Statically Discover Cross-Entry Use-After-Free Vulnerabilities in the Linux Kernel

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Use-After-Free: The Classic Problem

Consistently ranked as a most **dangerous** vulnerability in CWE Top 25 list.

Prevalent in critical software (e.g., Linux kernel).

Severe **consequences** (e.g., arbitrary code execution, privilege escalation).

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int foo(void) {
  int *ptr = malloc(sizeof(int));
  free(ptr); // FREE
  return *ptr; // USE
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```

Easily detectable.

UAF can be Tricky: Cross-Entry

- Use and free can happen in **different entry functions** with global variable relays.

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int *gp, *gq;
```

```
void entry0(void) {
  int *ptr = malloc(...);
  gp = ptr;
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```
void entry1(void) {
  gq = gp;
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void entry2(void) {
  return *gq; // USE
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(1) Escape
(2) FREE
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(6) USE

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void entry2(void) {
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- Use and free can happen in **different entry functions** with global variable relays.

- *Common in codebases with multiple entry functions (e.g., the Linux kernel).*

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UAF can be Tricky: Subtle Constraints

- Despite the lock protection and sanity check, UAF still happens due to **subtle flaws**.

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void entry0(void) {
  lock(o);
  free(gp); // FREE
  unlock(o);
  gp = NULL; //SET
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void entry1(void) {
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- *Fix: Swap line 03 and 04.*

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Our Goal and Challenges

Statically discover cross-entry UAFs in the Linux kernel (and potentially more).

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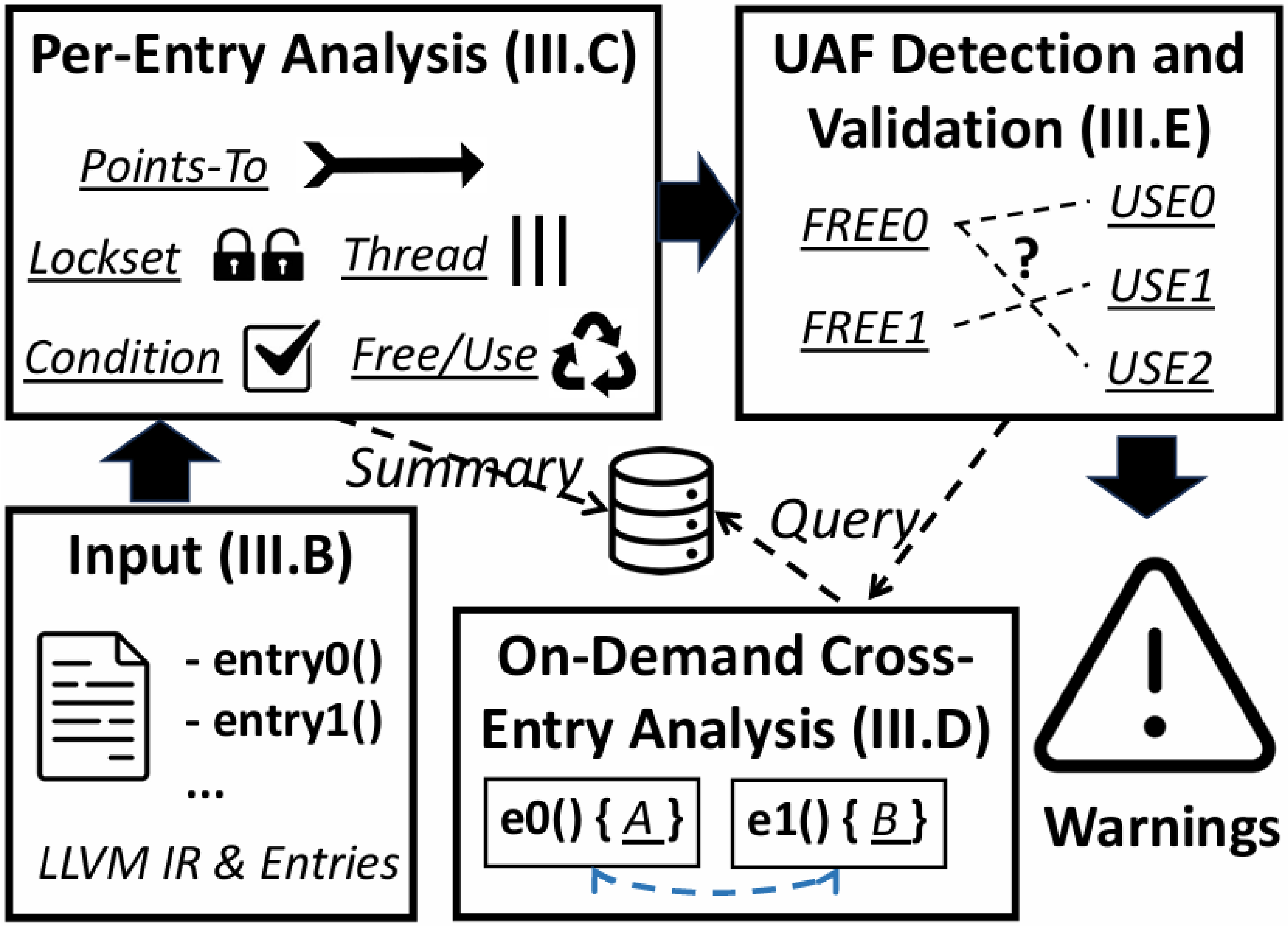
Challenges

#1: precise and efficient cross-entry alias analysis (between use and free).

