AGAMOTTO: How Persistent is your Persistent Memory Application?

Ian Neal[1], Ben Reeves[1], Ben Stoler[1], Andi Quinn[1],
Youngjin Kwon[3], Simon Peter[2], Baris Kasikci[1]

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The University of Texas at Austin Computer Science 2

KAIST School of Computing 3

Good News! PM has arrived!

Image Source: https://www.intel.com/content/www/us/en/architecture-and-technology/optane-dc-persistent-memory.html

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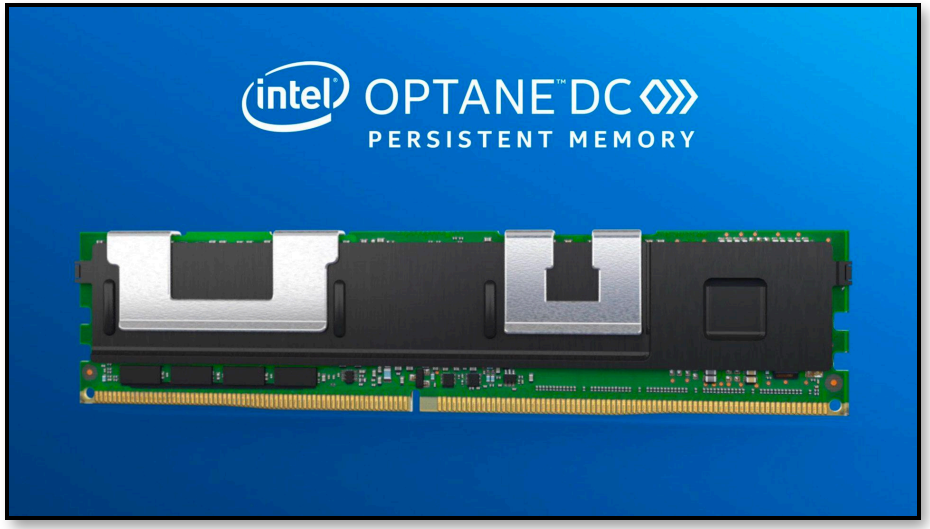

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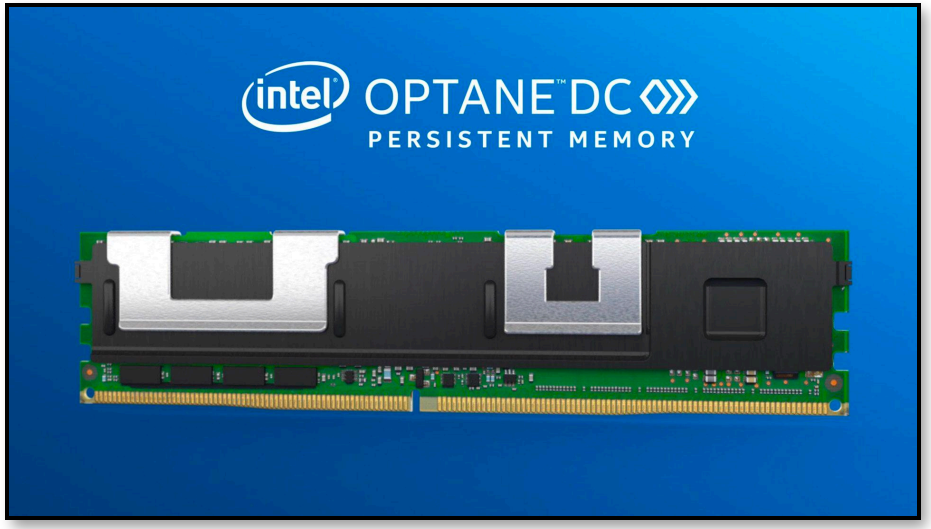
- Great, fast new storage technology called persistent main memory (PM)
  - AKA non-volatile memory (NVM)



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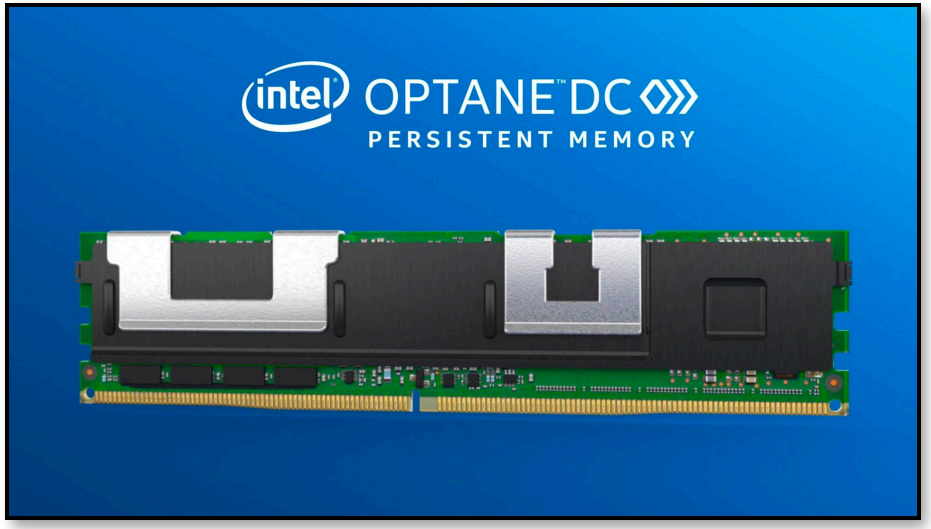
- Higher capacity, only 2−3x higher latency than DRAM



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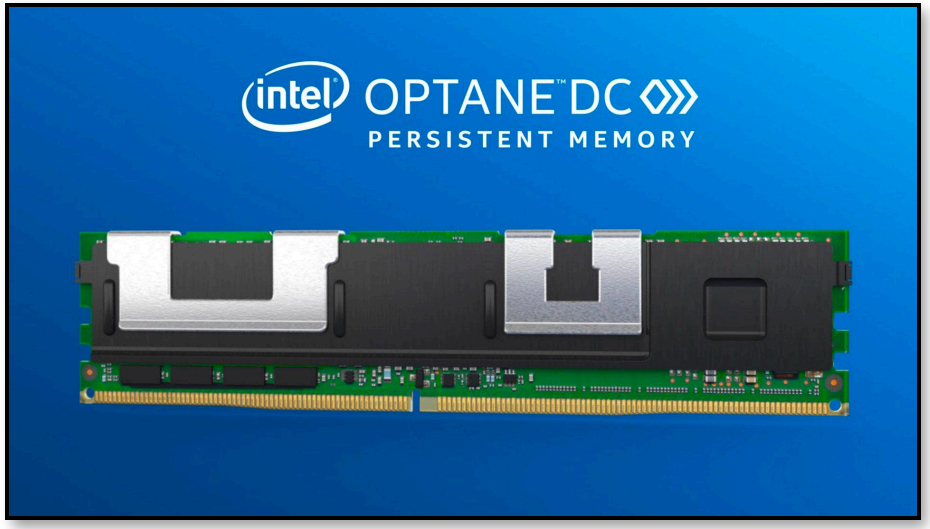
- Great, fast new storage technology called persistent main memory (PM)
  - AKA non-volatile memory (NVM)
- Higher capacity, only 2−3x higher latency than DRAM
- Can be used to increase main memory capacity (volatile)
- ***Can be used as durable storage and can be used directly in user space!***



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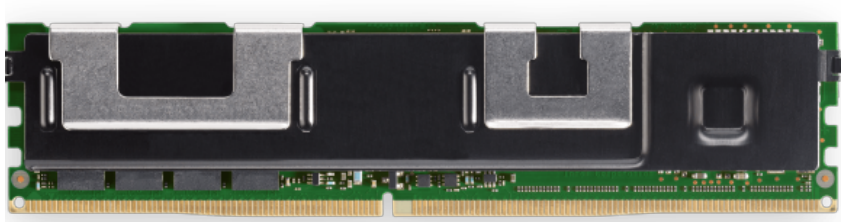
PM Programming Background



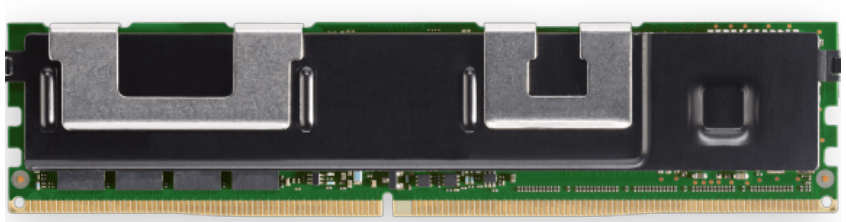
(Intel Optane PM DIMM)

CPU Cache

CPU

PM Programming Background

- Modern CPU architectures require special *persistence mechanisms* to ensure updates made durable



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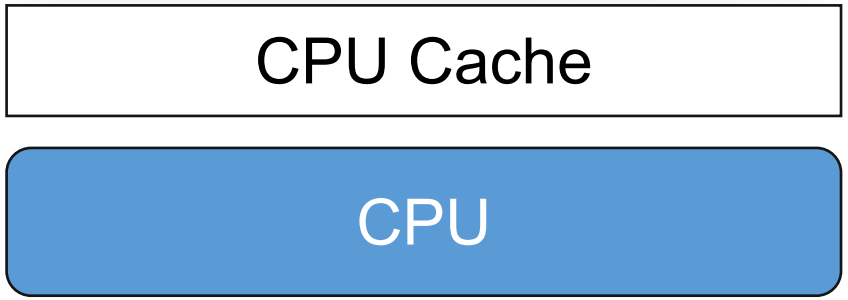

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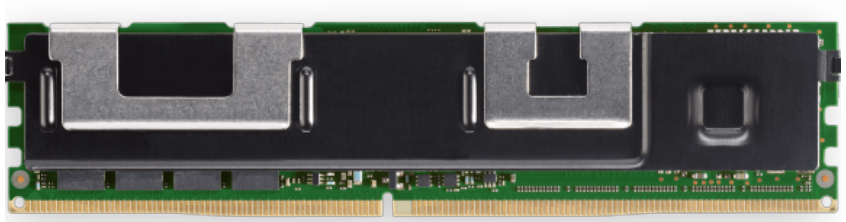

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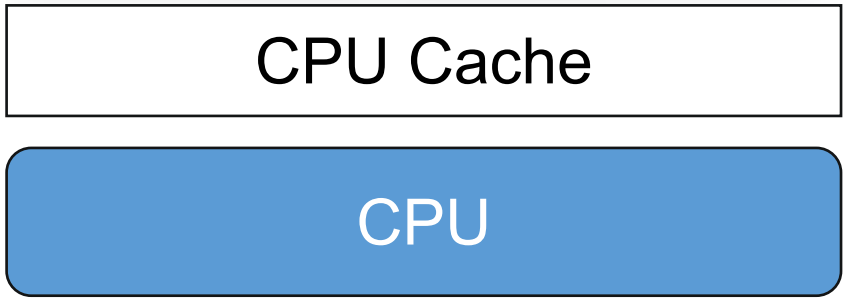


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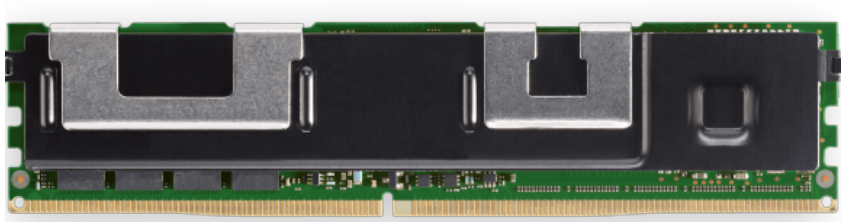

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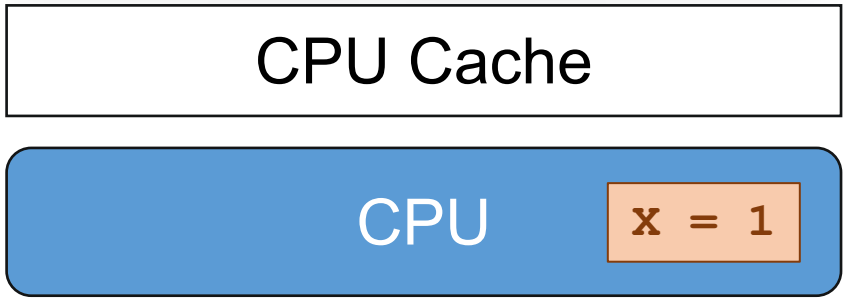


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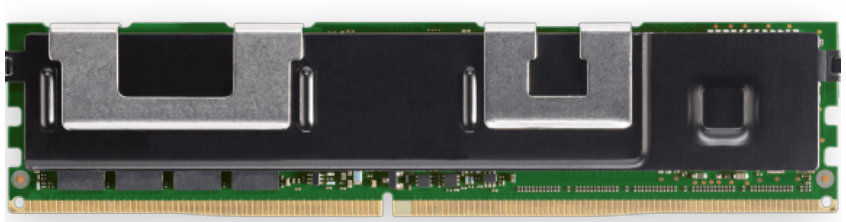

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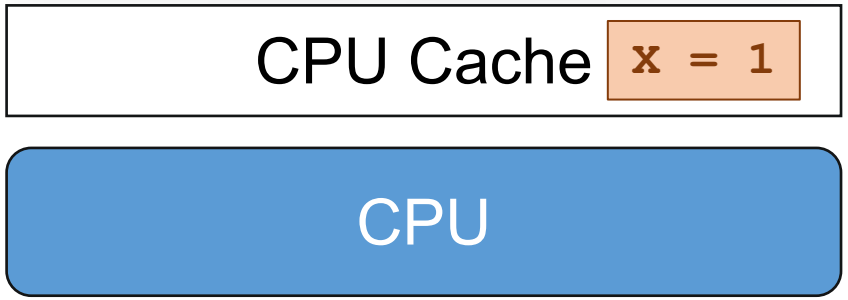


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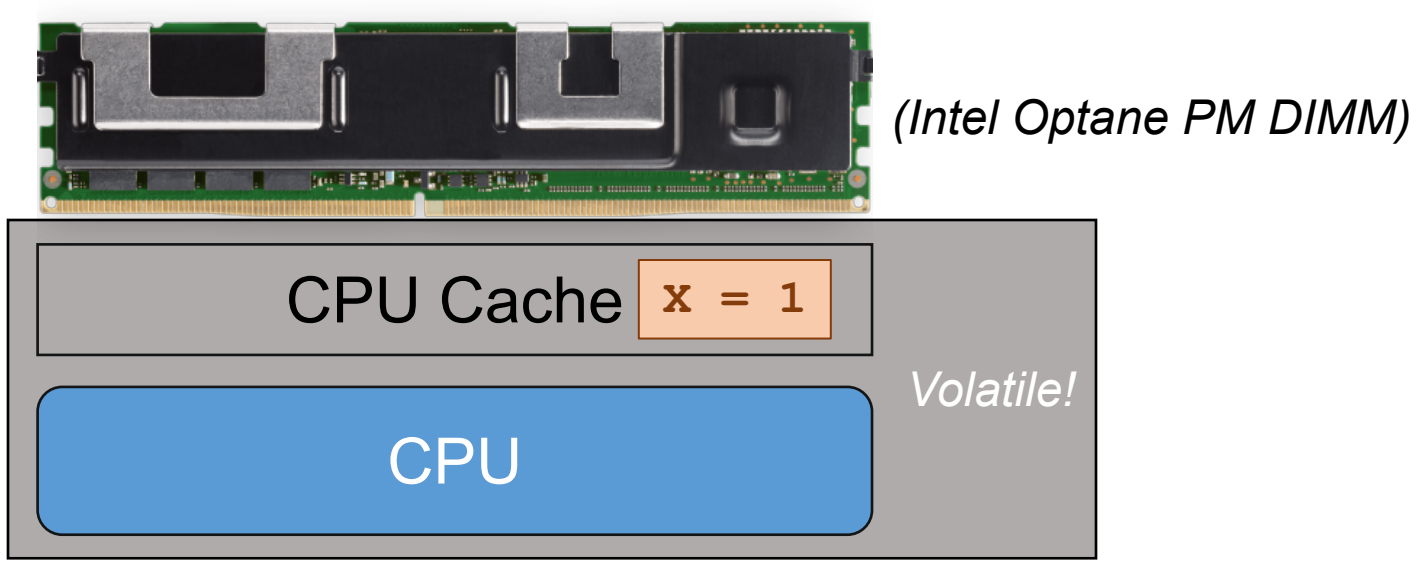


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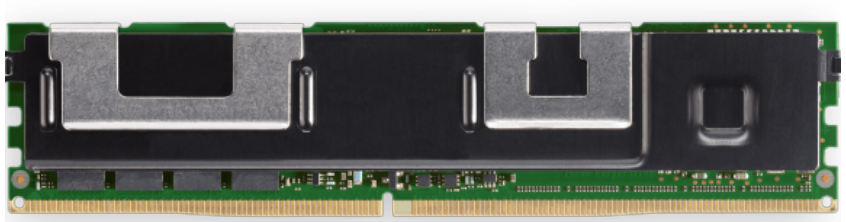

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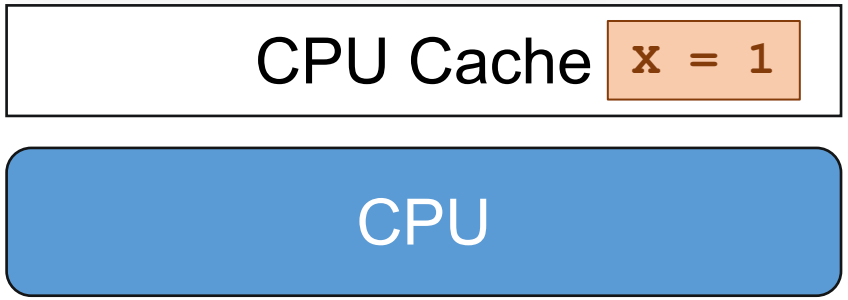


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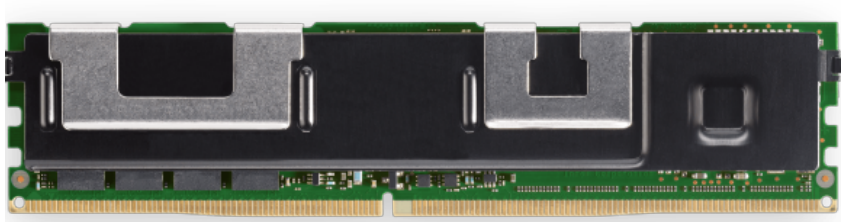

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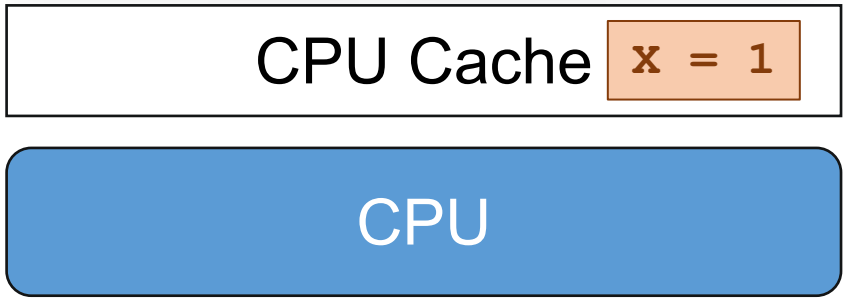


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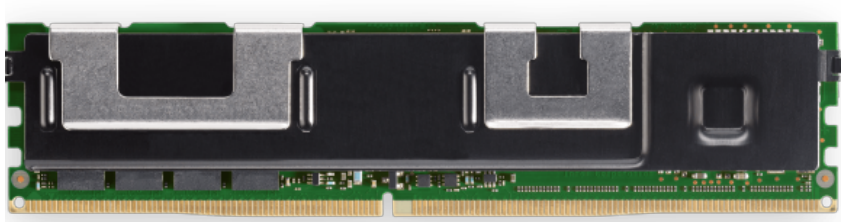

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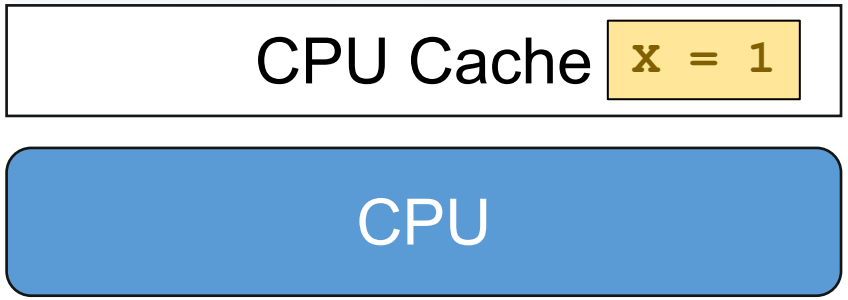


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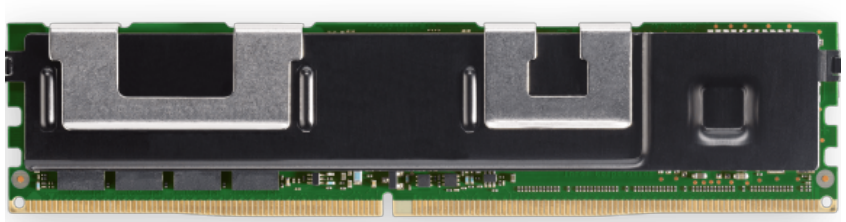

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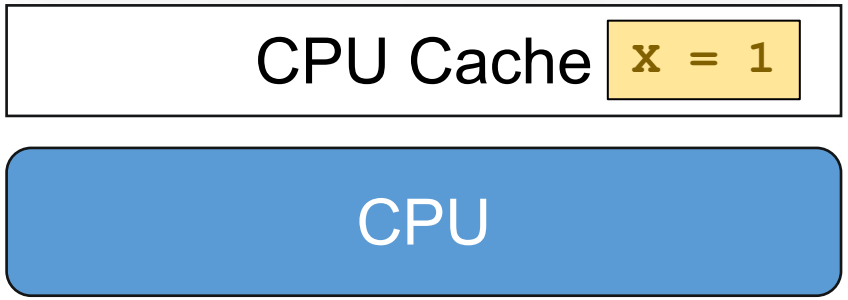


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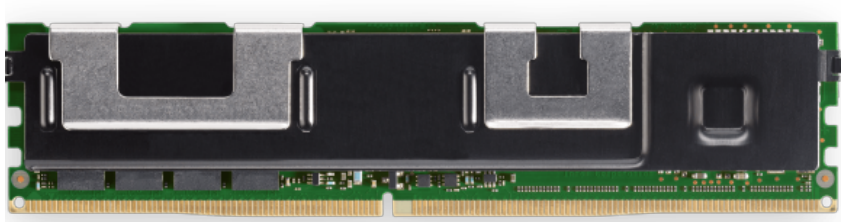

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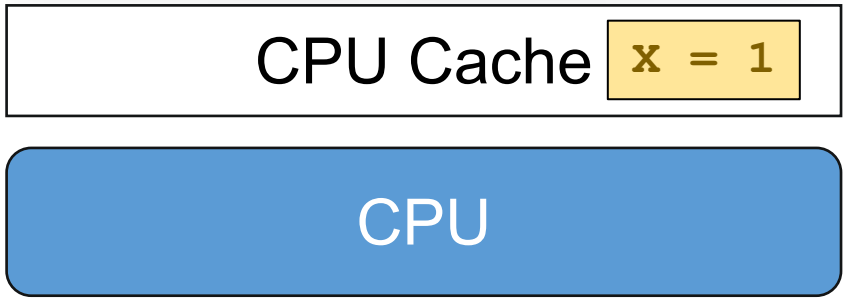


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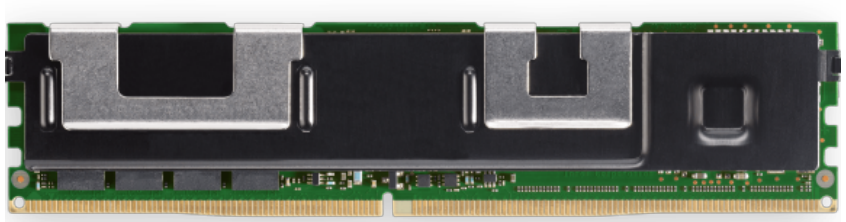

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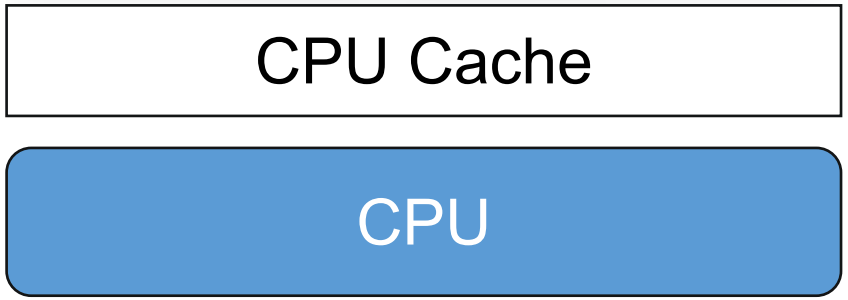


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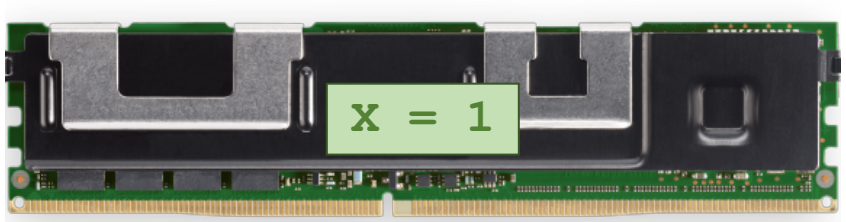

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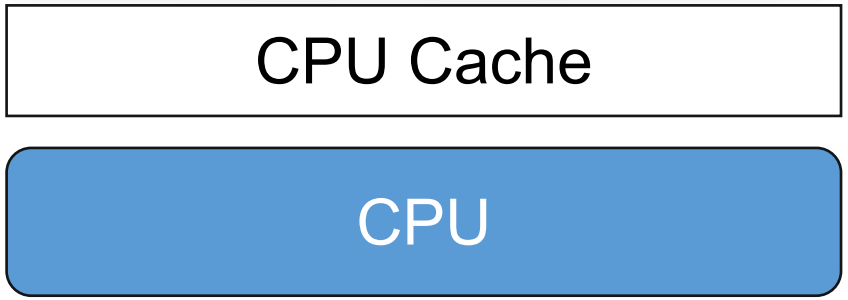


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Problem: PM Programming Requires Care

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- Writing correct ***and*** efficient PM code is hard

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1. store 1 into X
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```

```
1. store 1 into X
2. flush X
3. memory fence
...
4. store 1 into Y
5. flush Y
6. memory fence
...
```

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1. store 1 into X
2. flush X
3. memory fence
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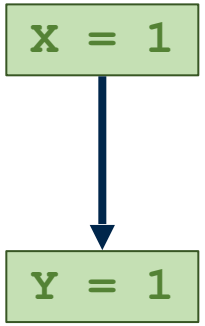

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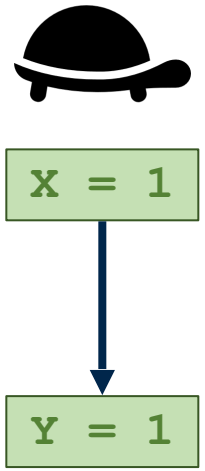

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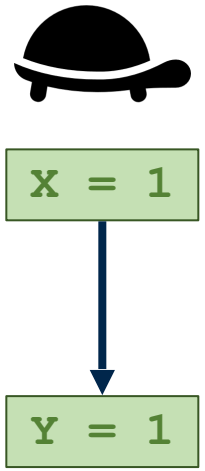


```
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2. store 1 into Y
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3. flush X
4. flush Y
5. memory fence
...
```

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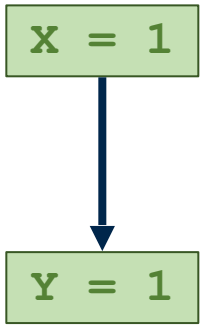


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1. store 1 into X
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3. flush X
4. flush Y
5. memory fence
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X = 1

Y = 1

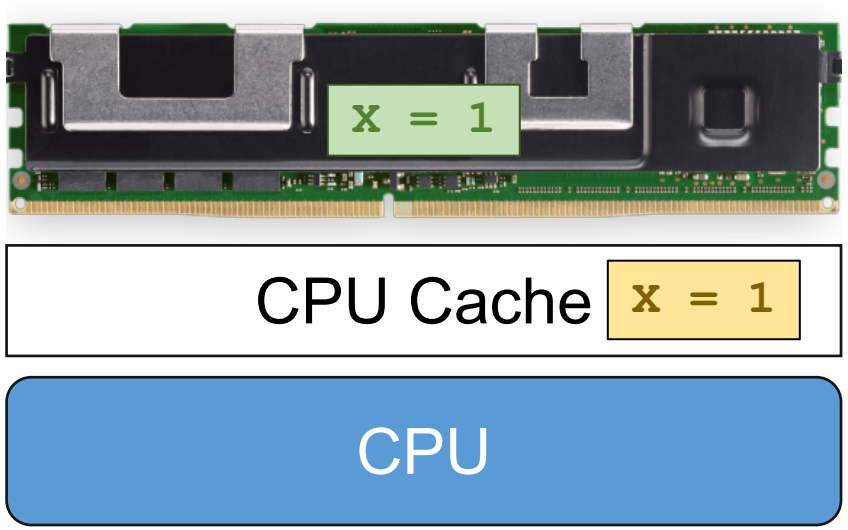
```
1. store 1 into X
2. store 1 into Y
...
3. flush X
4. flush Y
5. memory fence
...
```

X = 1

???

