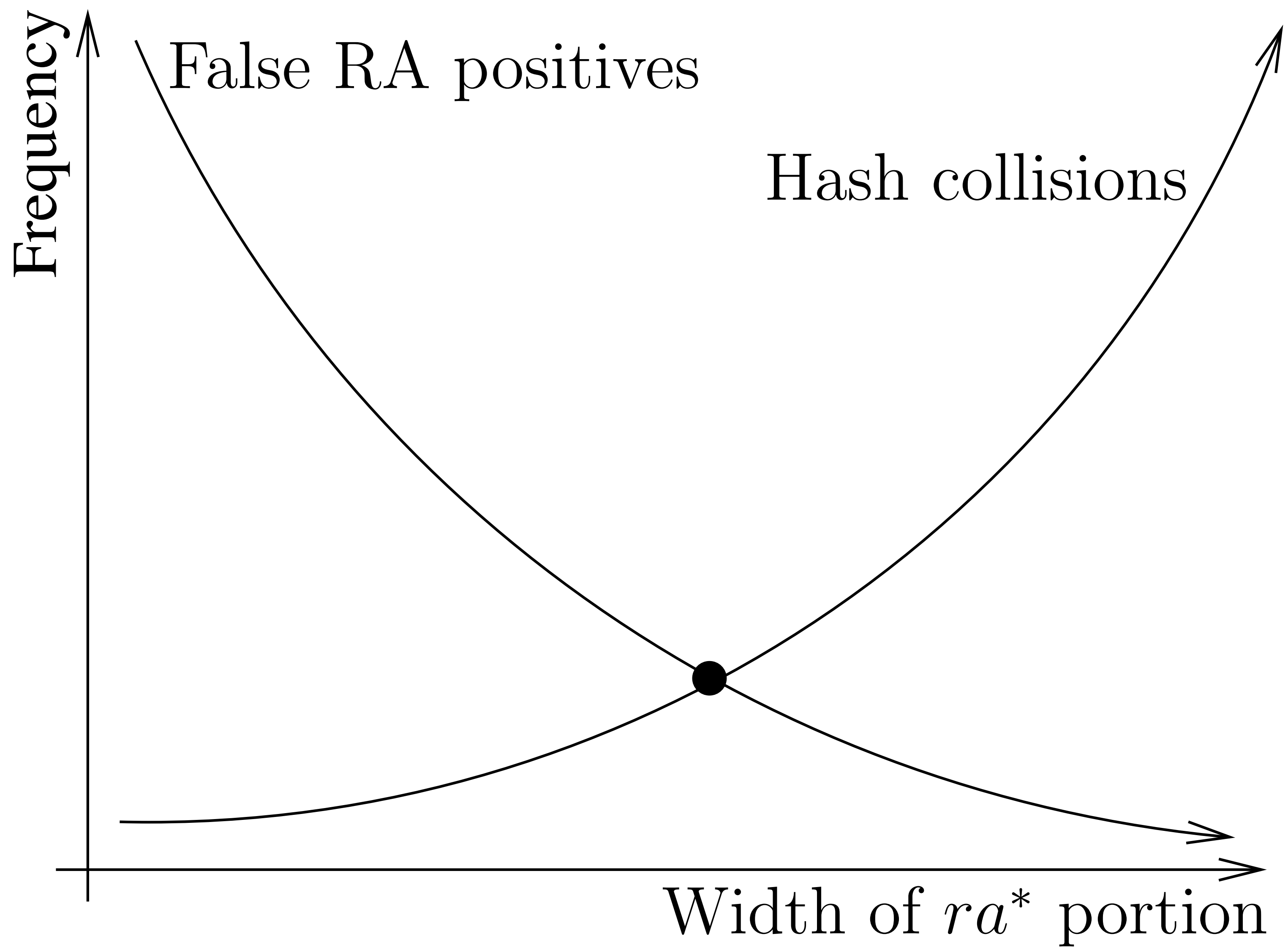




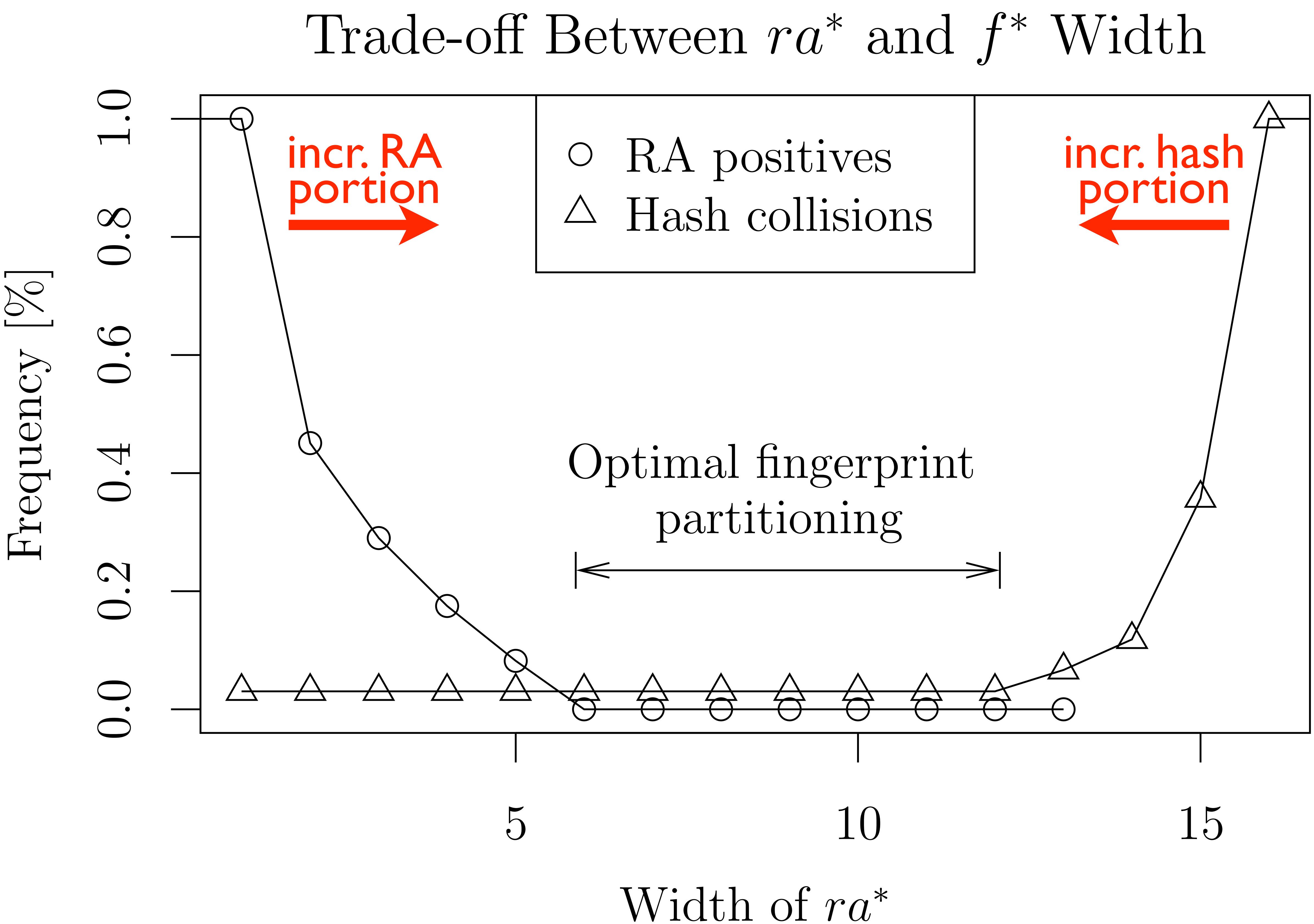
Sunday, June 21, 2009

How best to use the FP bits?

- Give all to the hash value? *(minimize hash collisions)*
- Give all to the RA? *(minimize false RA positives)*



Engineering the Fingerprint



Conclusions

- Debugging embedded systems is painful
  => Replay debugging can help [ST08]

- Frequency-based selection function ✓
- Round robin hashing ✓
- Tradeoff engineering for RA vs hash ✓

- Future work: Lots, see discussion section

Questions?

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CIMIT under U.S. Army Medical Research Acquisition Activity Cooperative Agreement W81XWH-07-2-0011