Y = 1

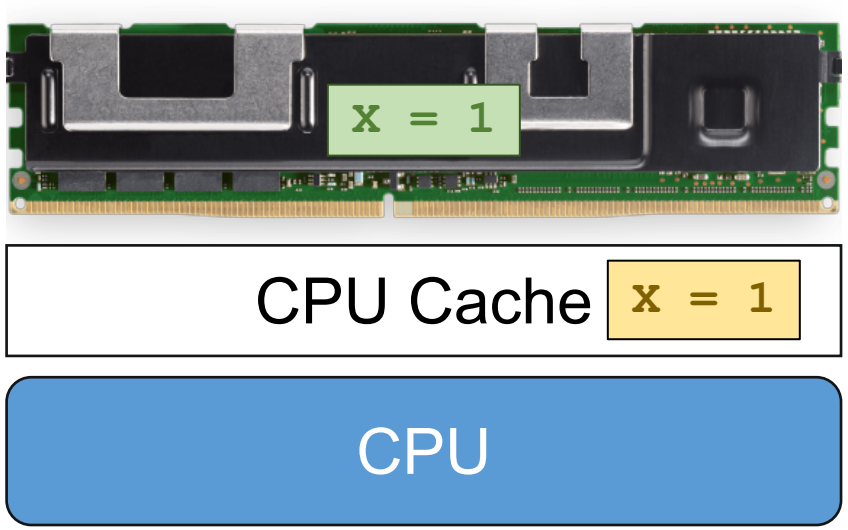
Problem: PM Programming Requires Care (cont.)



1. `store 1 into X`
2. `flush X`
3. `memory fence`

Problem: PM Programming Requires Care (cont.)

- Can have large consequences (data inconsistency, loss)

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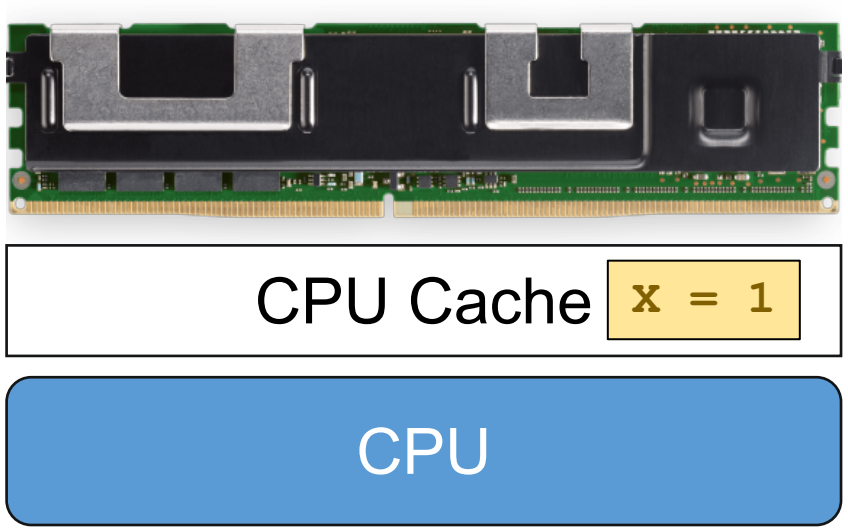


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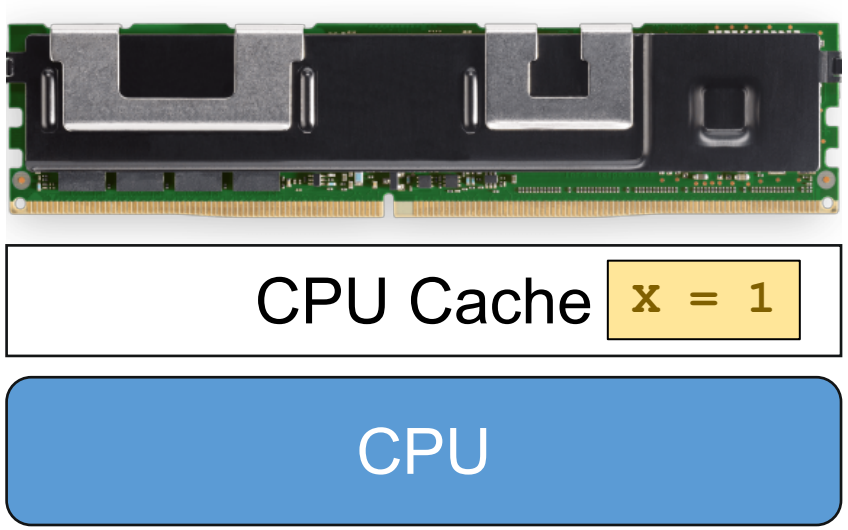


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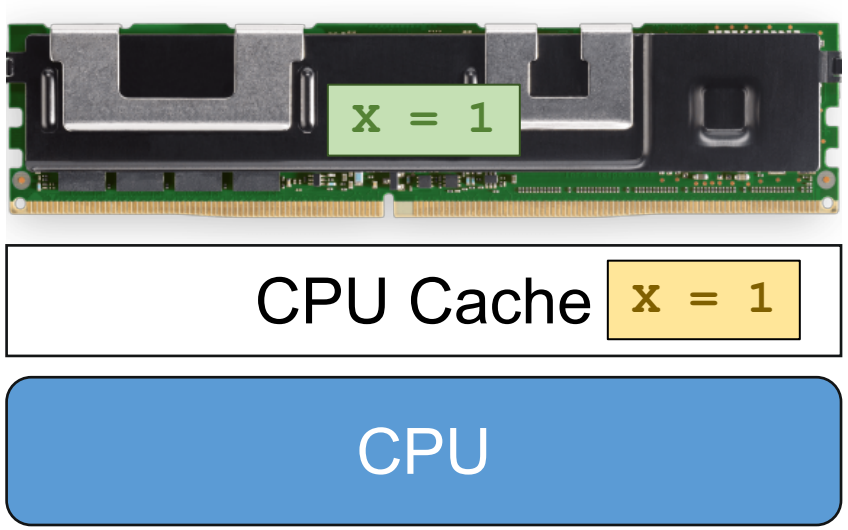


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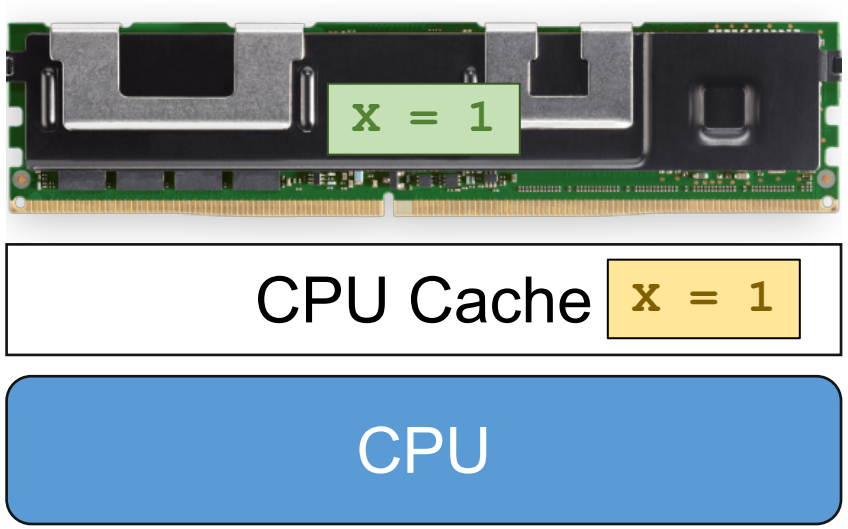
- Can have large consequences (data inconsistency, loss)
- Resulting bugs are hard to find (opaque, non-determinism)

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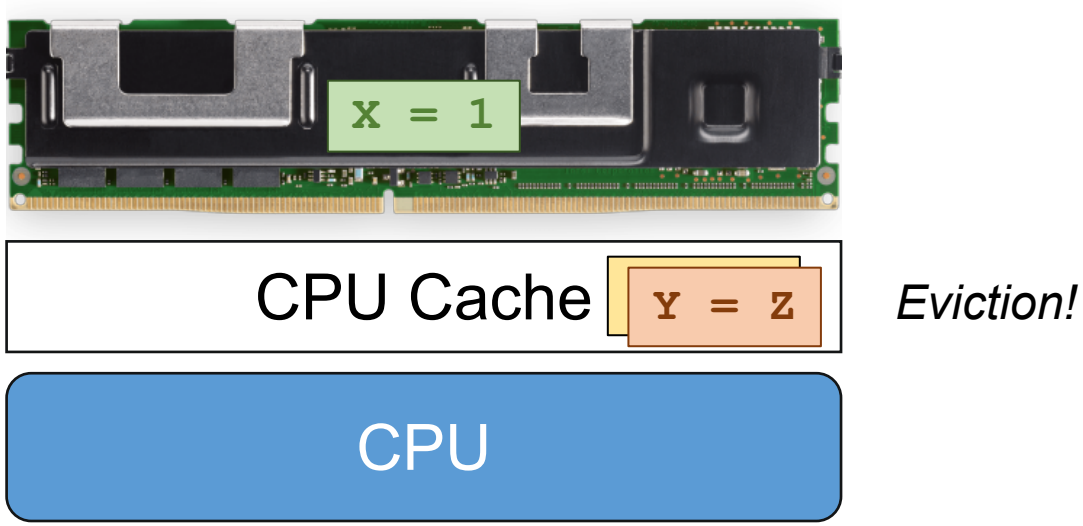


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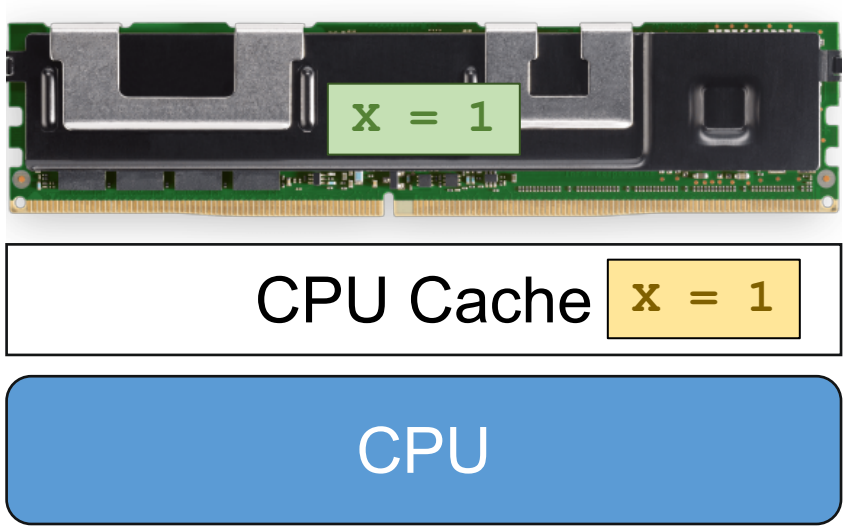


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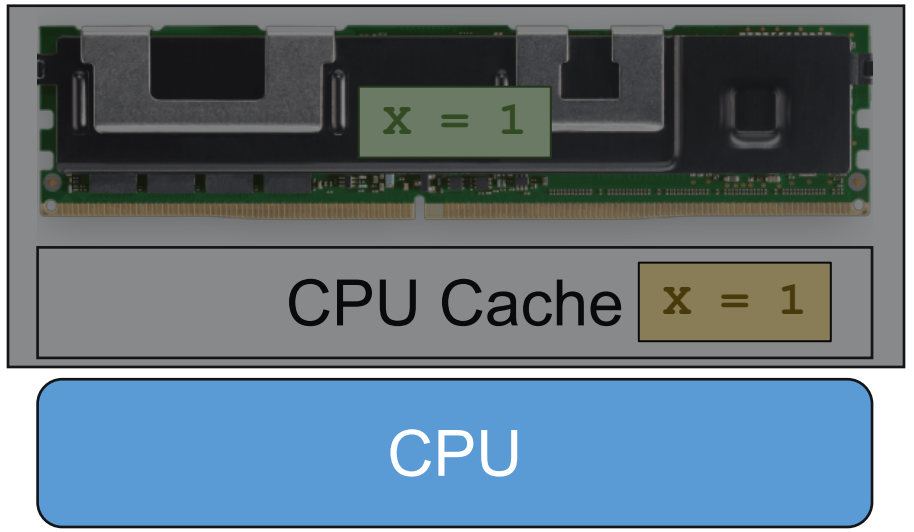


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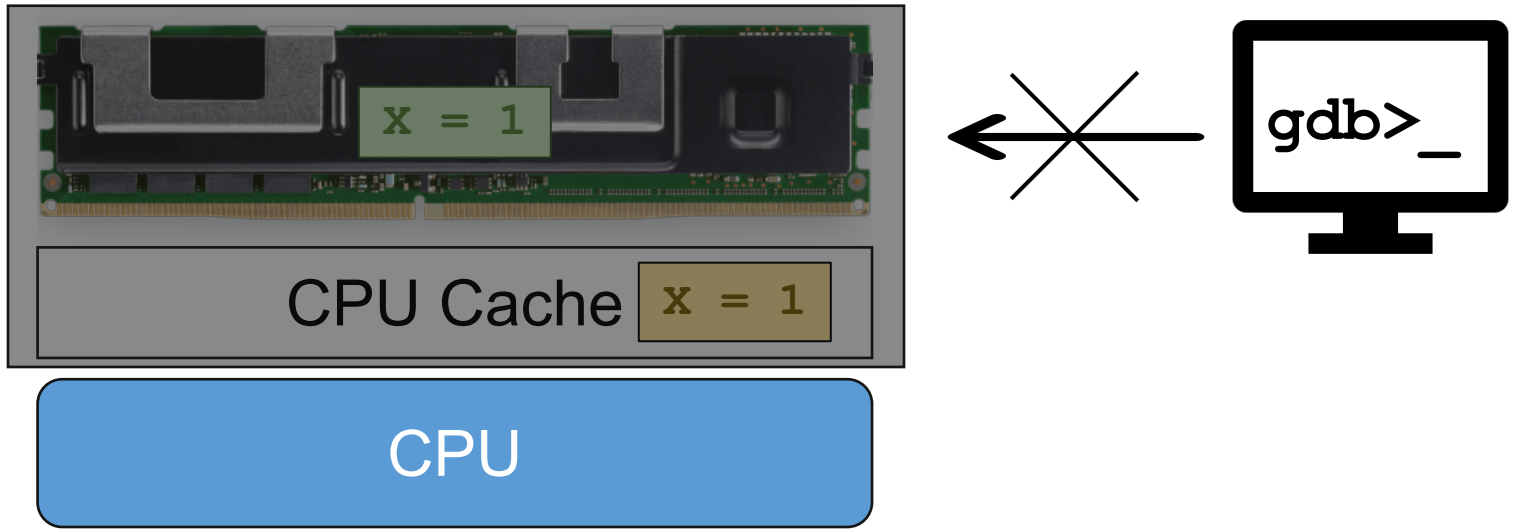


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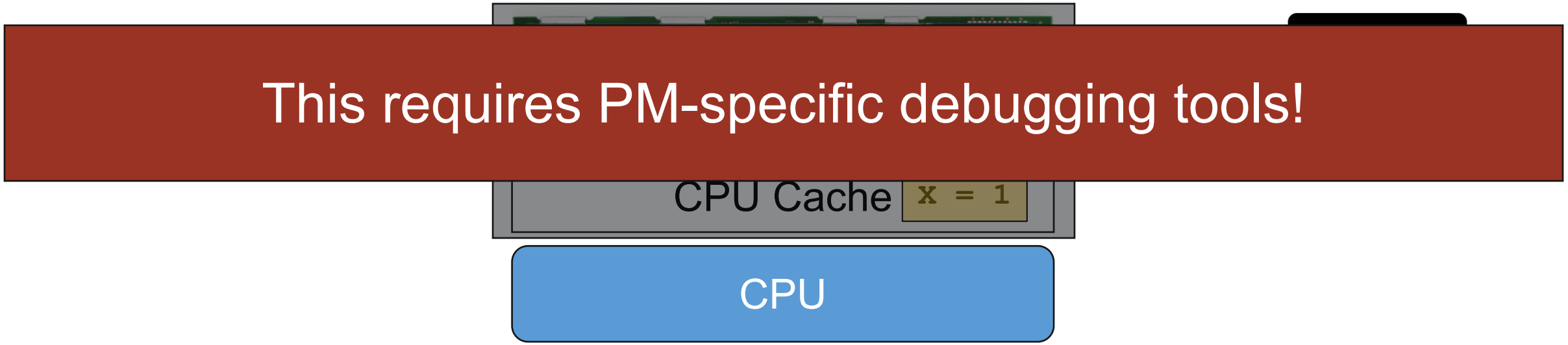


```
1. store 1 into X
2. flush X
3. memory fence
```

Prior Work

Prior Work

Yat: A Validation Framework for Persistent Memory Software

Philip Lantz, Subra

https://www.usenix.or

Development Topics & Technologies

intel

ors with Pmemcheck

Cross-Failure Bug Detection in Persistent Memory Programs

Sihang Liu, Korakit Seemakhupt, Yizhou Wei, Thomas Wenisch, Aasheesh Kolli, and Samira Khan
The International Conference on Architectural Support for Programming Languages and Operating Systems (ASPLOS), 2020

Intel® Inspector

Deliver reliable applications. Locate and debug
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Sihang Liu, Yizhou Wei, Jishen Zhao, Aasheesh Kolli, and Samira Khan
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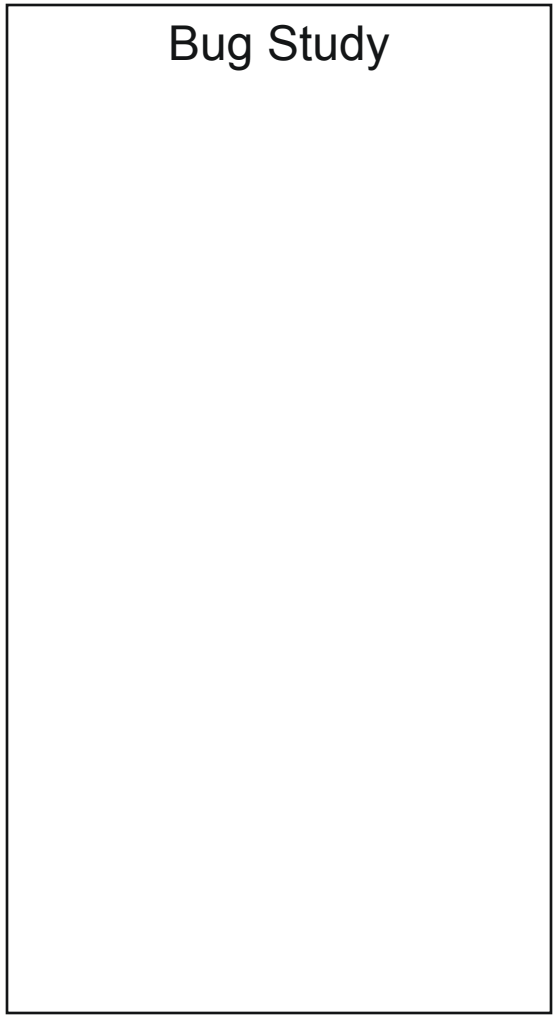

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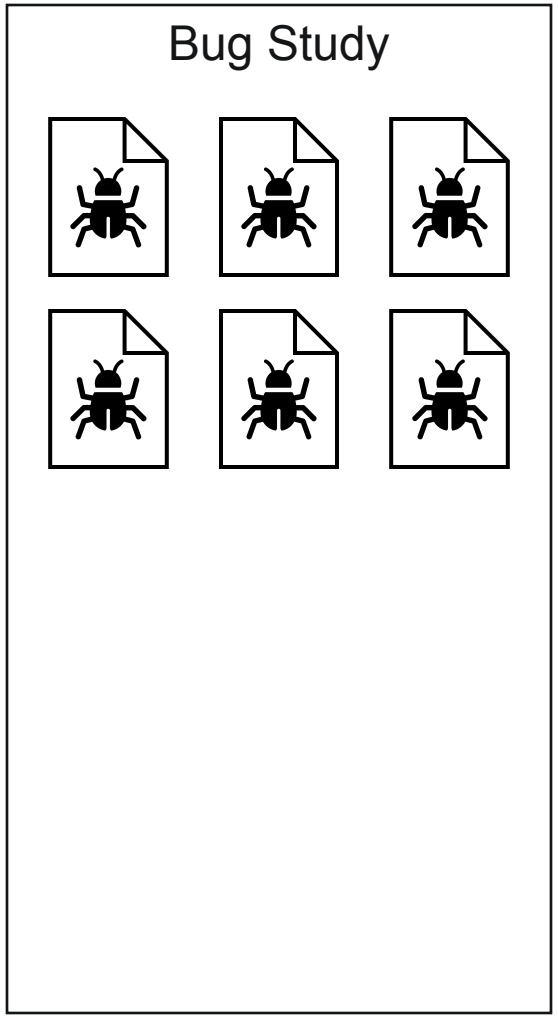

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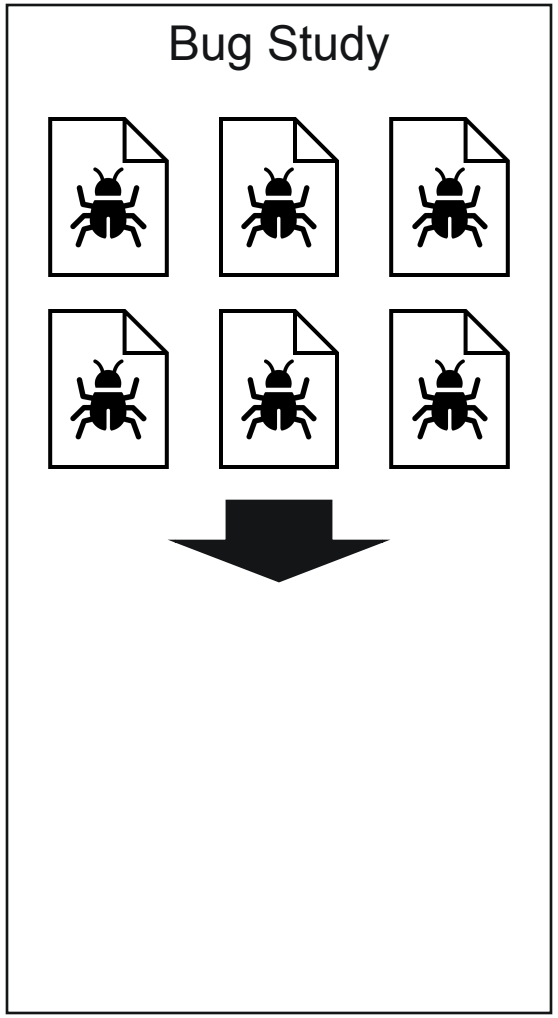

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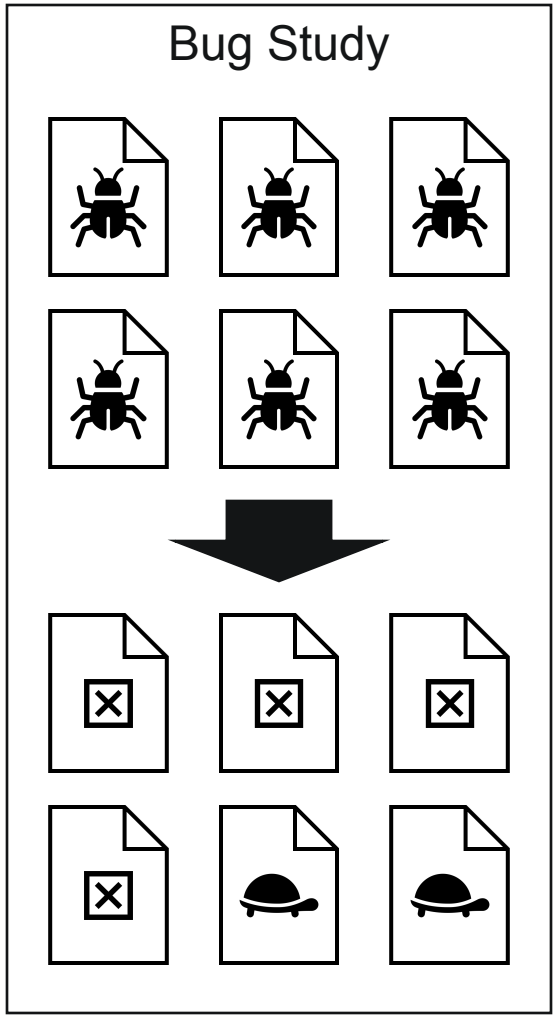

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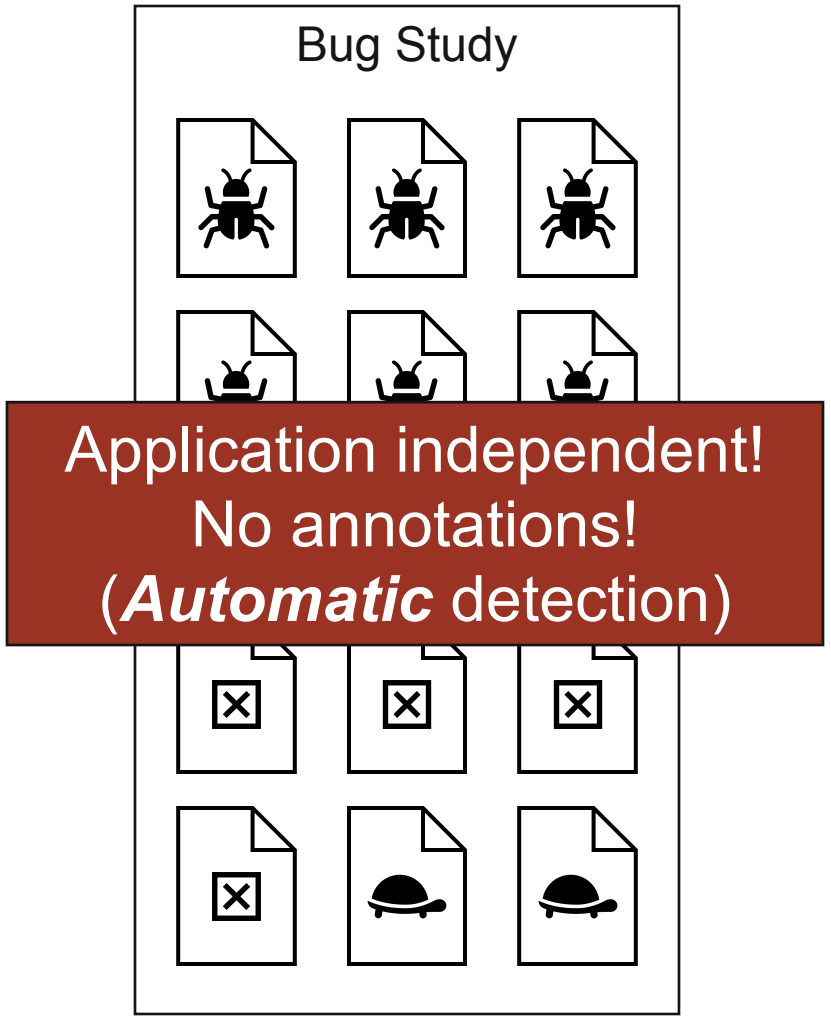

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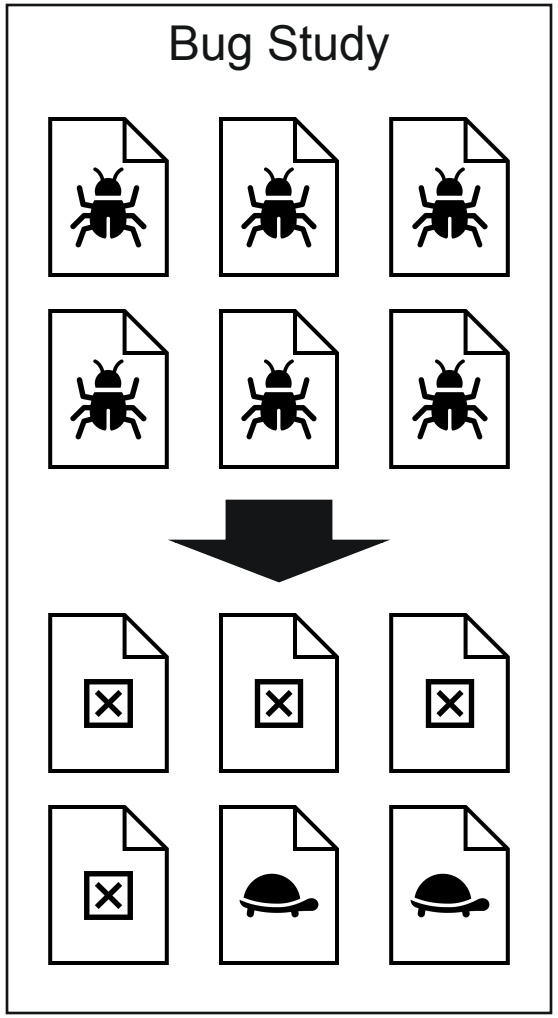

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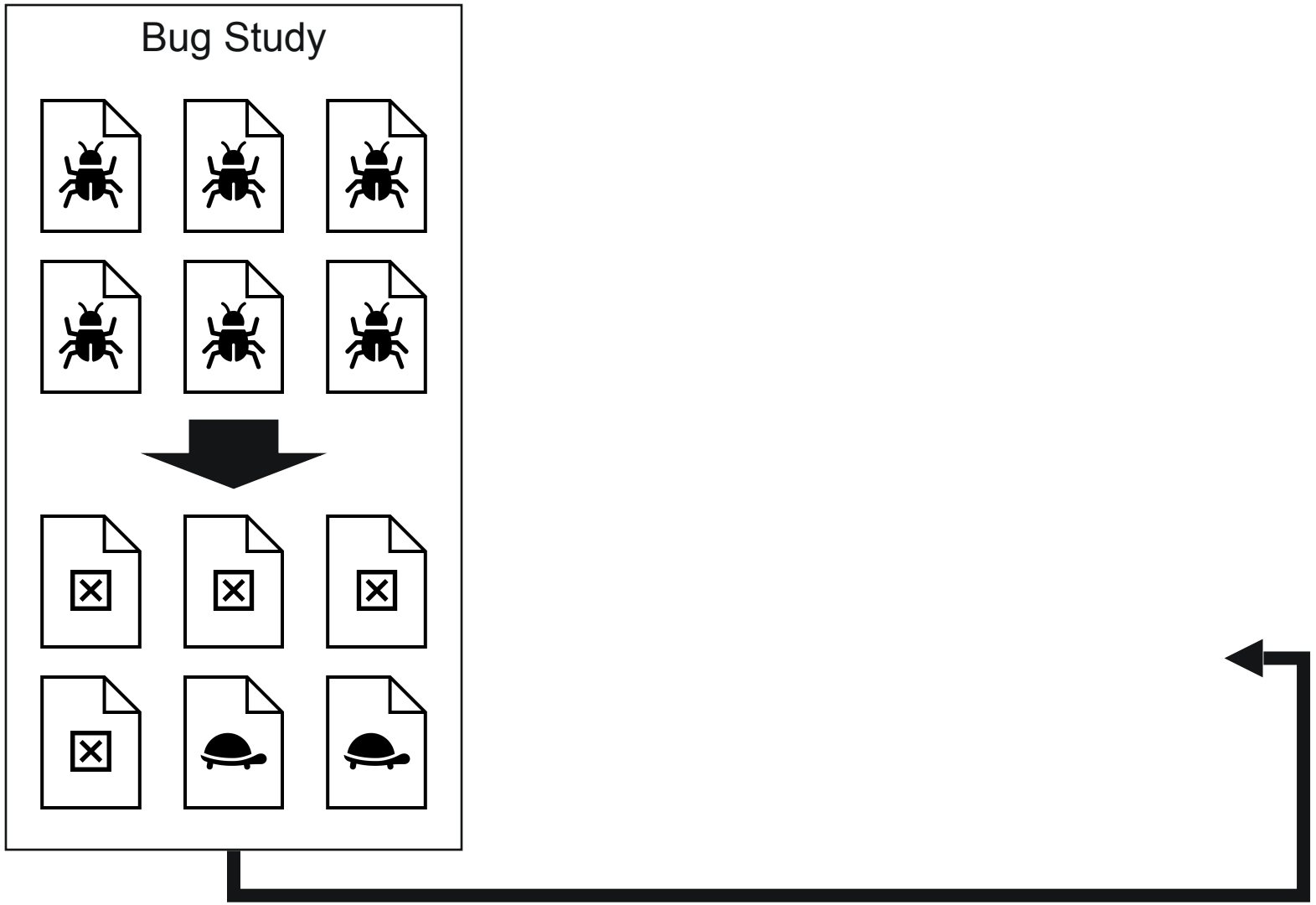

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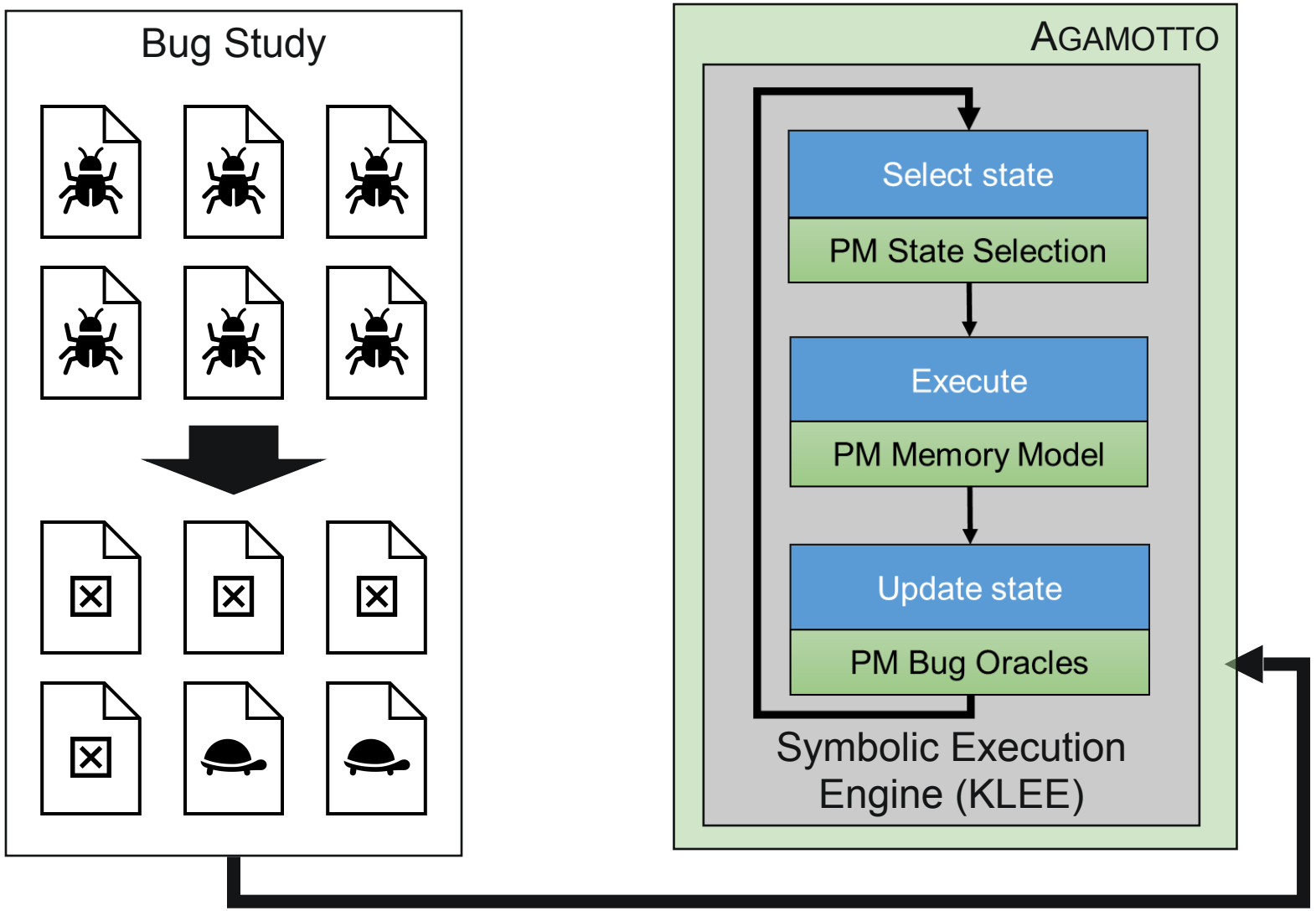

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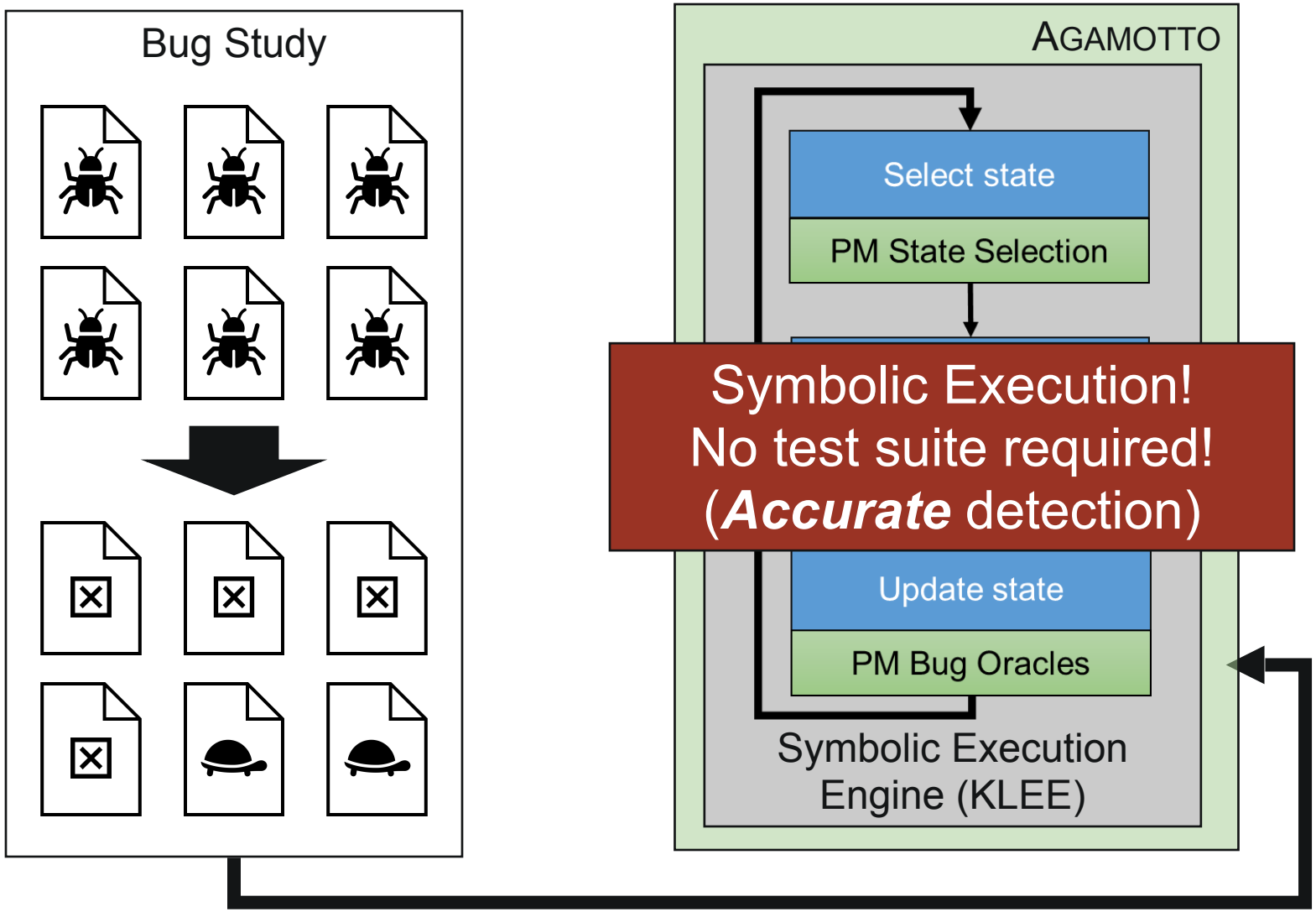

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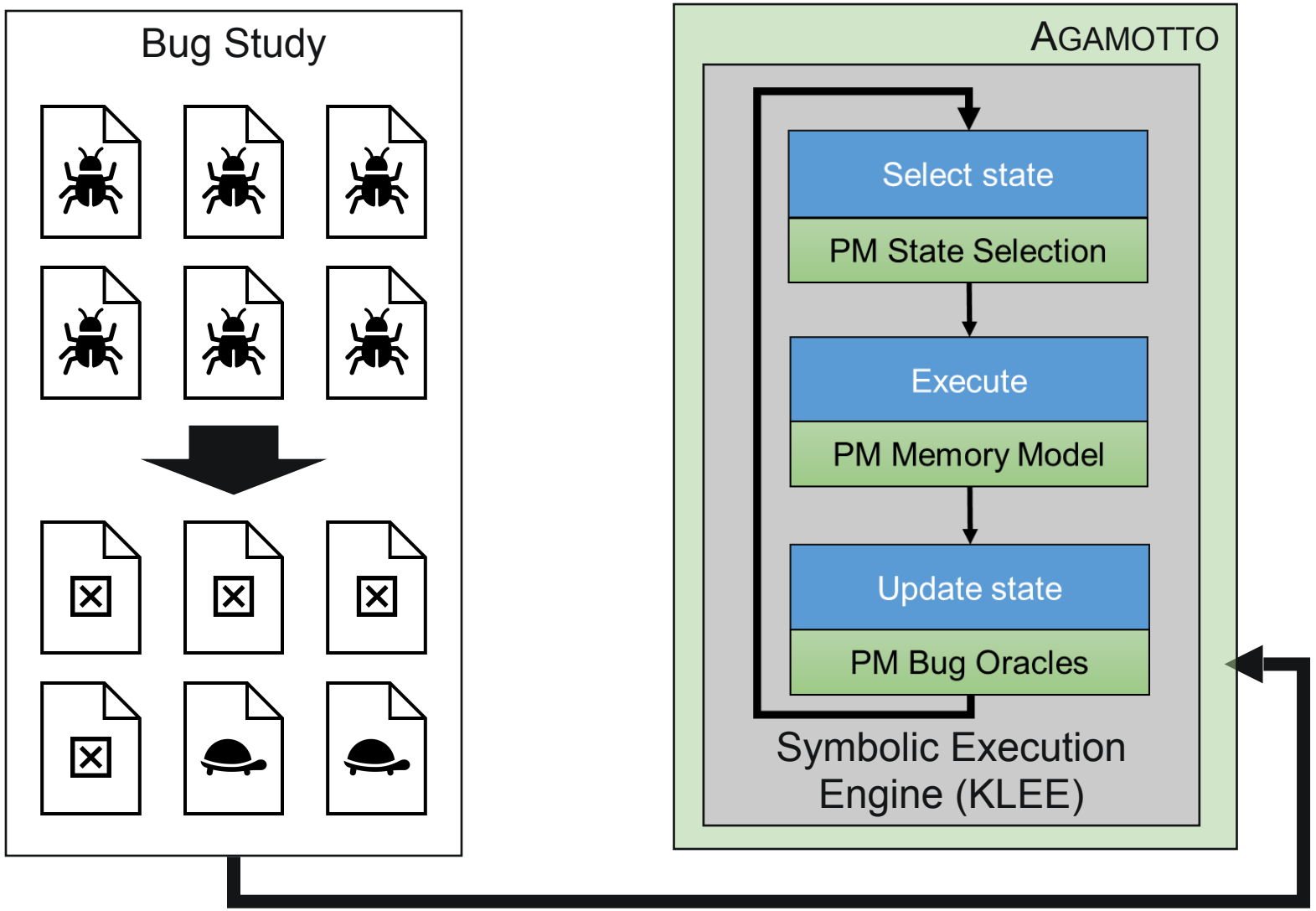

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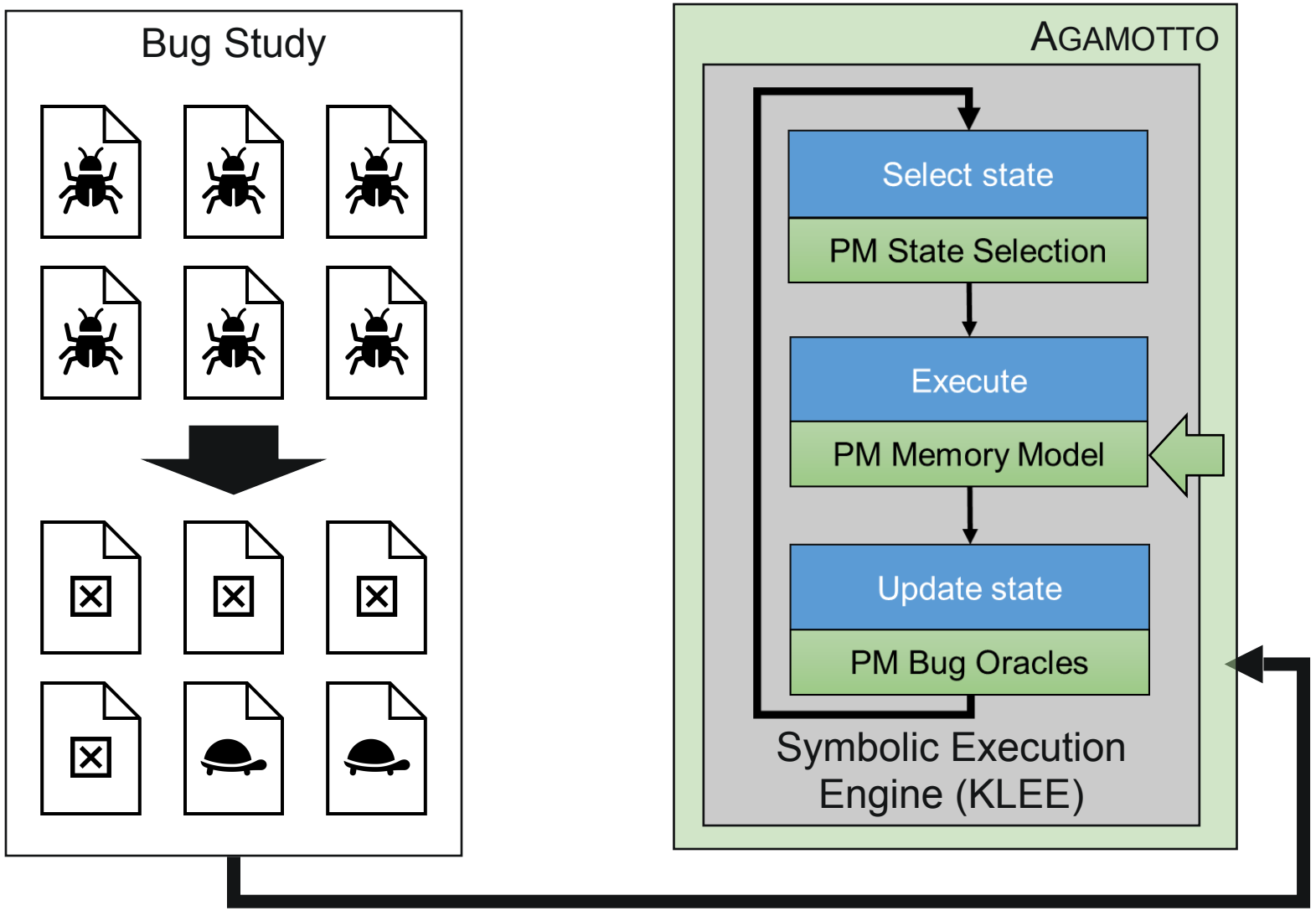

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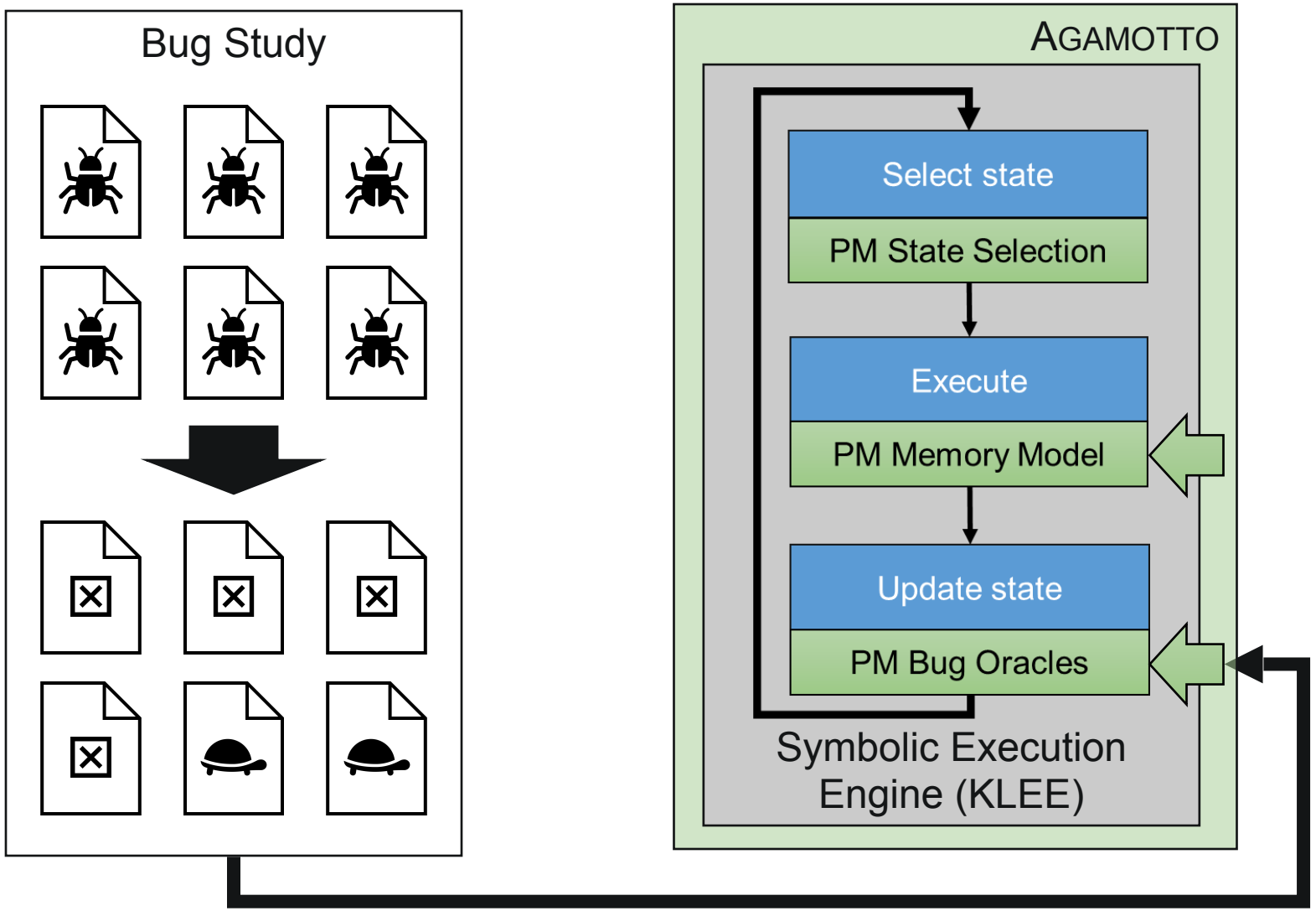

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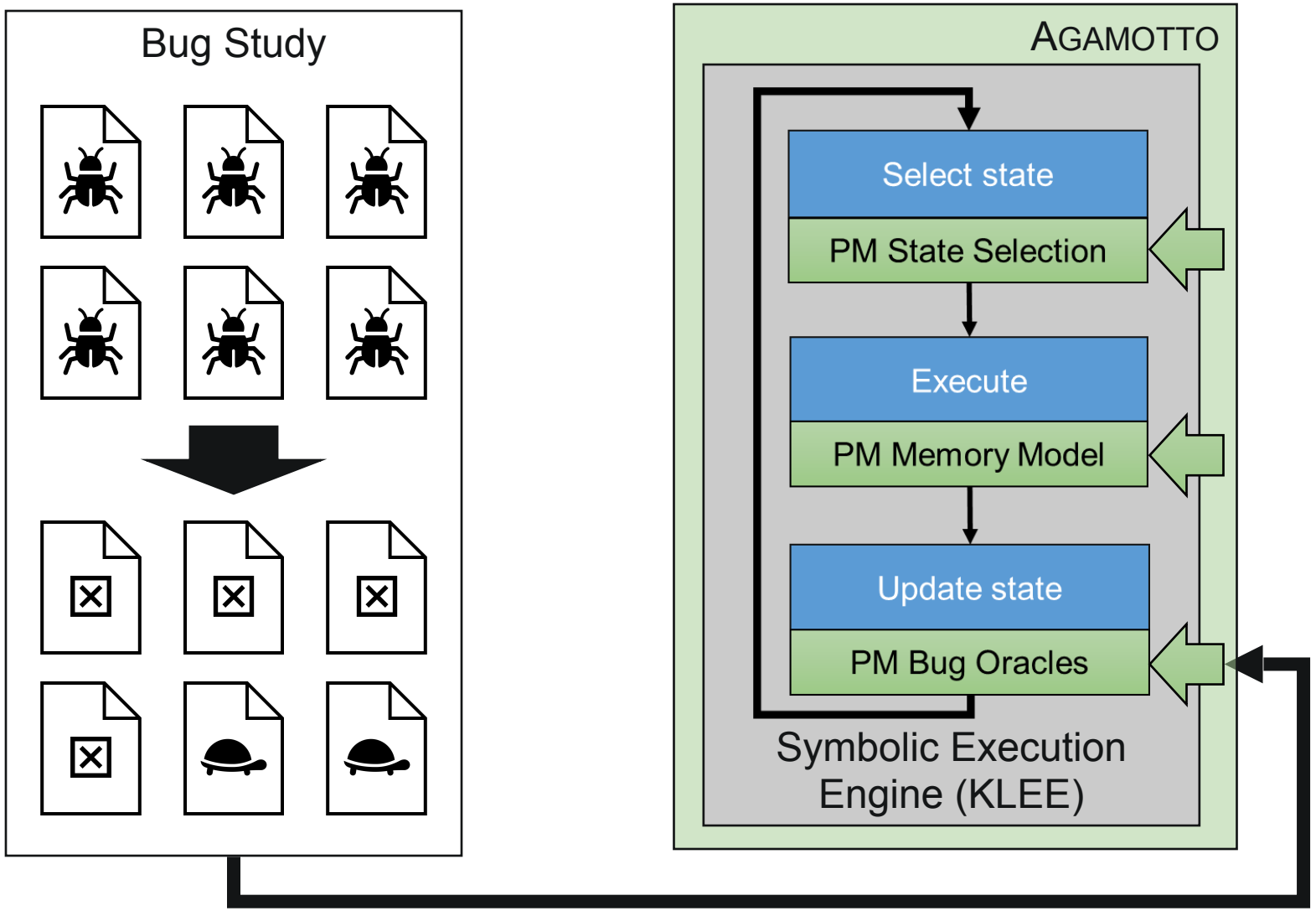

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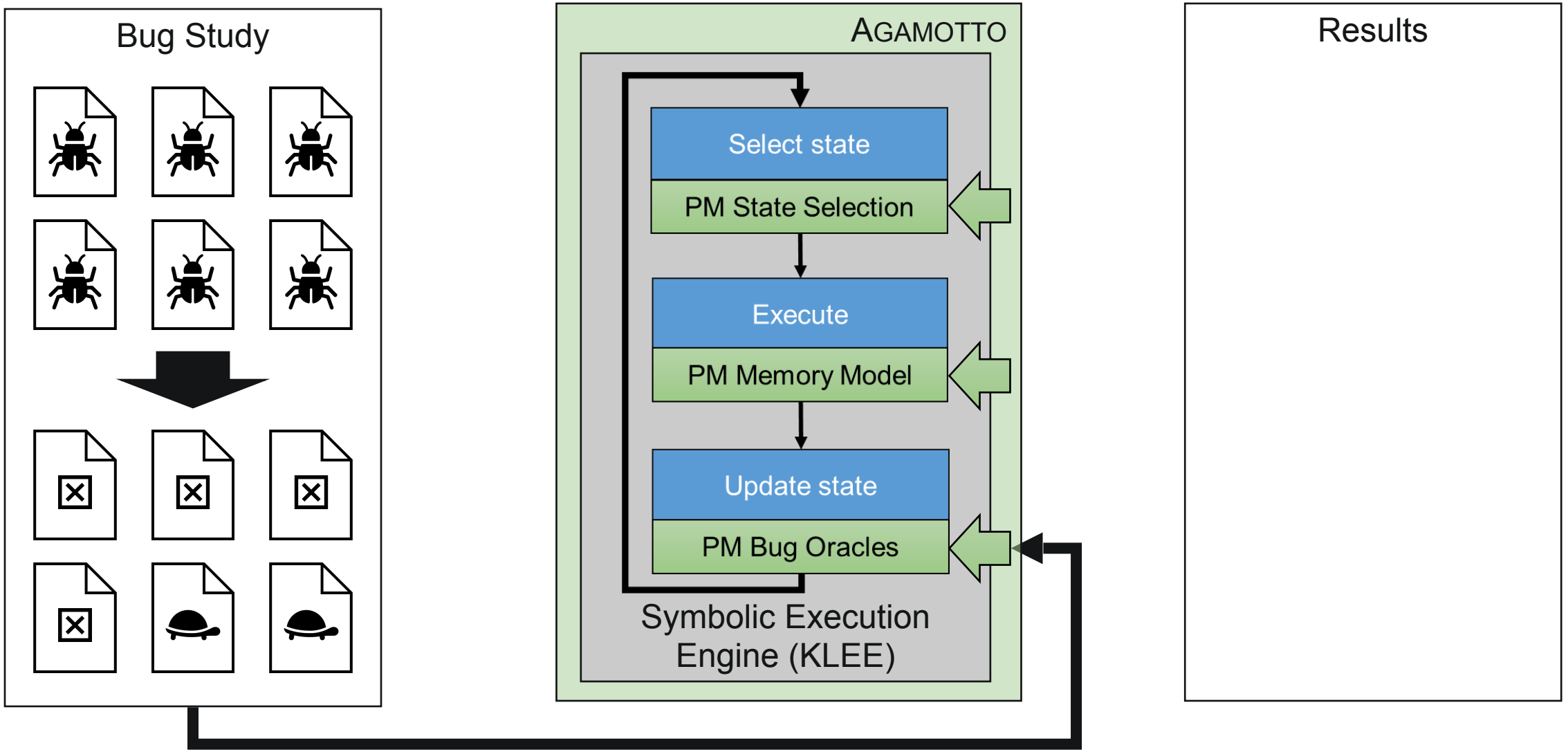

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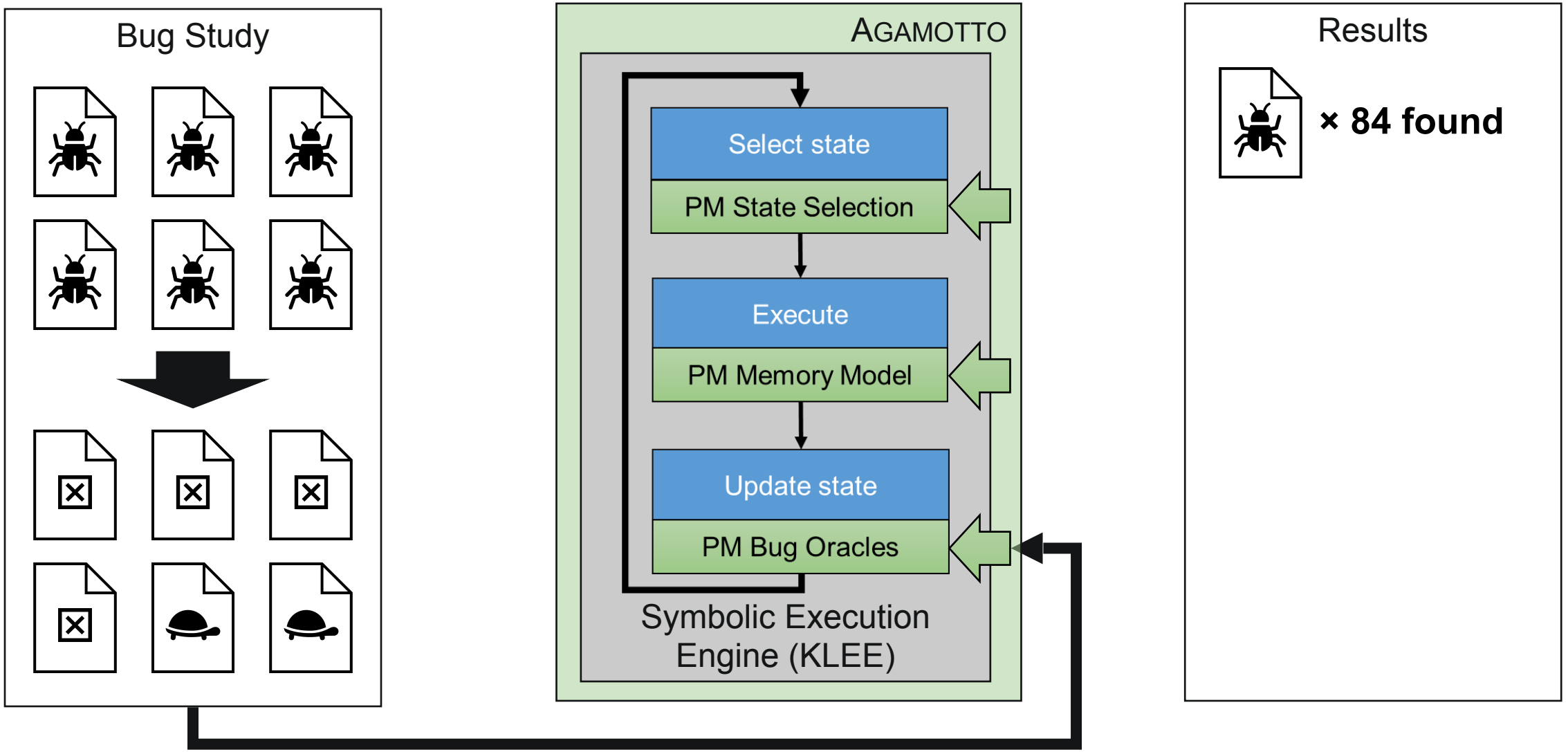

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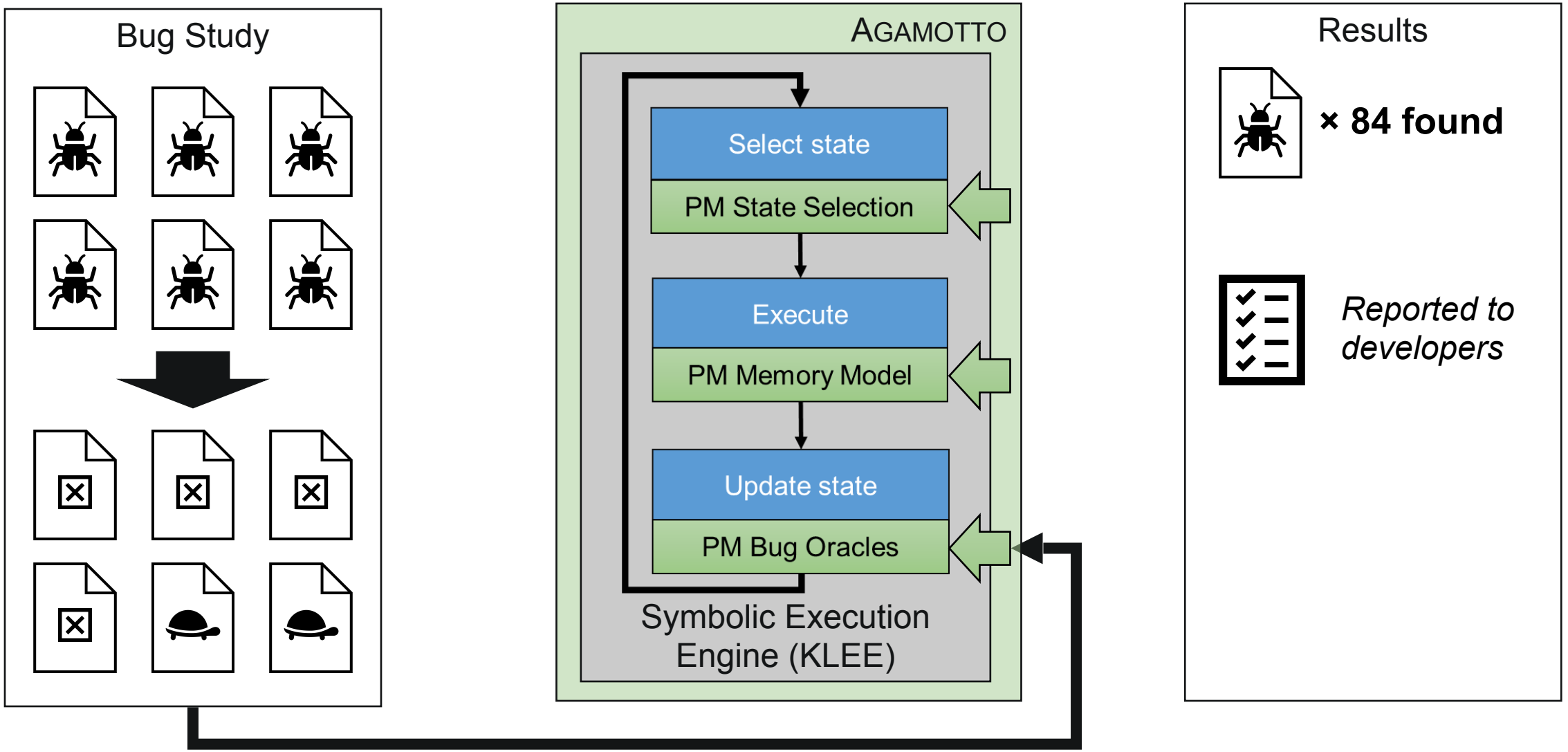

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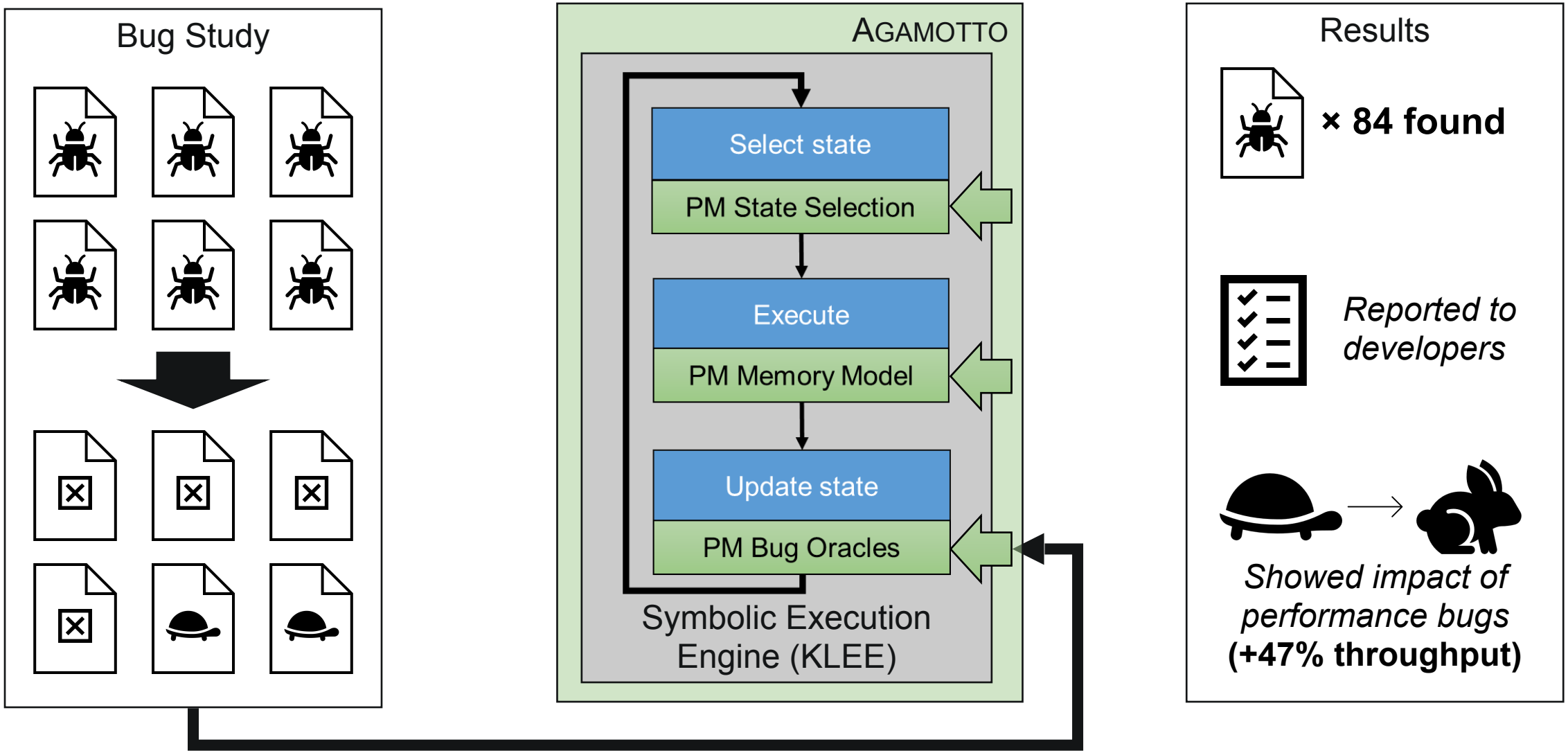

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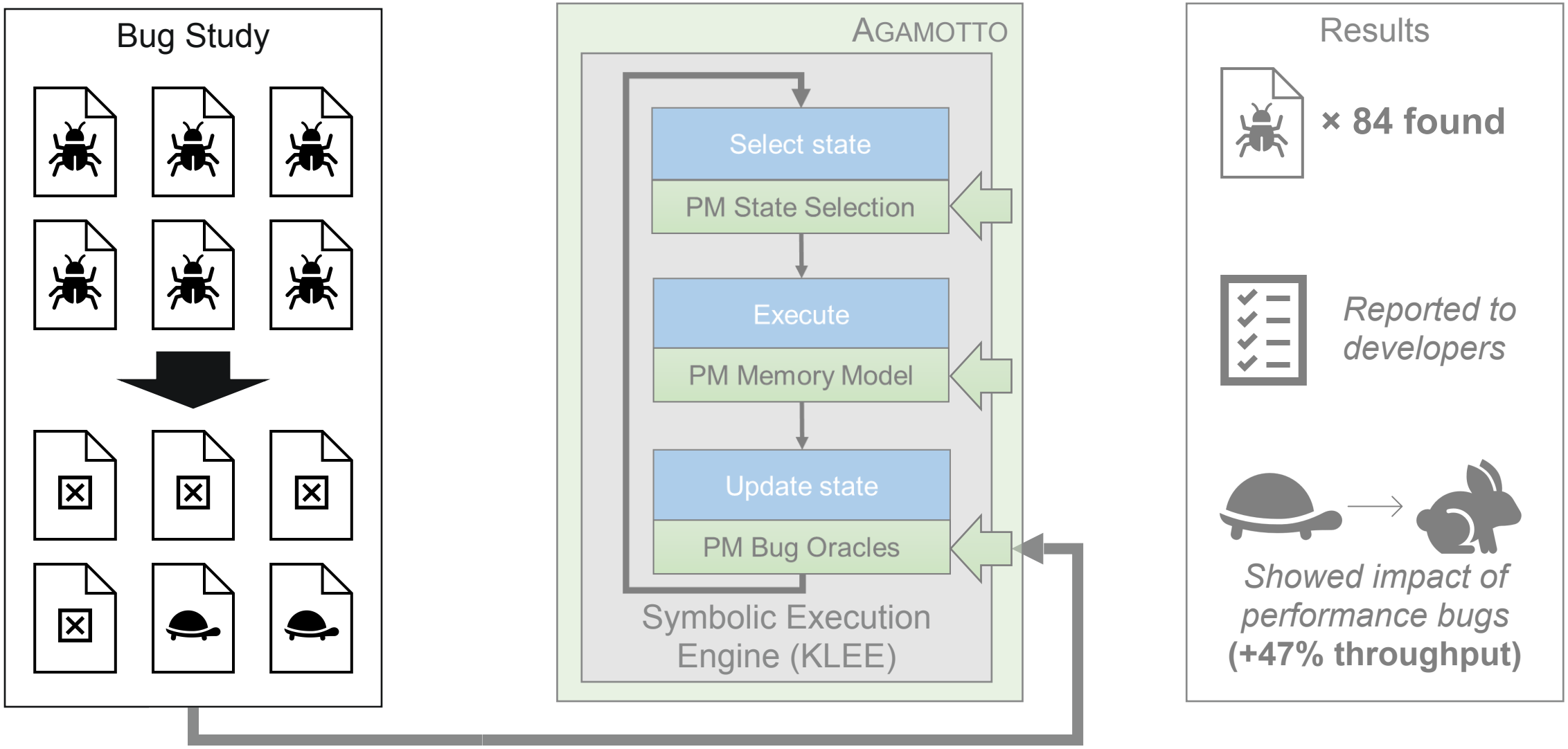
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  - Most from PMDK's issue tracker
  - Also analyzed bugs from PMTest, XFDetector

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- Surveyed 63 previously recorded bugs
  - Most from PMDK's issue tracker
  - Also analyzed bugs from PMTest, XFDetector
- Identified two predominant patterns
  - Later use these to build bug detectors (i.e., bug *oracles)*

(1) Missing flush/fence

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- Example: `oid` should be made durable, but never is

```
1   // oid is a pointer to PM
2   if (if_free != 0) {
3       *oid = NULL;
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- Not making updates explicitly durable in PM
- Not tied to any application-specific logic
- Accounts for **79%** of the bugs in our survey (50/63)
- Not guaranteed to be false-positive free
  - We don’t discover any in our testing

(2) Redundant flush/fence

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- Example: overuse of flush/fence instructions

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1  // oid is a pointer to PM
2  if (if_free != 0) {
3      *oid = NULL;
4      FLUSH(*oid);
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- Unnecessary use of durability mechanisms
- Is a performance issue regardless of program logic
- Accounts for **11%** of the bugs in our survey (7/63)

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- Two patterns, **90%** of the bugs (57/63), *are application independent!*
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- Application-specific bugs, **~10%** of the bugs (6/63), are still important
  - Allow developers to define their own patterns!

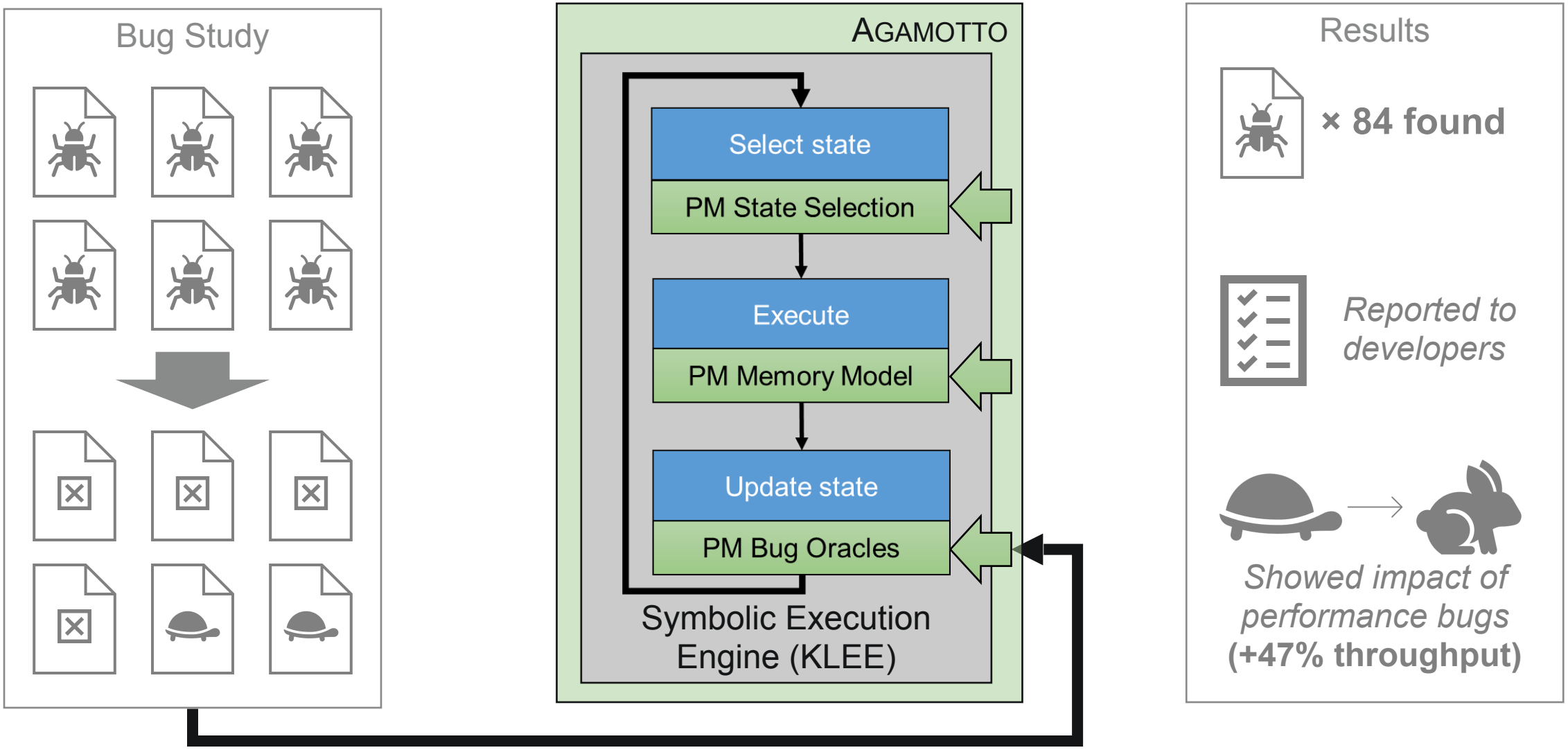
Bug Study Conclusions

- Two patterns, **90%** of the bugs (57/63), *are application independent!*
  - Can automated their detection

Pattern-based detection allows us to avoid source code modifications!

  - Allow developers to define their own patterns!

Overview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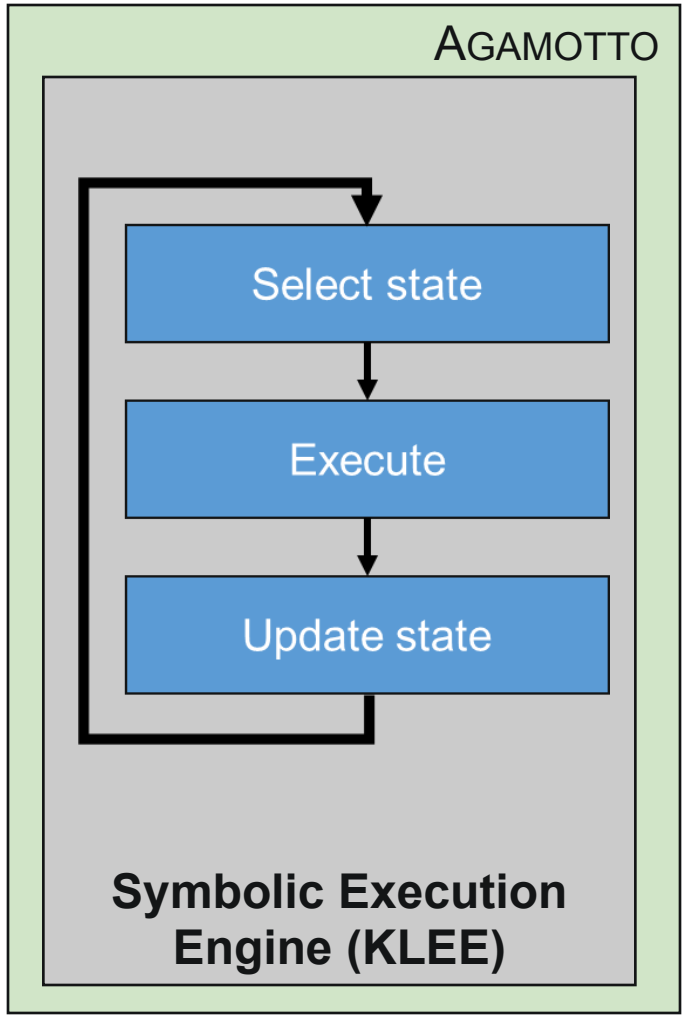
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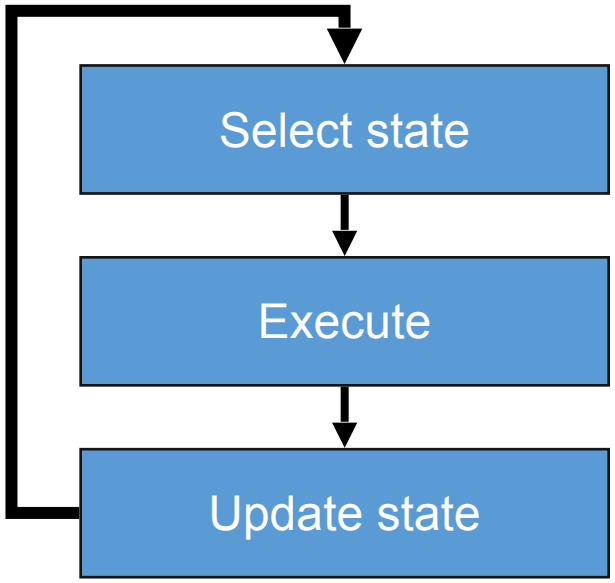


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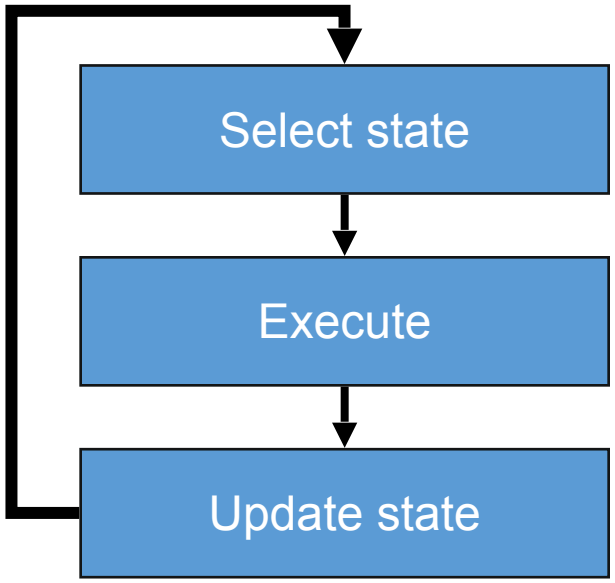

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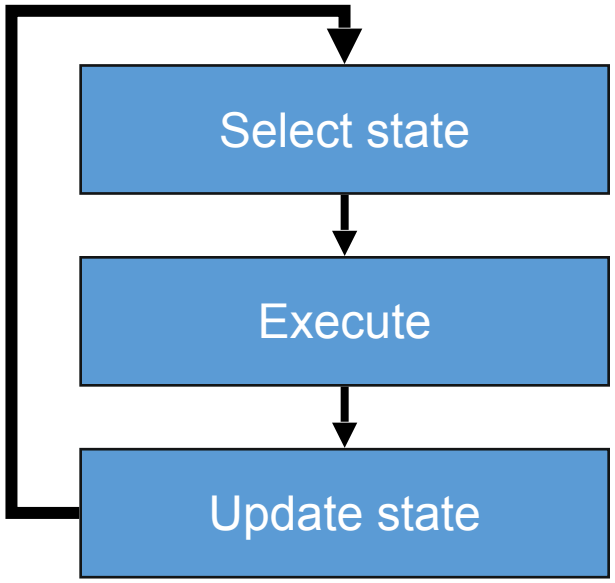

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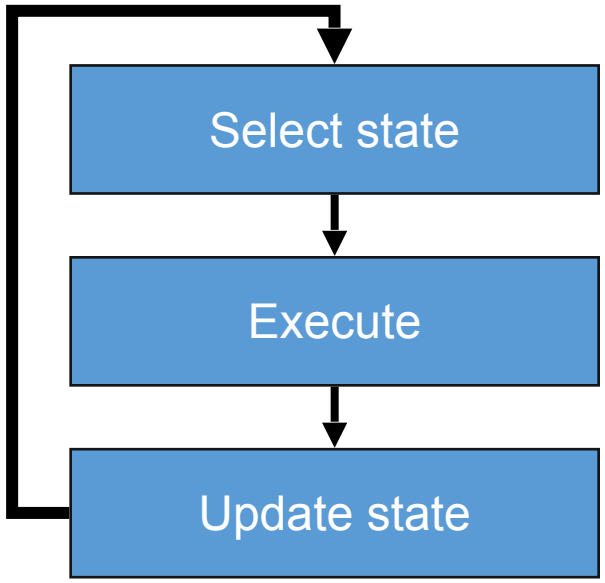

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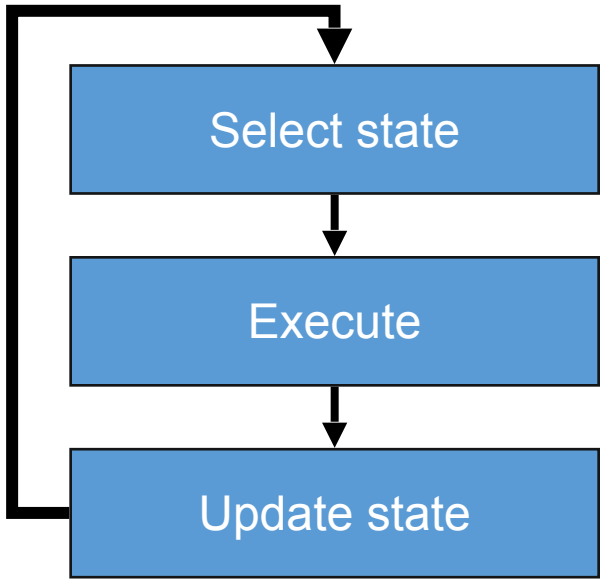

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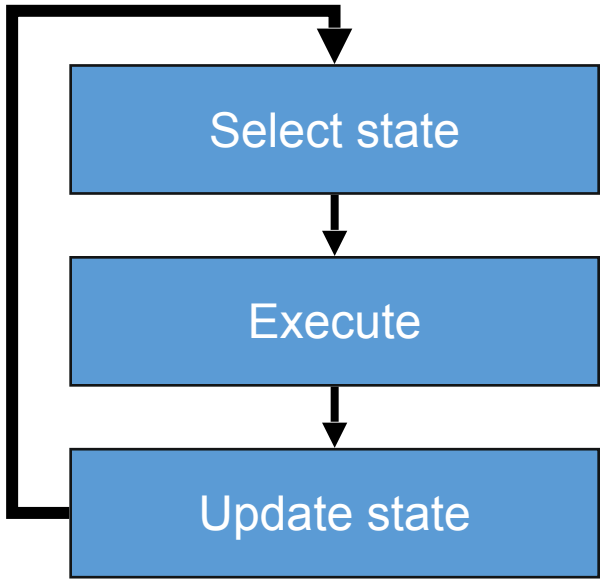

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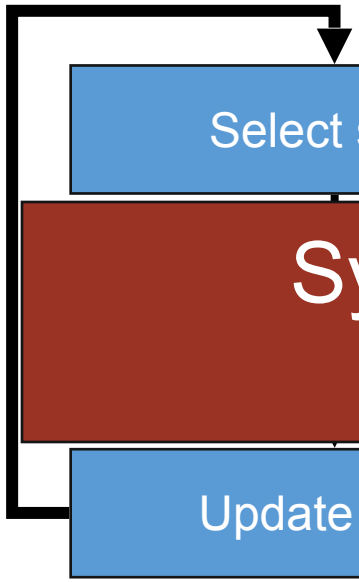


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Symbolic execution gives us high code coverage!
(no need for extensive test suites)

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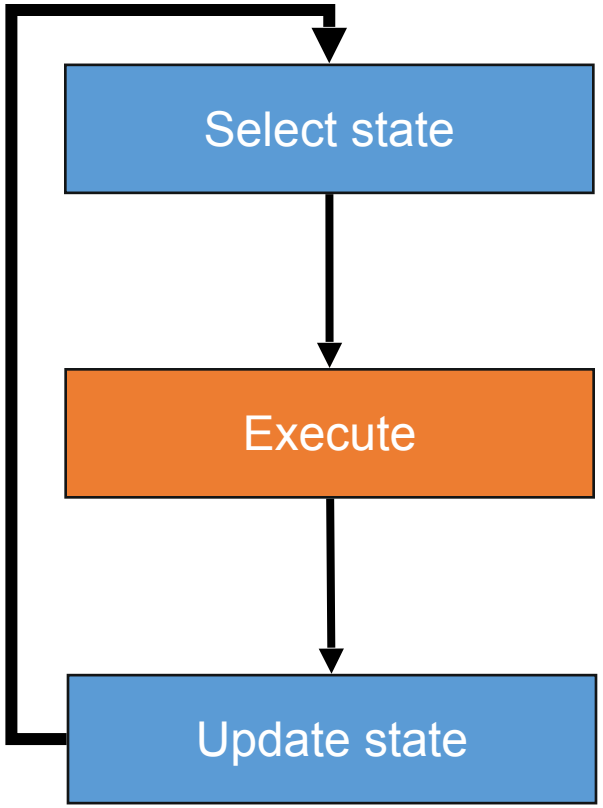

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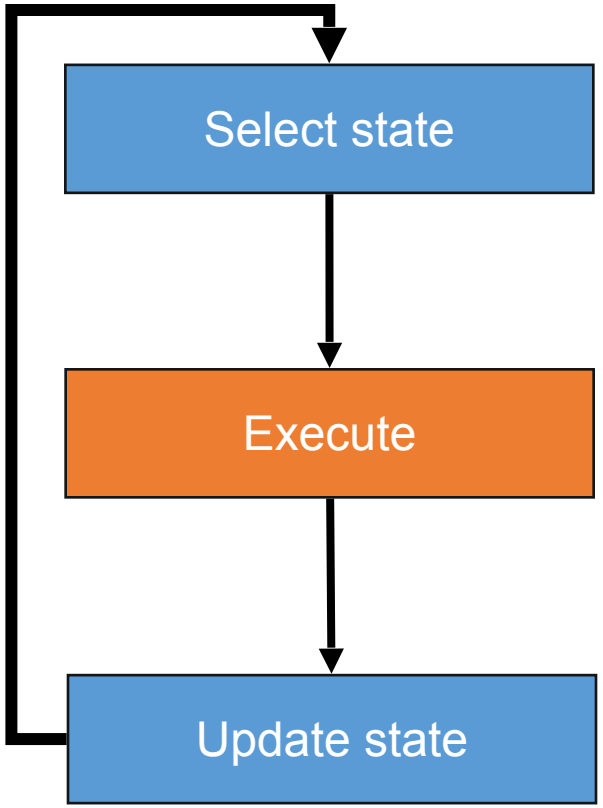


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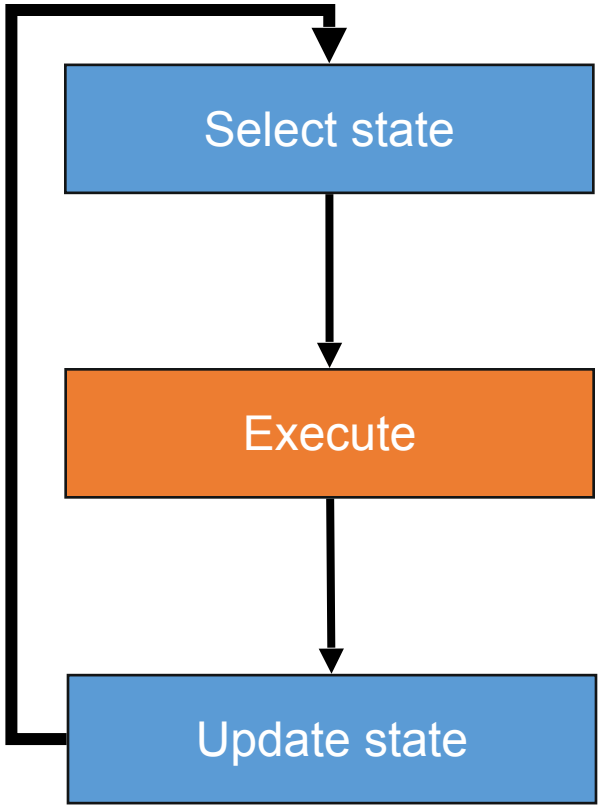


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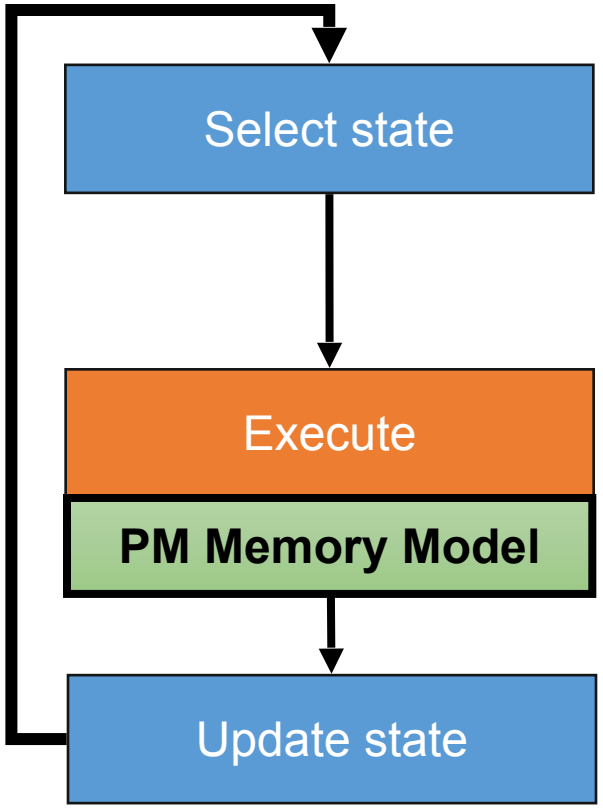


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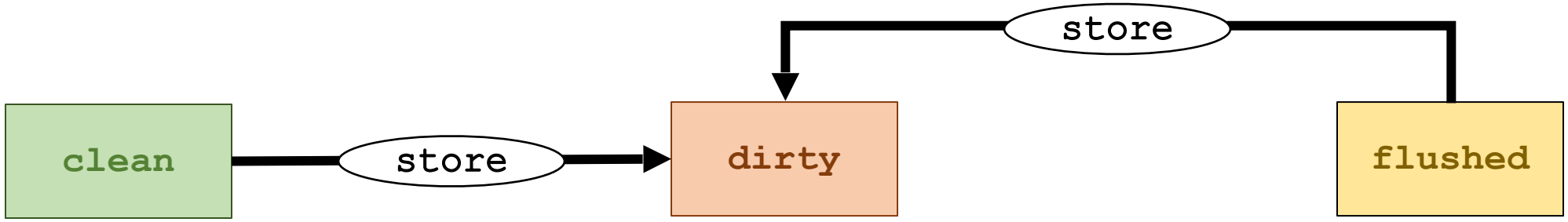

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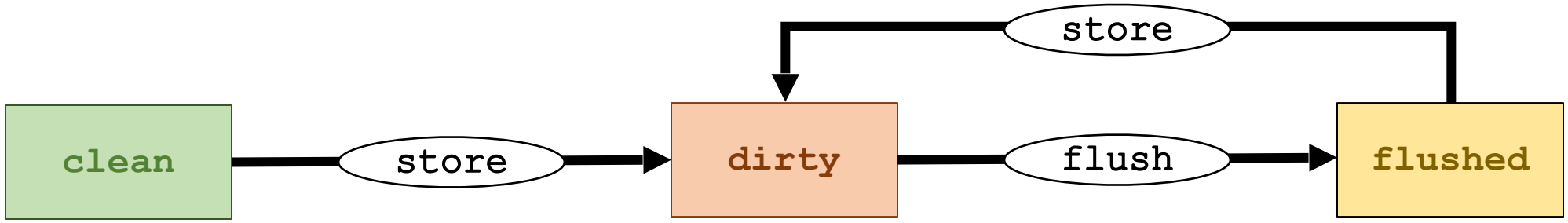

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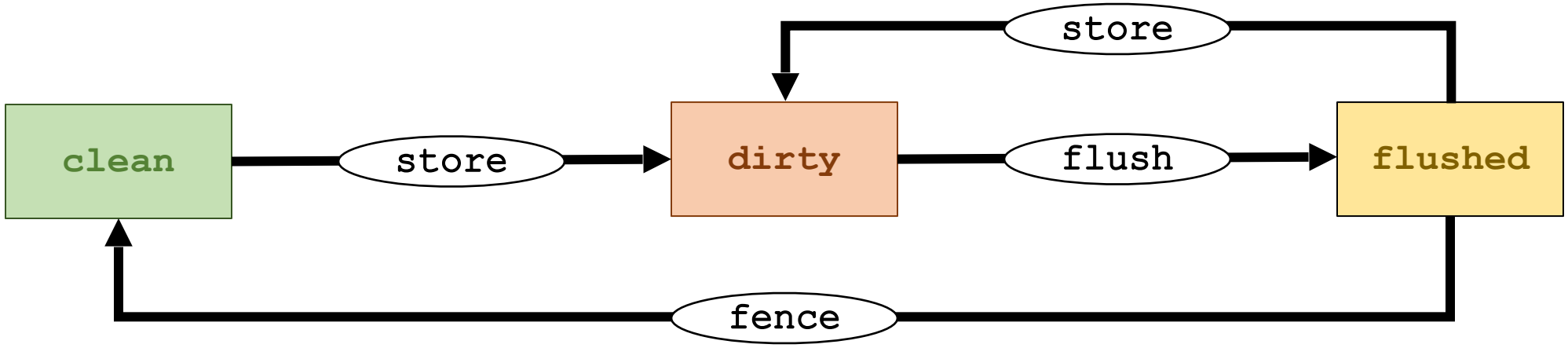
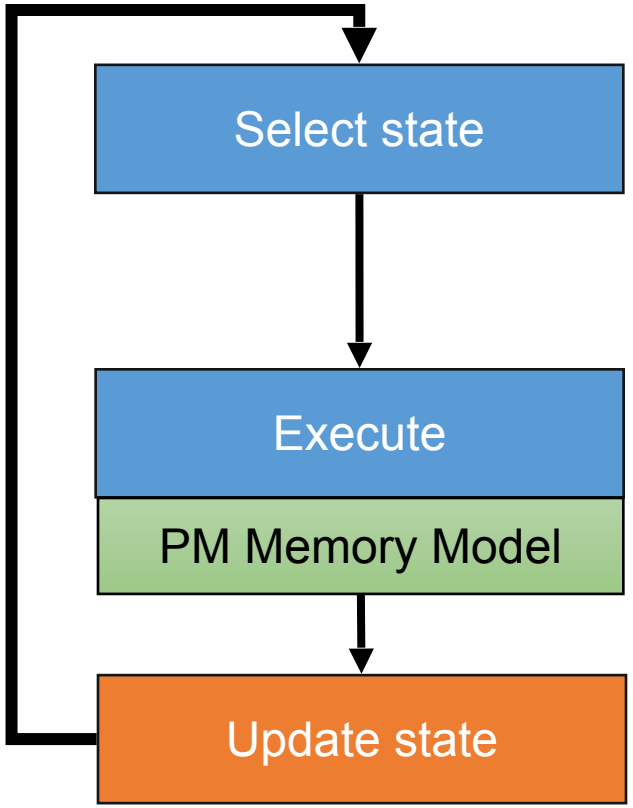


How does AGAMOTTO work?

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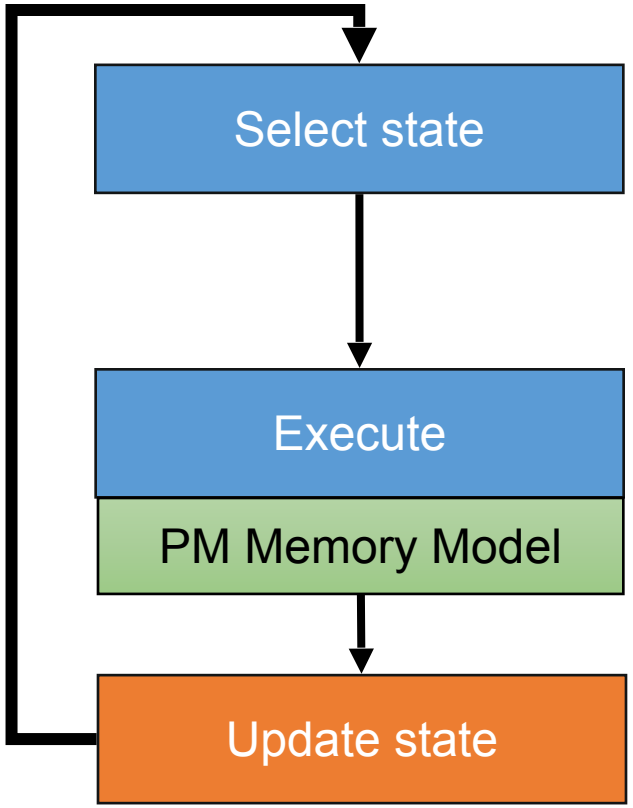


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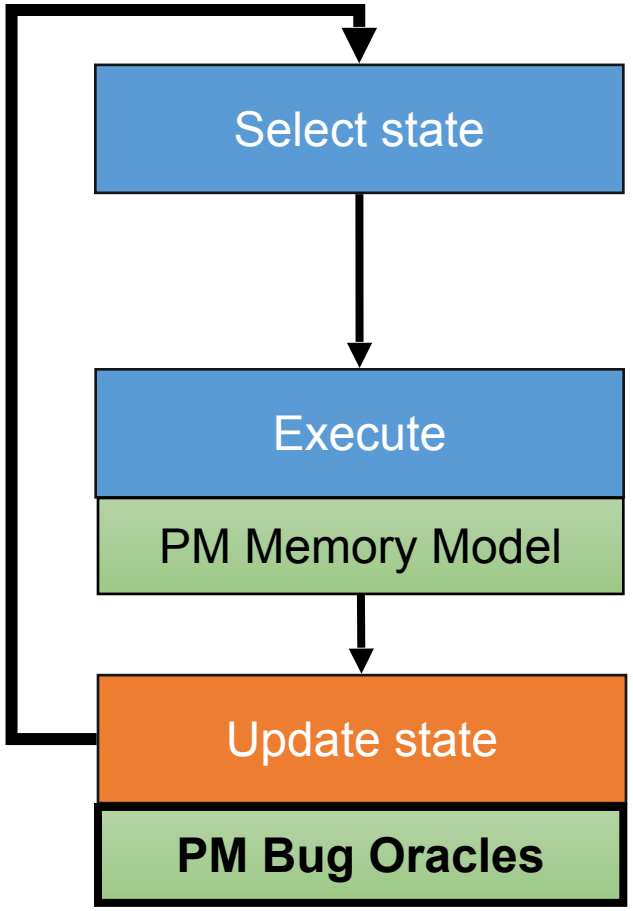


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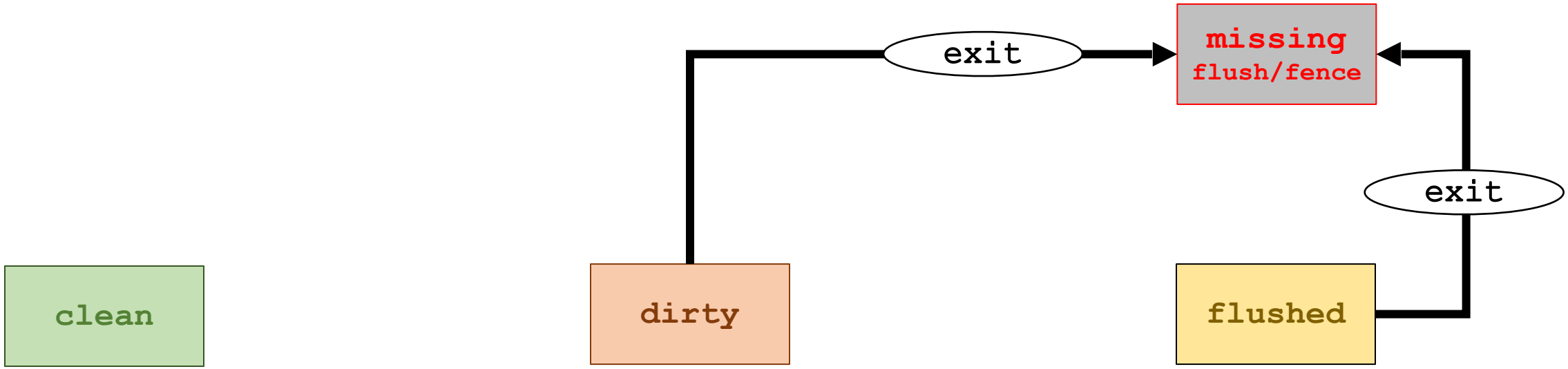

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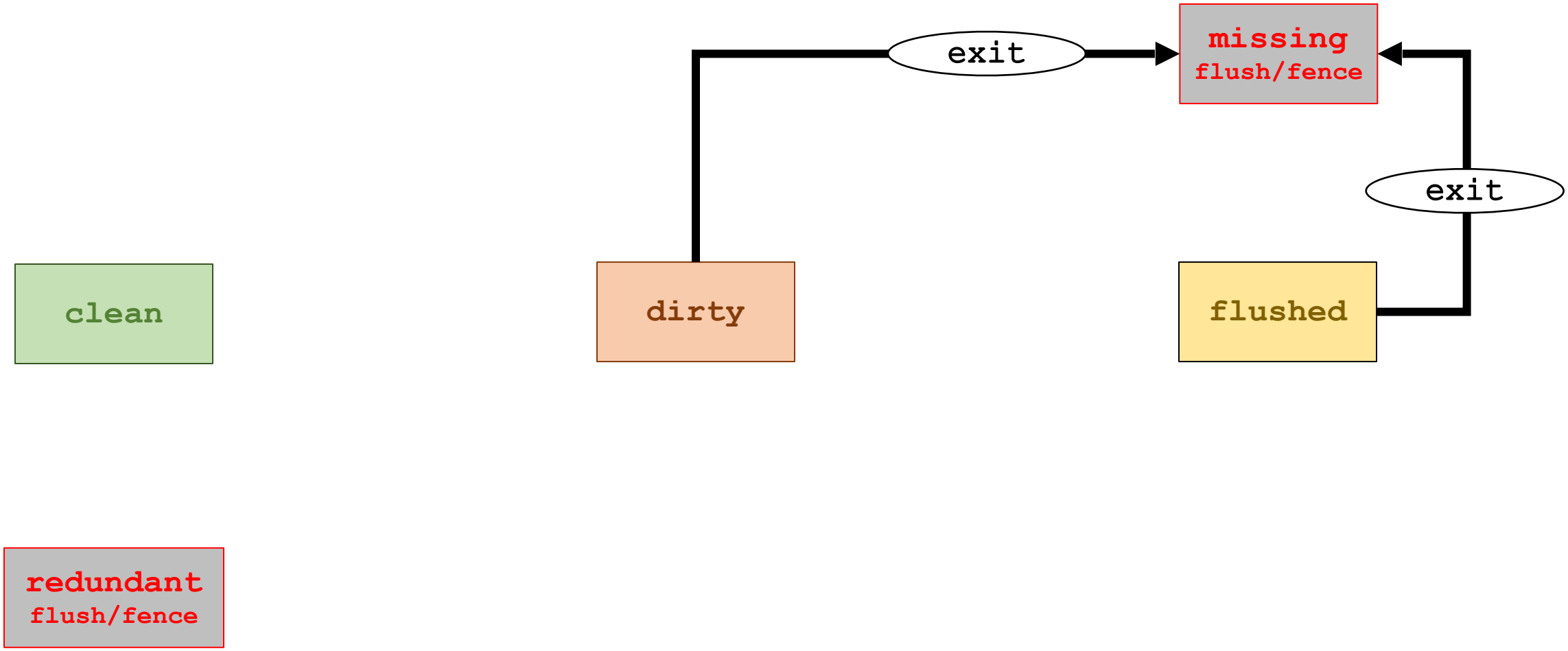

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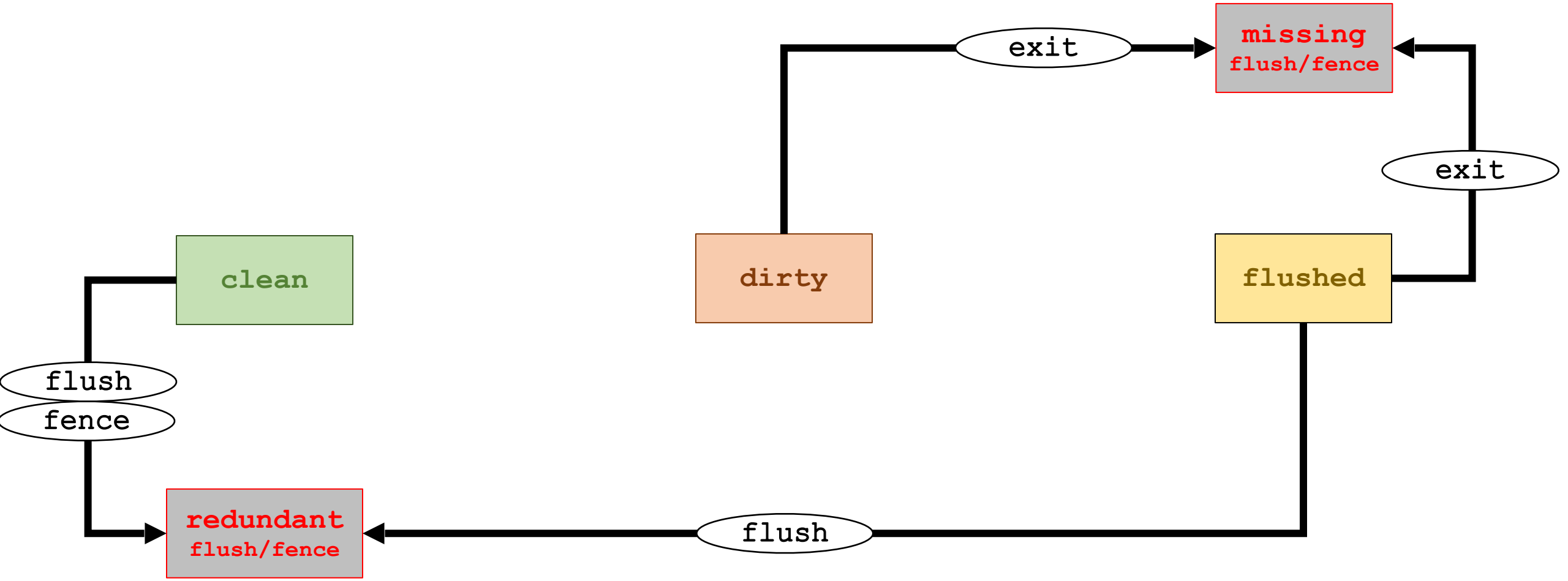

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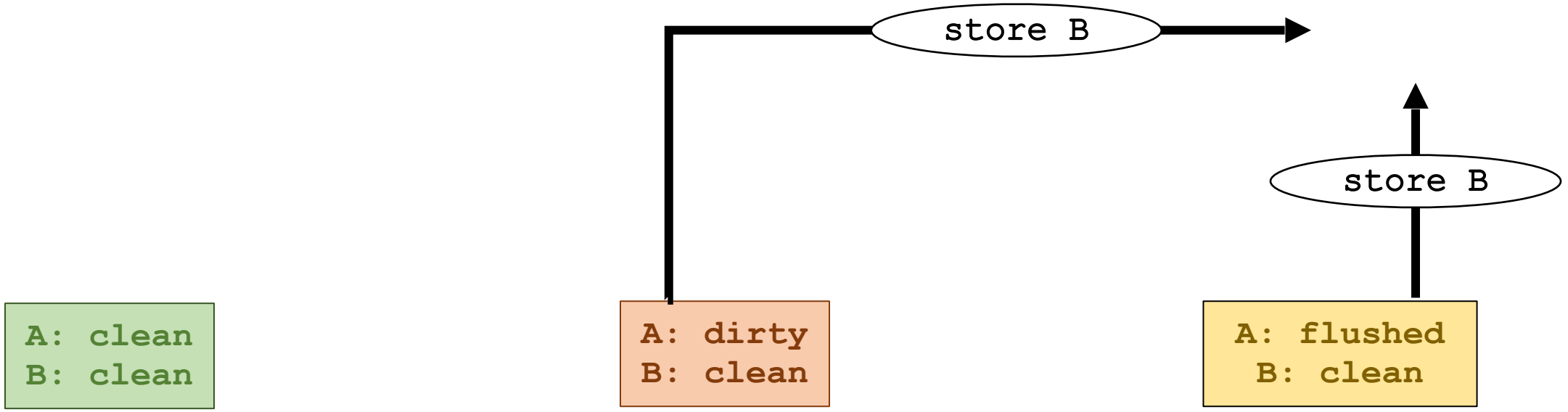

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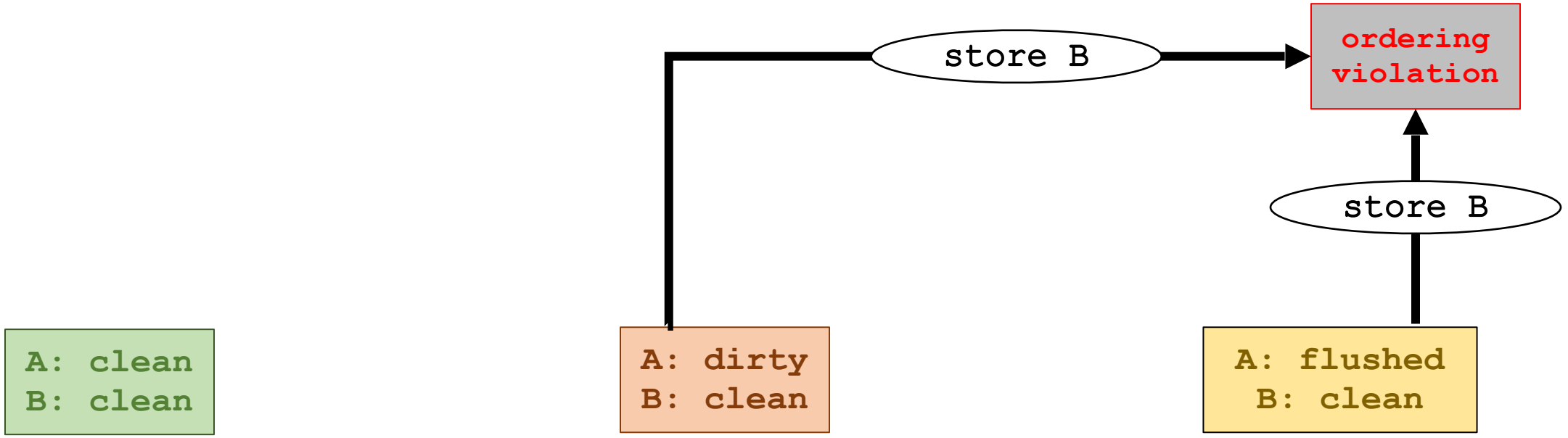

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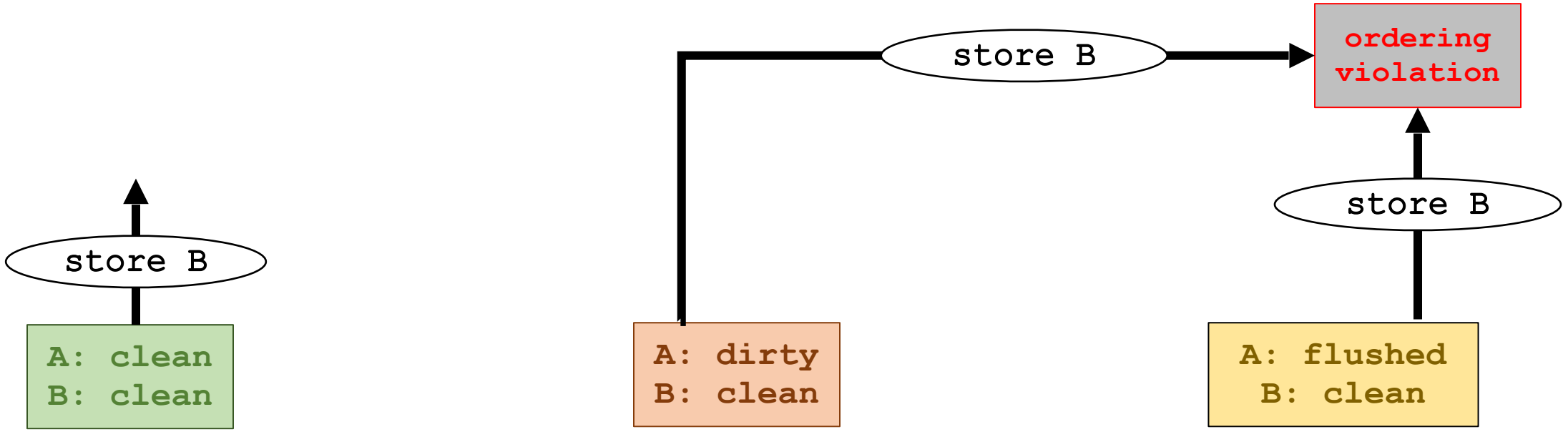

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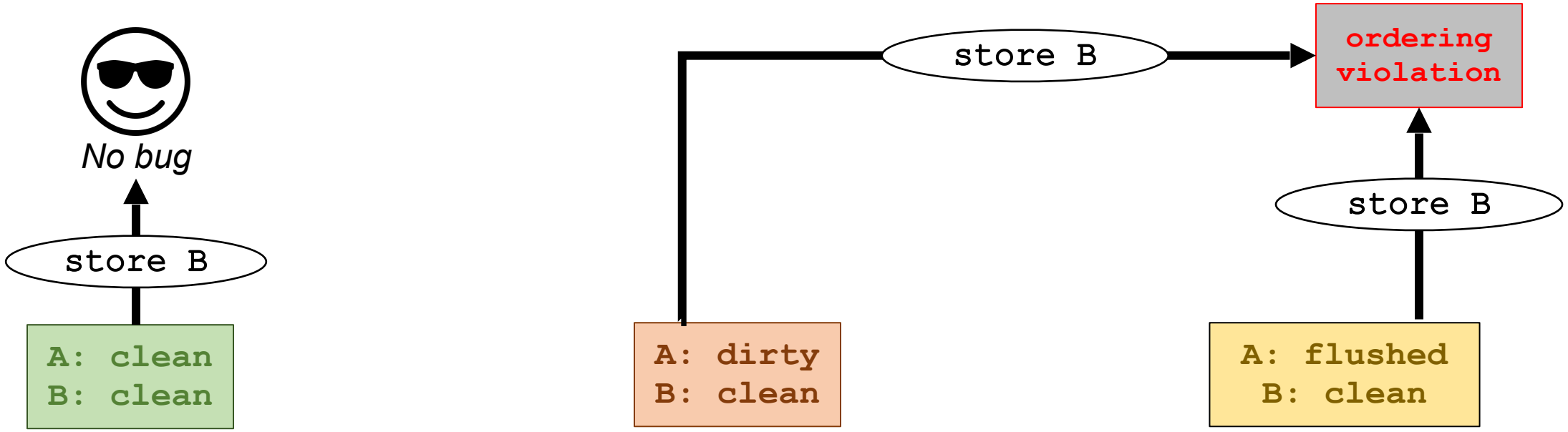

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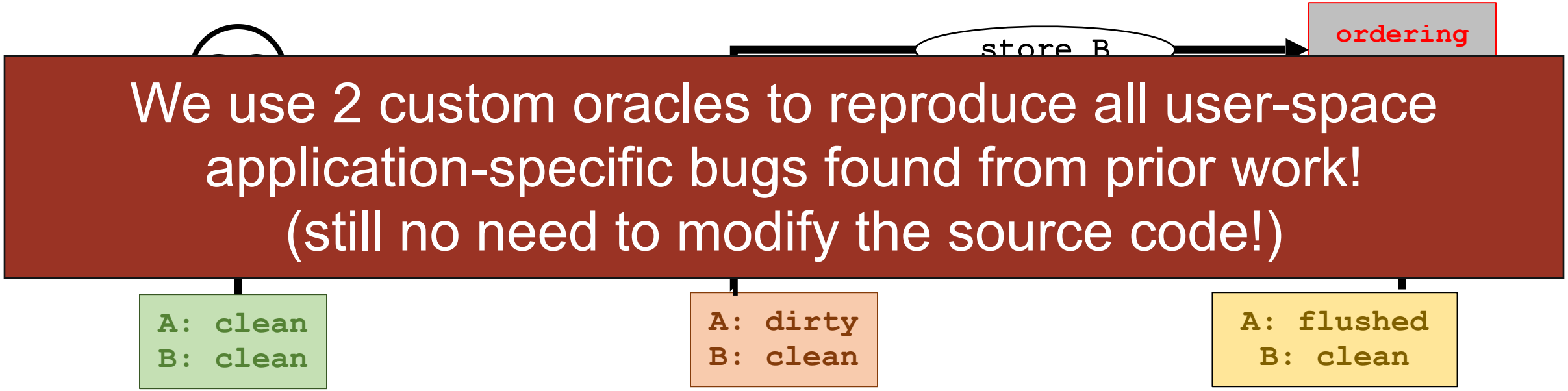

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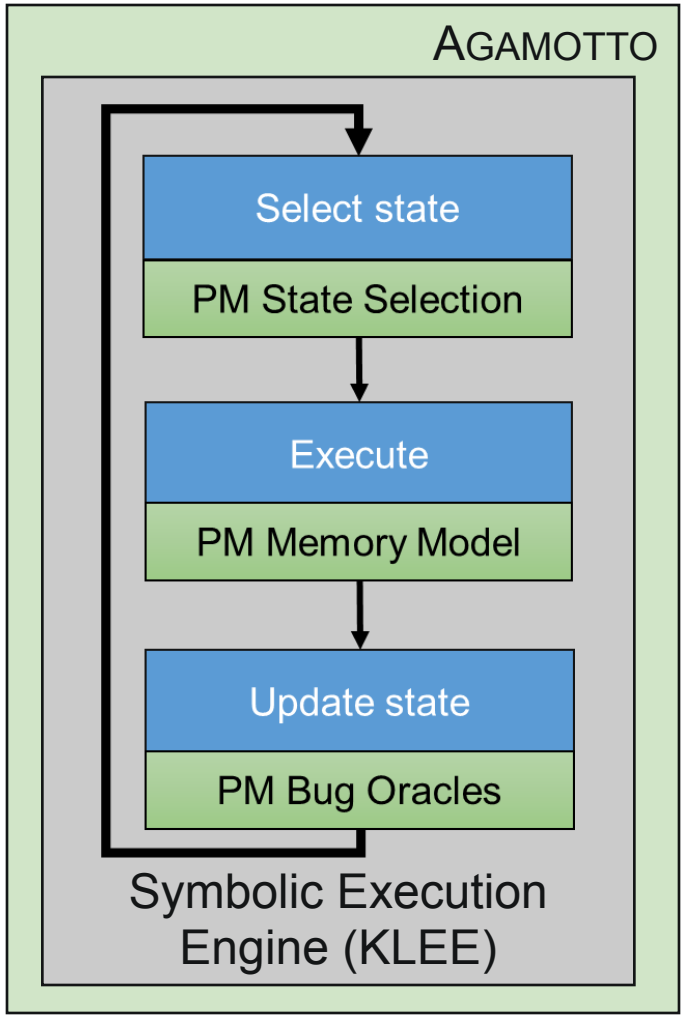
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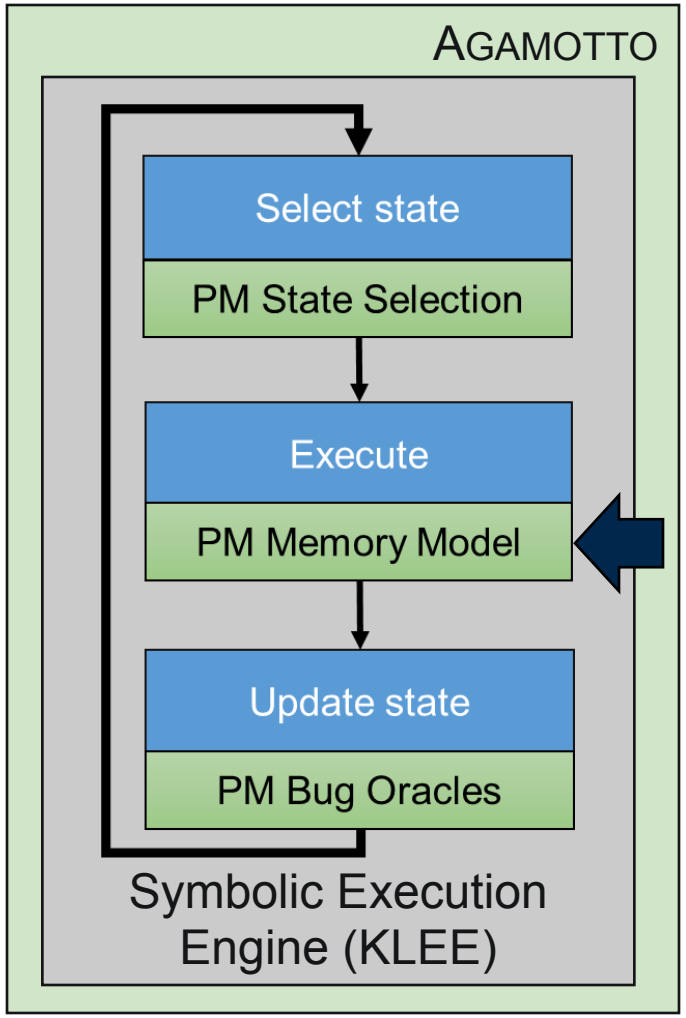
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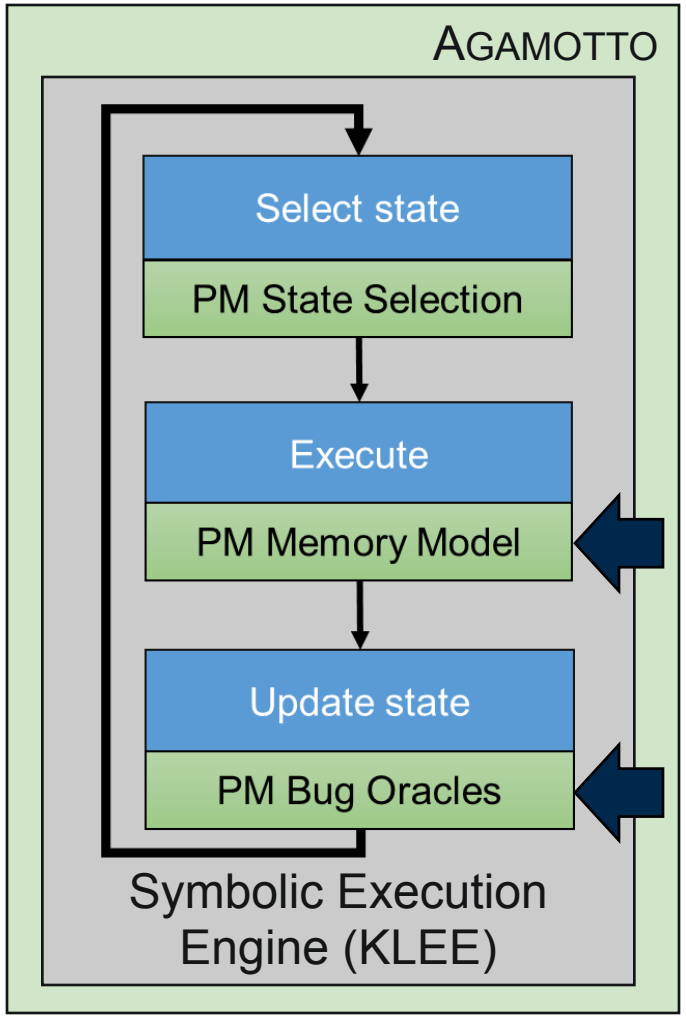
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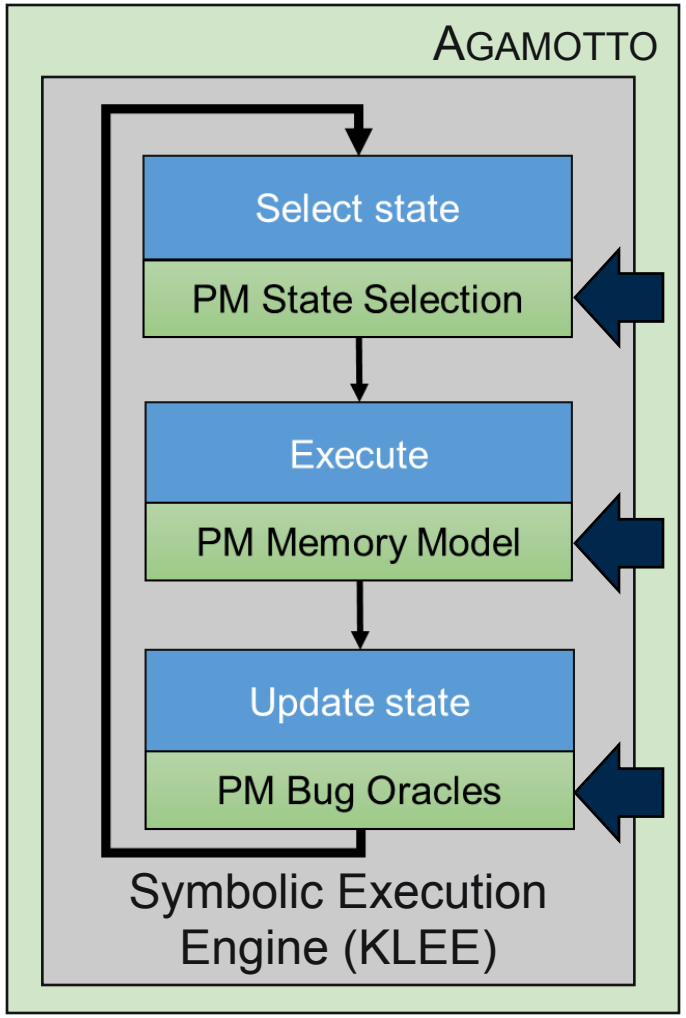

Why? To handle "State Space Explosion"!

Problem: State Space Explosion

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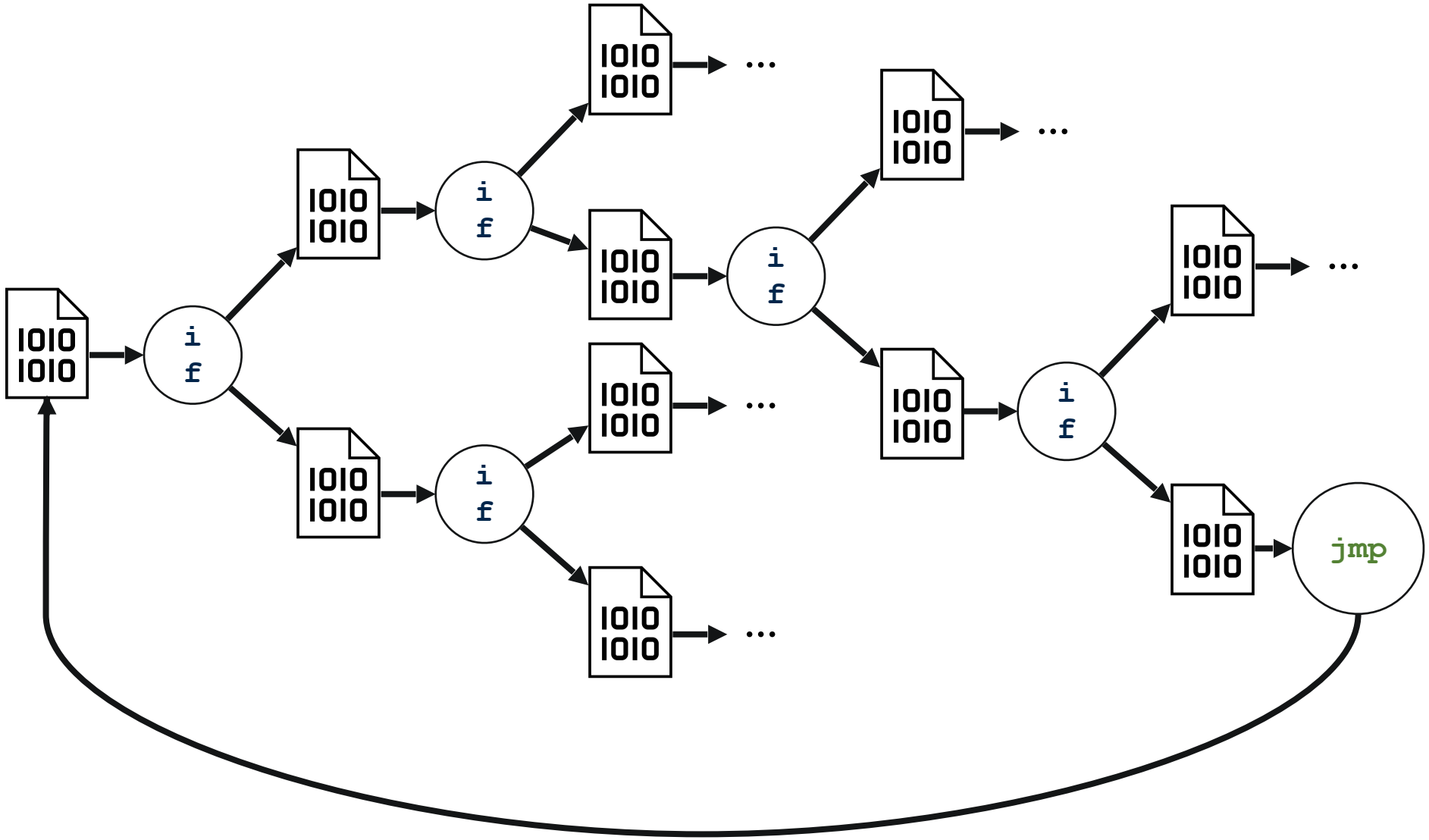

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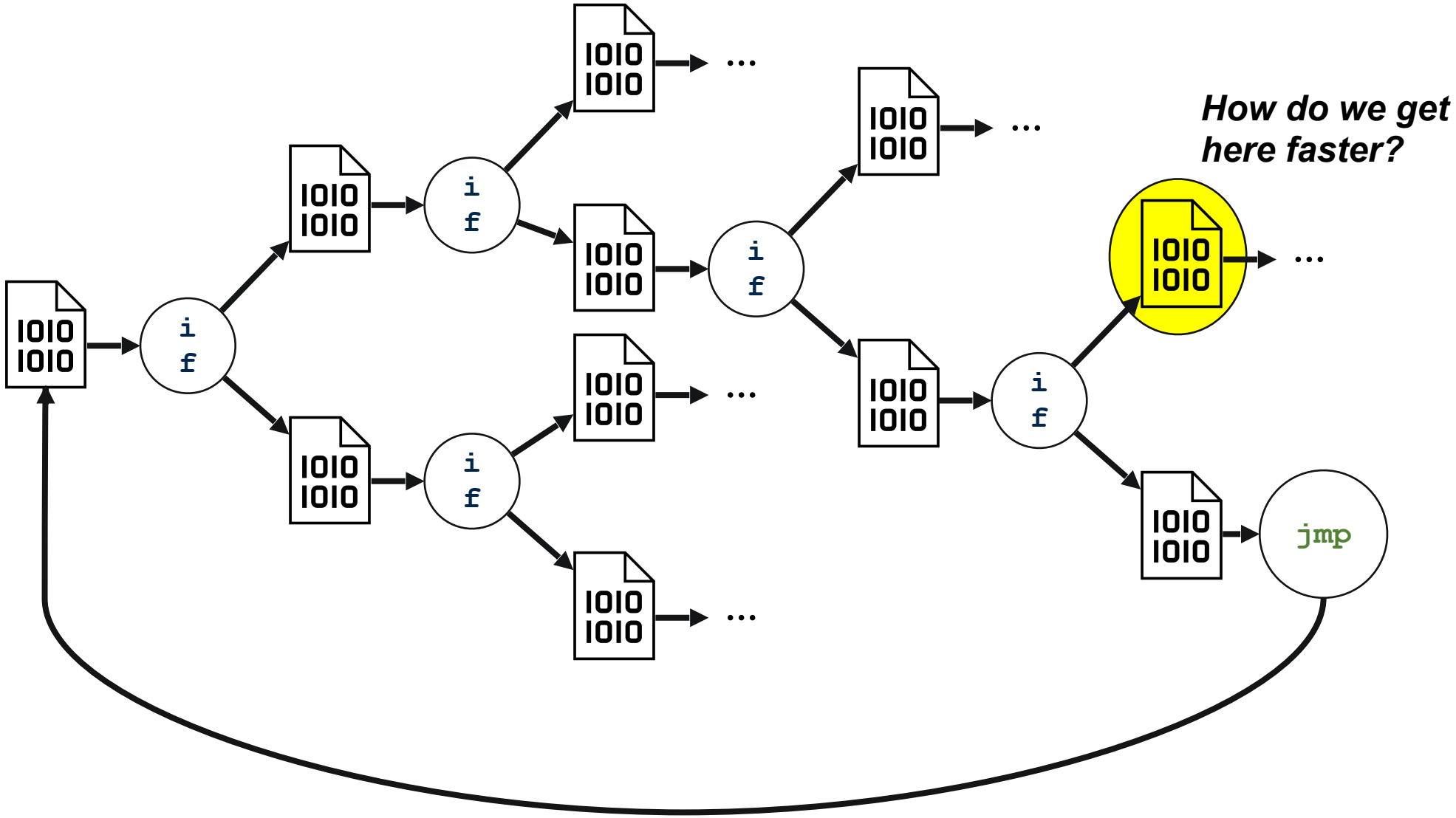

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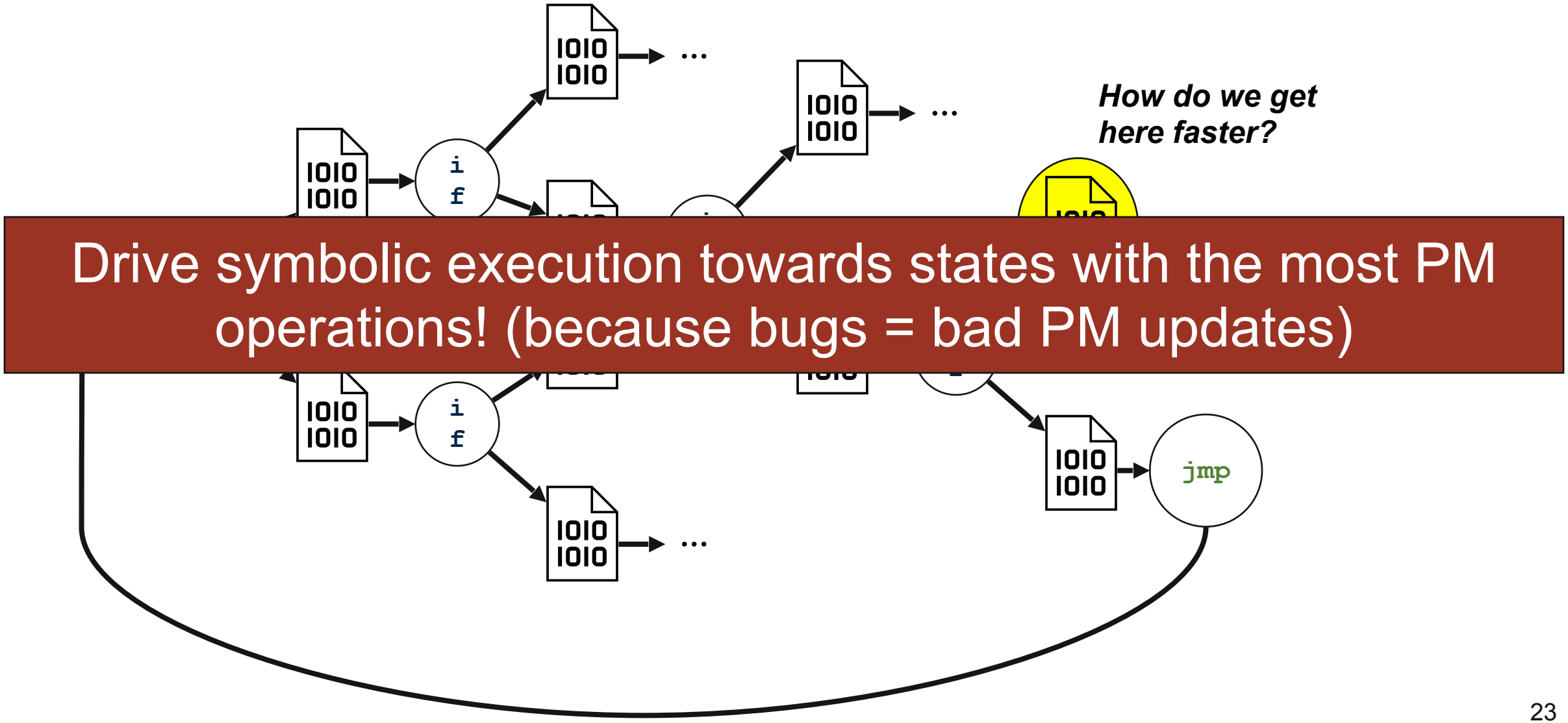

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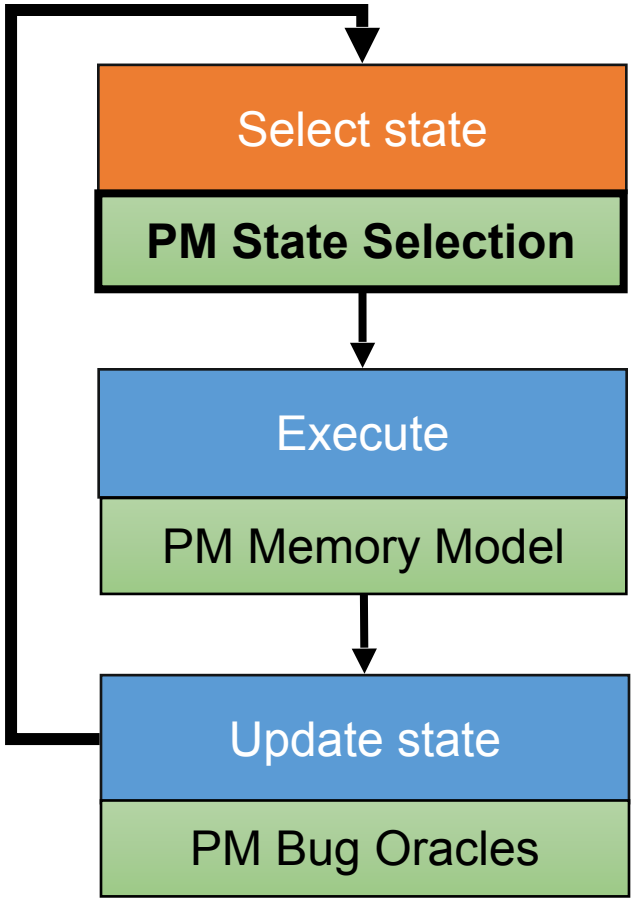


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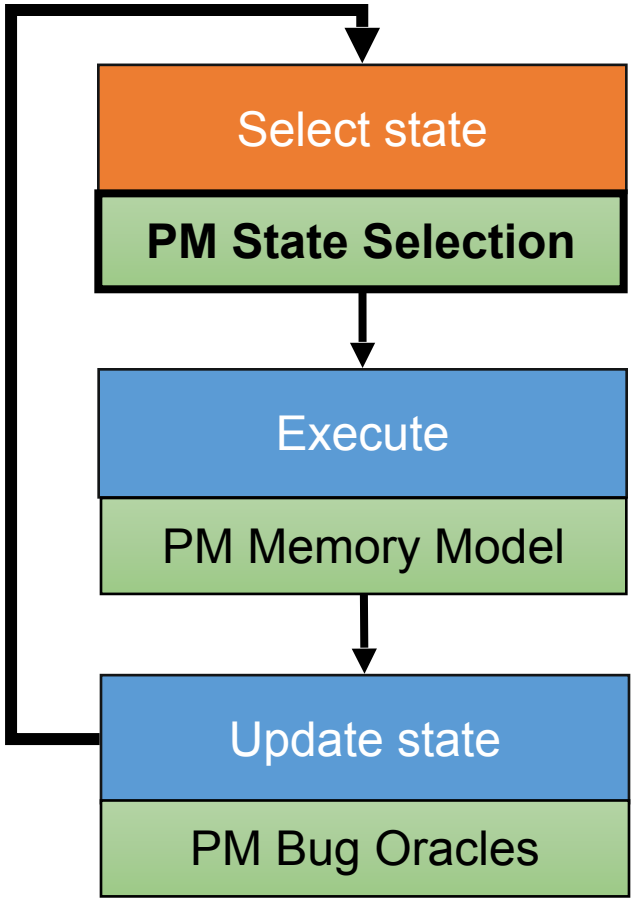


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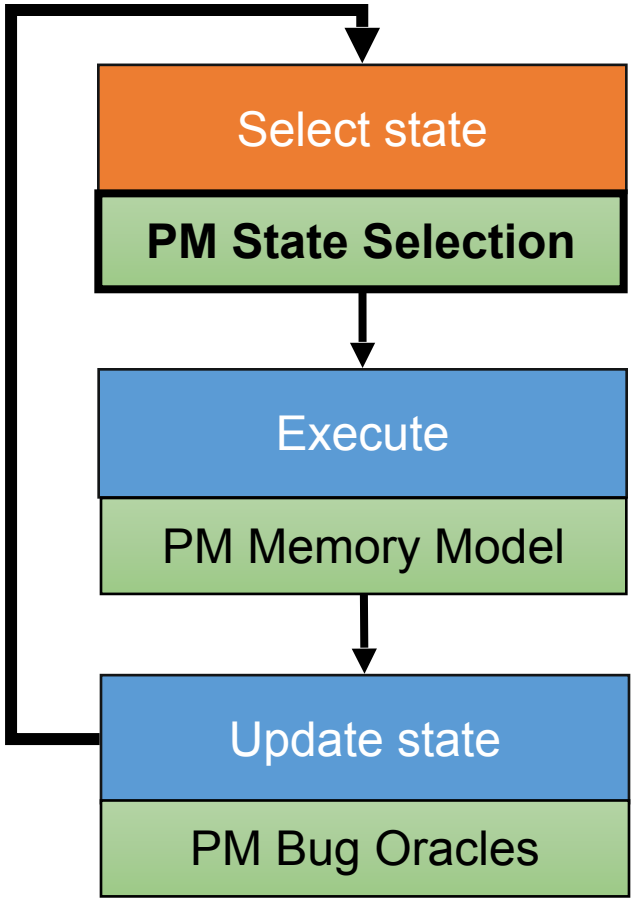


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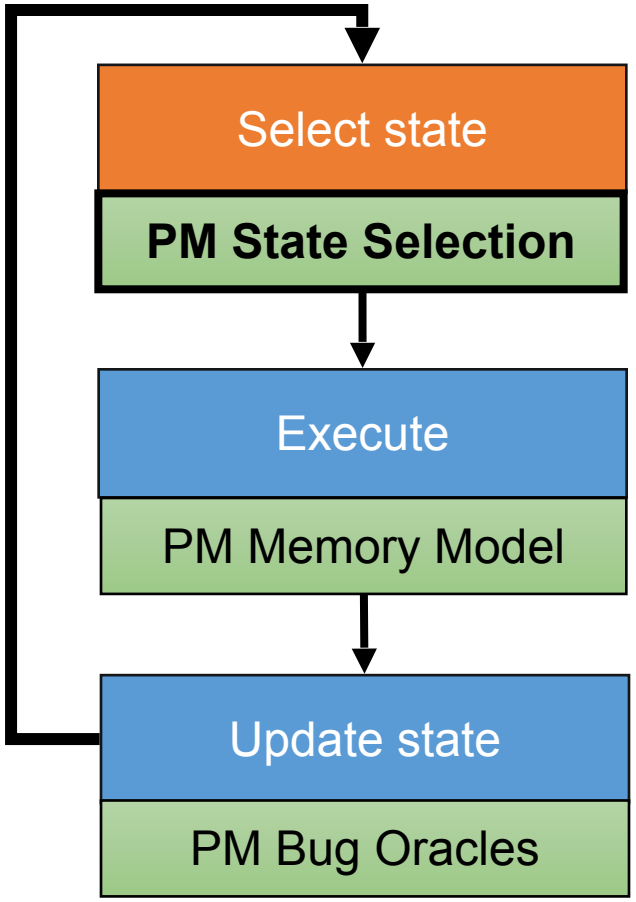


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`do_read = λ≠0` → `pbuf[x]: clean`

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1. *Identify PM instructions (static analysis)*
2. *Assign unit weight*

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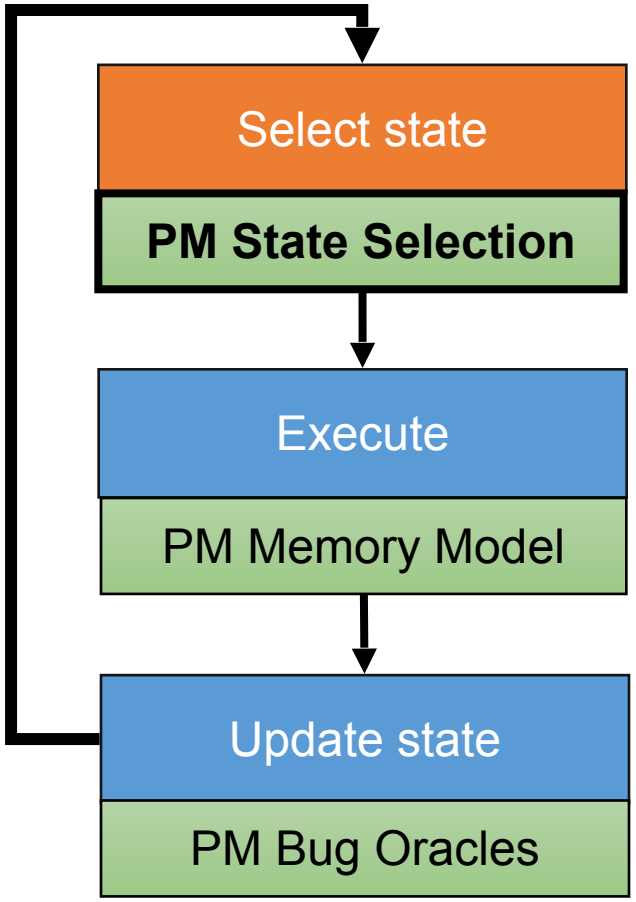


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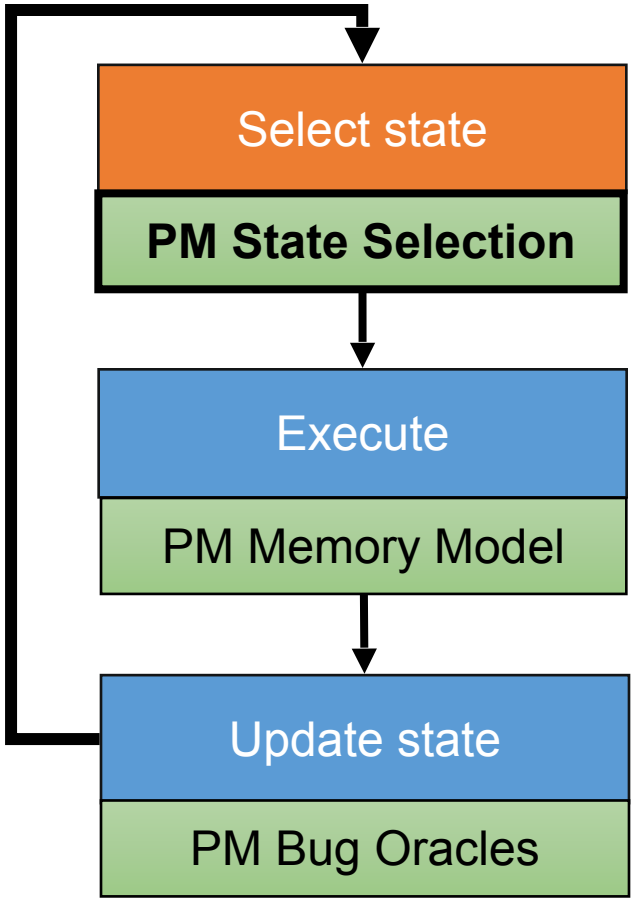


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Priority: 1

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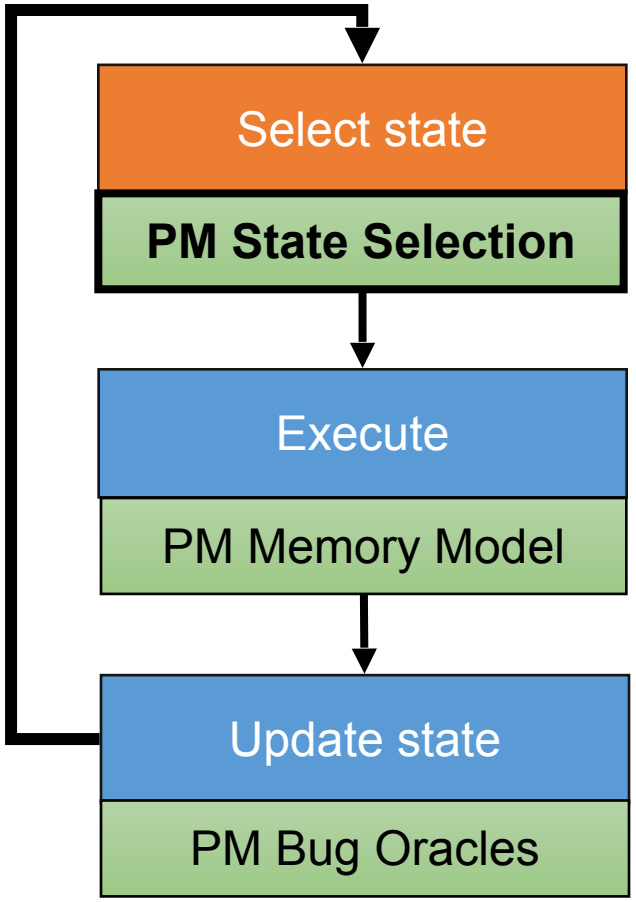


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Priority: 2

Priority: 1

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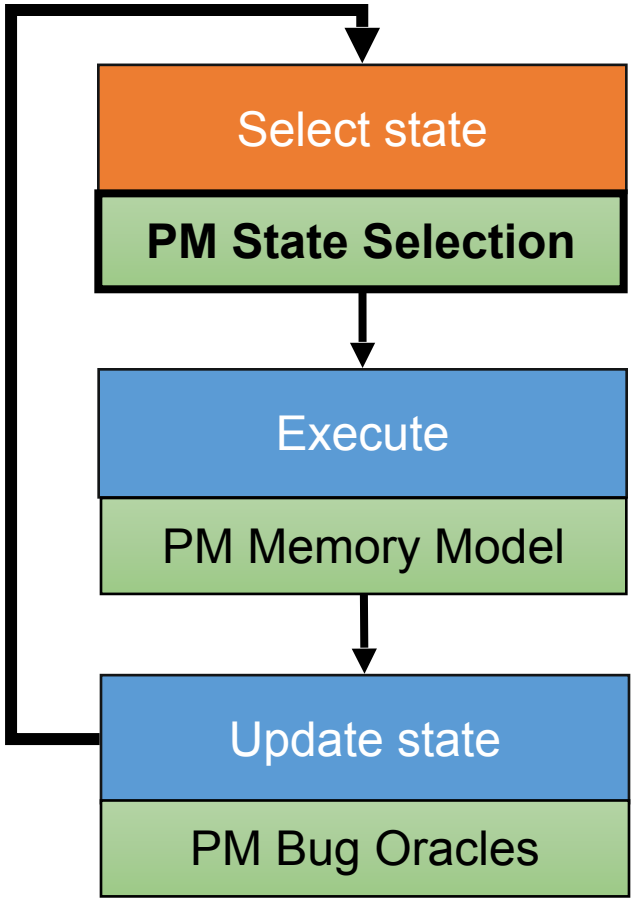


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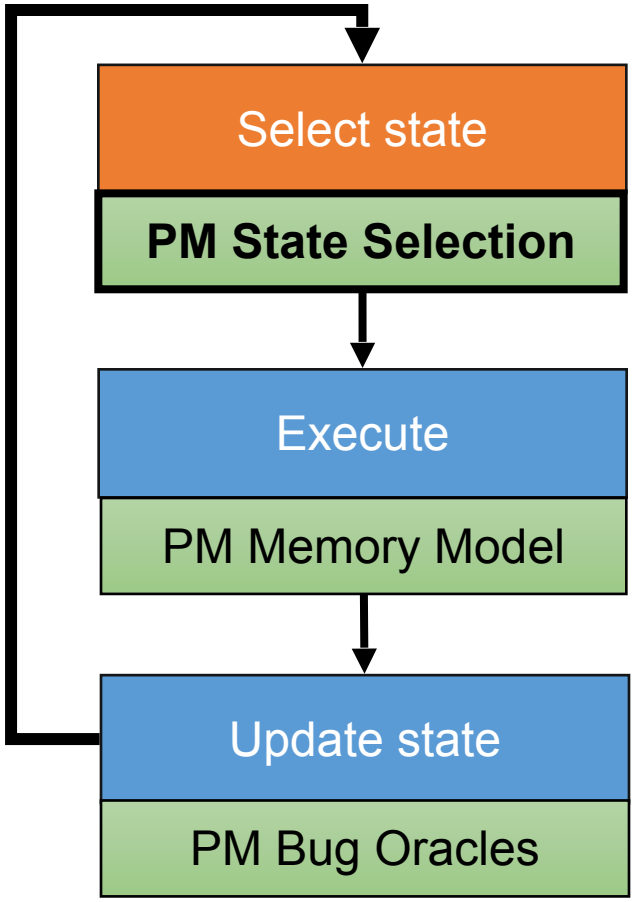


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Priority: 0

Priority: 2

Priority: 2

Priority: 1

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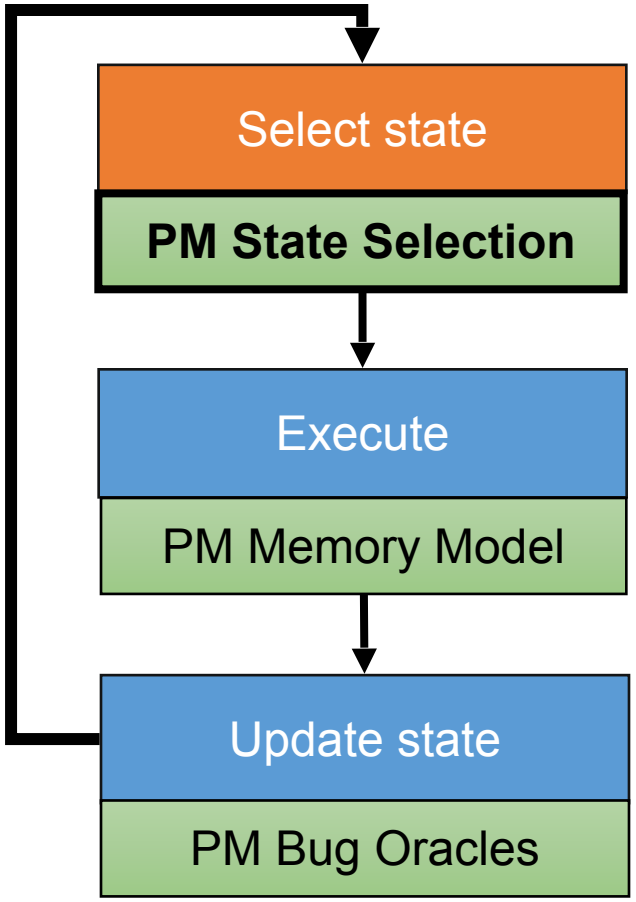


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Priority: 0 (line 5)

Priority: 0 (line 6)

Priority: 2 (line 8)

Priority: 2 (line 9)

Priority: 1 (line 10)

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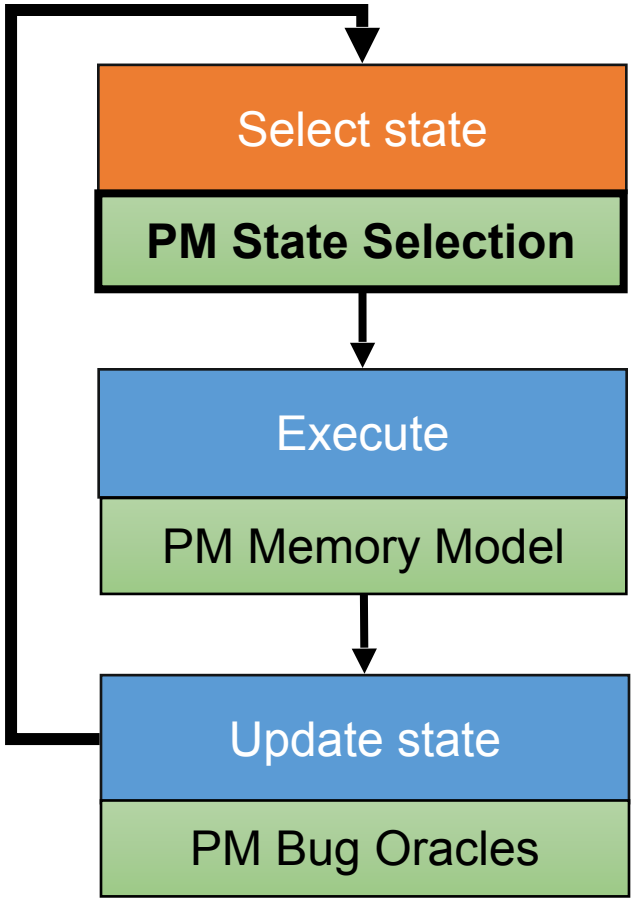
(3) PM State Selection

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3  do_read = ...
4  if (do_read)                          Priority: 2
5      a = pbuf[x]                       Priority: 0
6      foo ()                            Priority: 0
7  else
8      a = ...                           Priority: 2
9      pbuf[x] = a                       Priority: 2
10     clwb(pbuf[x])                     Priority: 1
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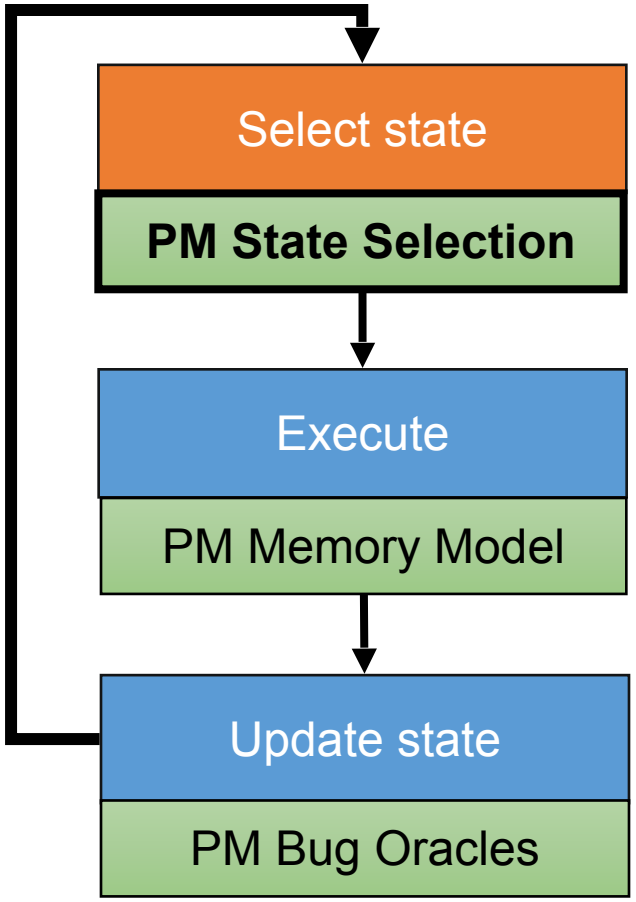


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1  char *pbuf = mmap(<PM file>);
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3  do_read = ...                          Priority: 2
4  if (do_read)                           Priority: 2
5        a = pbuf[x]                      Priority: 0
6        foo ()                           Priority: 0
7  else
8        a = ...                          Priority: 2
9        pbuf[x] = a                      Priority: 2
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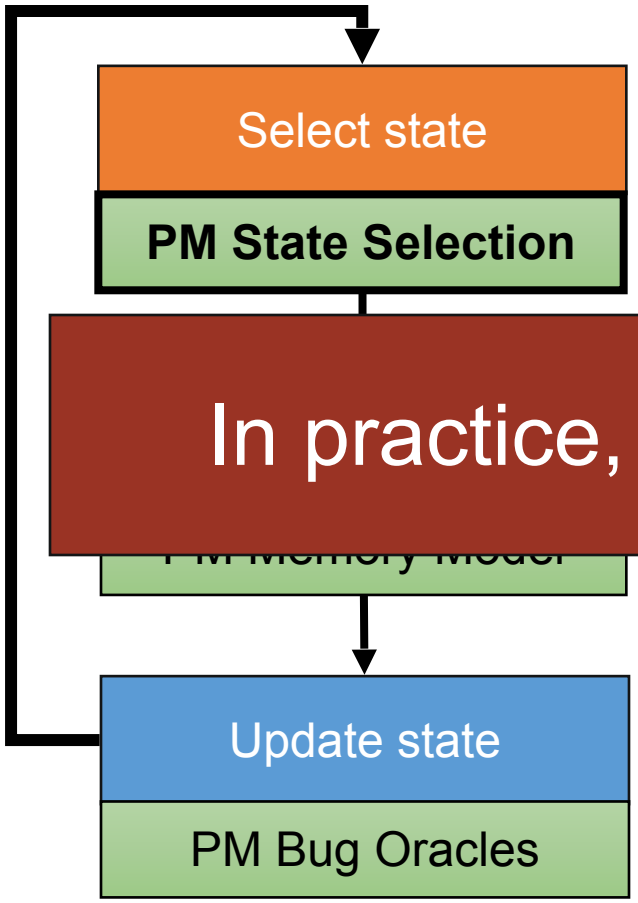


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1  char *pbuf = mmap(<PM file>);
2  ...
3  do_read = ...
4  if (do_read)
```

Priority: 2

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In practice, ***<10%*** of instructions have non-zero priority!

```
do_read = 0
```

pbuf[x]: dirty

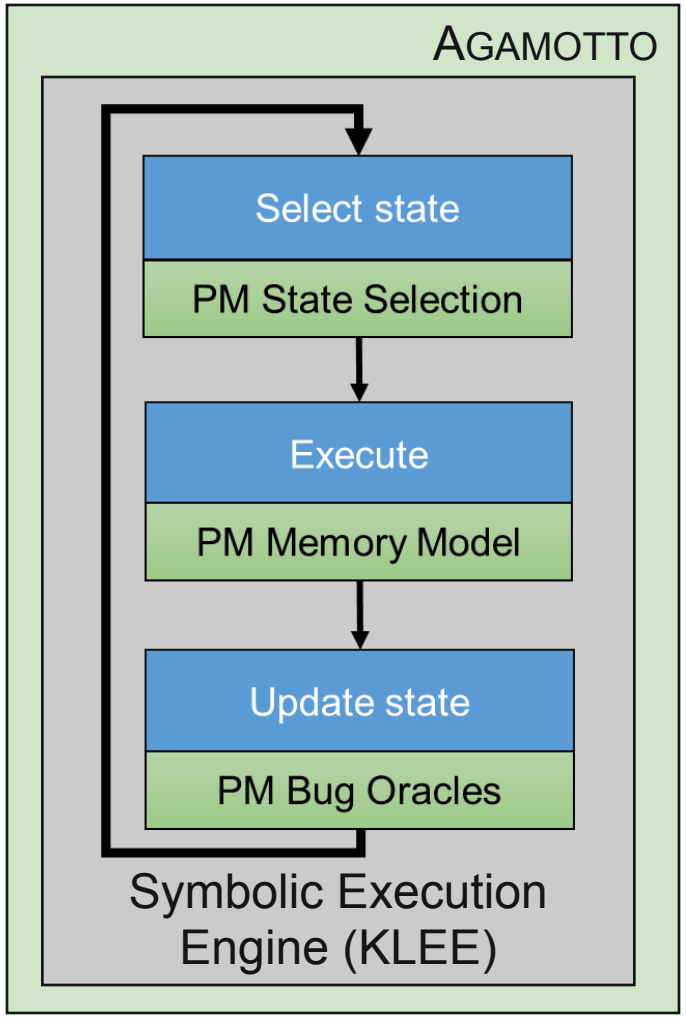
```
9      pbuf[x] = a
10     clwb(pbuf[x])
11     // BUG: Missing sfence!
12 exit(0)
```

Priority: 2

Priority: 1

1. *Identify PM instructions (static analysis)*
2. *Assign unit weight*
3. *Back-propagate priorities*

Design Summary



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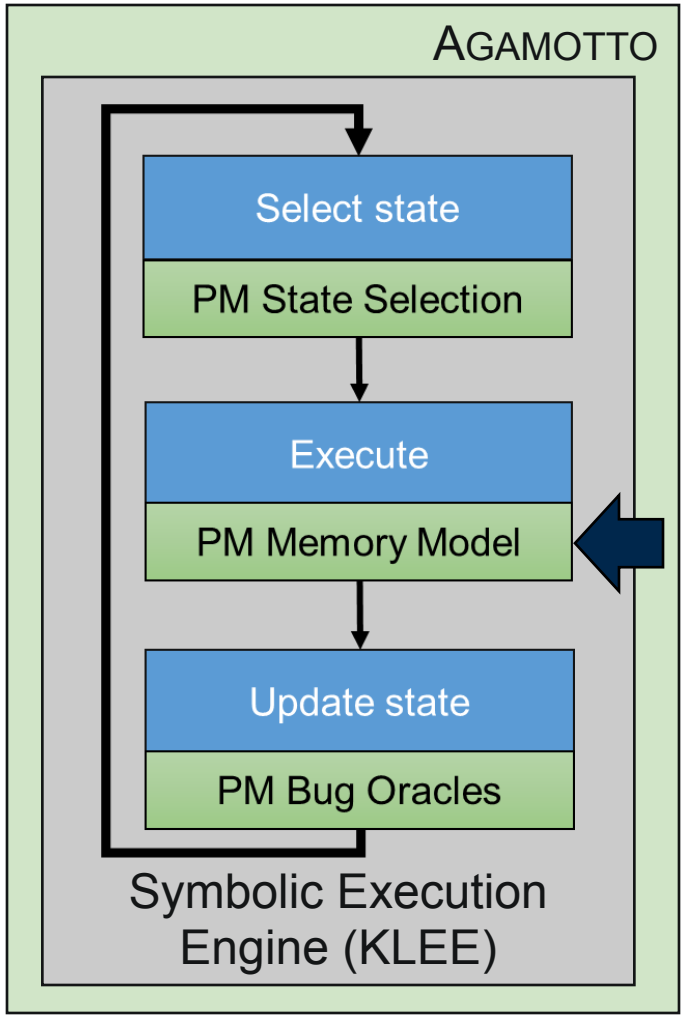
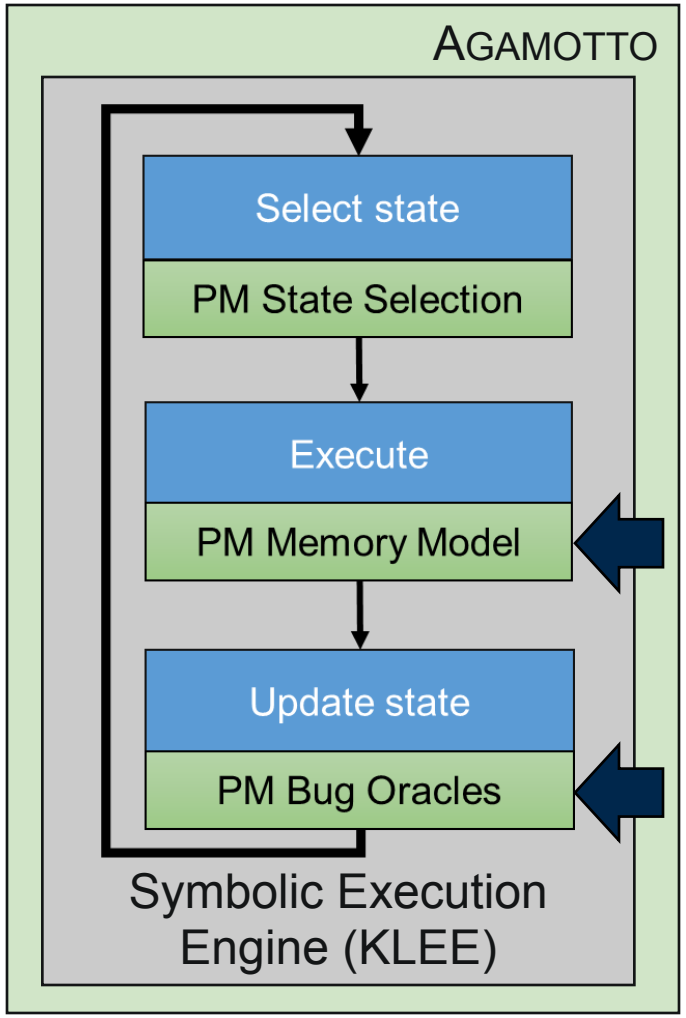


1. Create a model for PM and add to symbolic states

Design Summary



1. Create a model for PM and add to symbolic states

2. Add rules to detect application-independent bug signals

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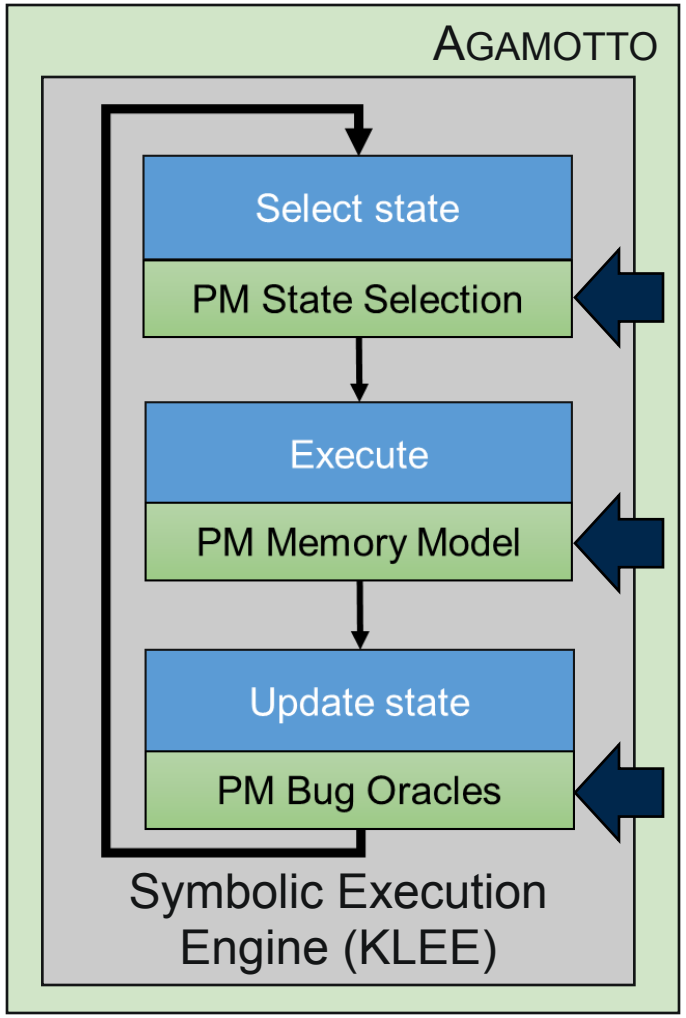
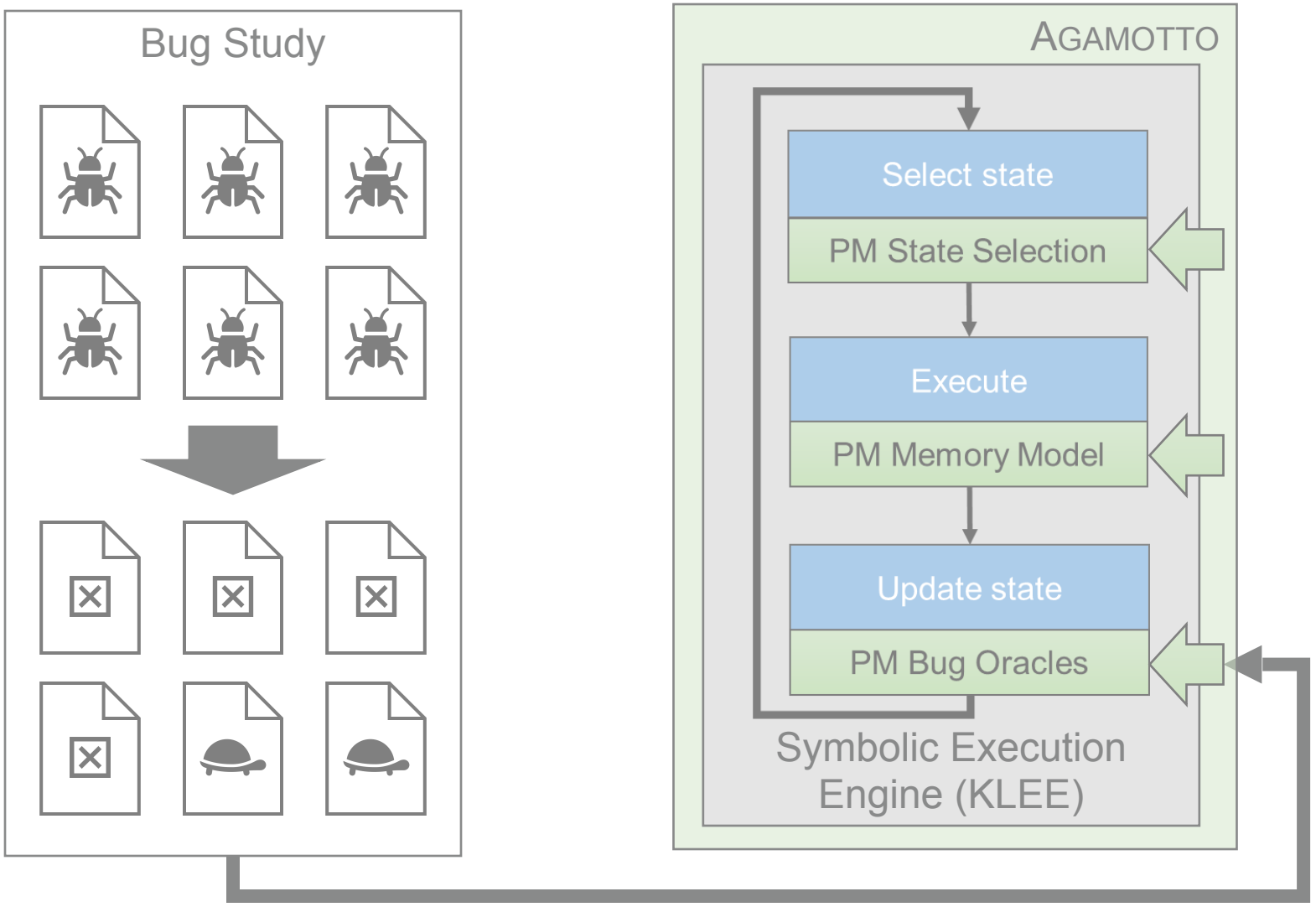


3. Select states based on PM priority to maximize chances of finding bugs

1. Create a model for PM and add to symbolic states

2. Add rules to detect application-independent bug signals

Overview



Results

× 84 found

Reported to developers

Showed impact of performance bugs
(+47% throughput)

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- **84** new bugs found so far (across 5 systems)
  - 14 correctness bugs, 70 performance bugs
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- Performance study on RECIPE (SOSP ‘19):
  - **23–47%** overall throughput increase in key-value store workloads!

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- RECIPE’s authors confirmed and started patching all the bugs we reported.
  - “These are some really good finds, since it was difficult to debug our own code without having a proper tool.”

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https://github.com/efeslab/agamotto

Email: iangneal@umich.edu

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Trivia: AGAMOTTO's name was inspired by the "Eye of Agamotto," which is another name for the Time Stone in the Avengers franchise.