#2: comprehensive multi-aspect UAF validation (e.g., lock, condition check, etc.).

Our Solution: UAFX ("X" for "Xross")



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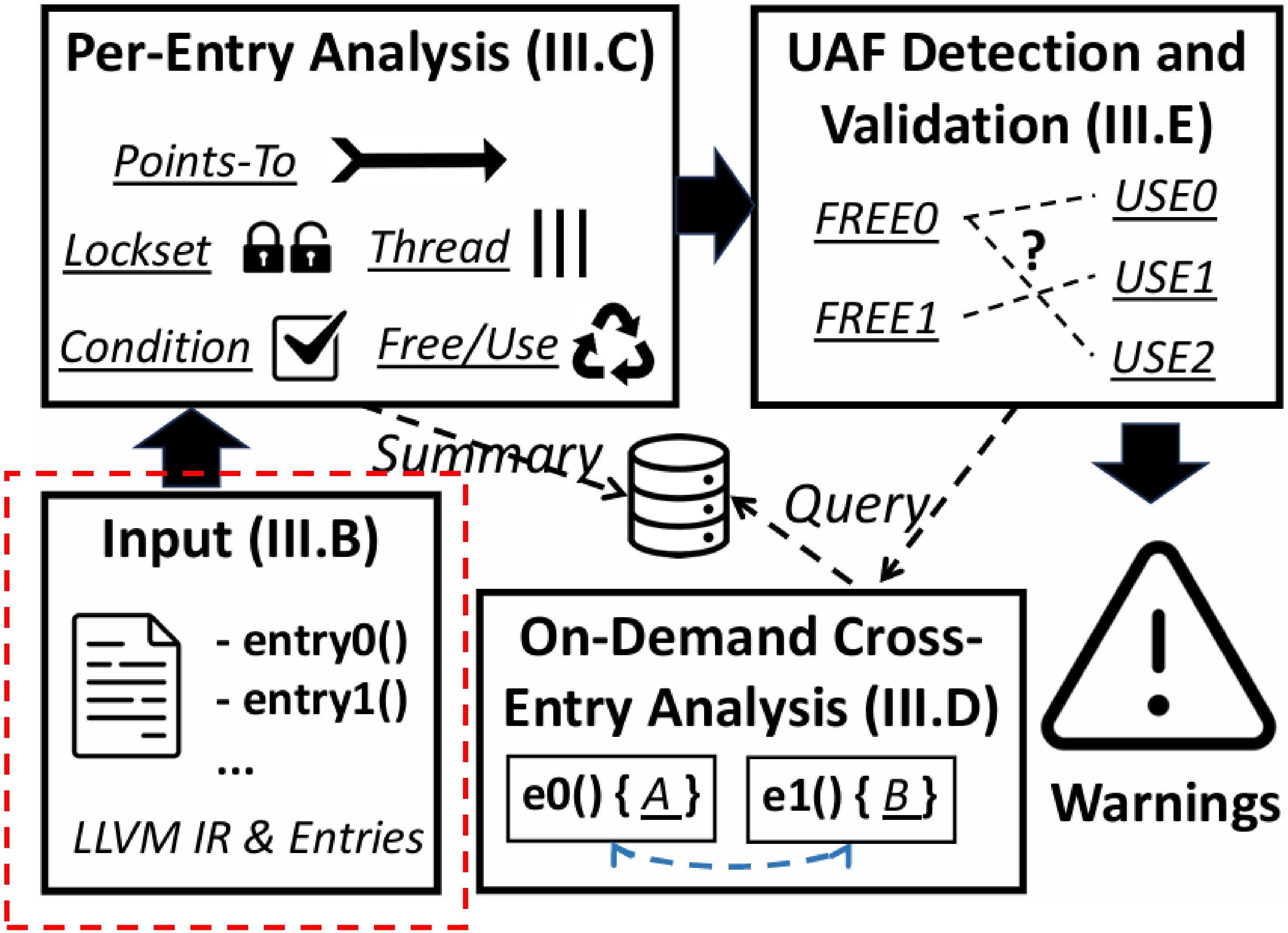

UAFX: Input

```
@entry0 (    ) {
   %0 = load ...;
   store ...;
   %1 = gep ...;
}
@entry1 (...) {
   ...
}
@entry2 (    ) {
   ...
}

...
```

LLVM

Target Program in LLVM Bitcode

\+

Entry Functions
entry0()
entry1()
entry2()

Entry Function List

UAFX: Identify Cross-Entry UAF Candidates

- **Step 1**: Per-entry alias and escape-fetch analysis → Entry summaries

```
int *gp, *gq;
```

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void entry0(void) {
  int *ptr = malloc(...);
  gp = ptr;
  free(ptr); // FREE
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void entry1(void) {
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void entry2(void) {
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Summary:

(1) obj@1 → (escape) → gp

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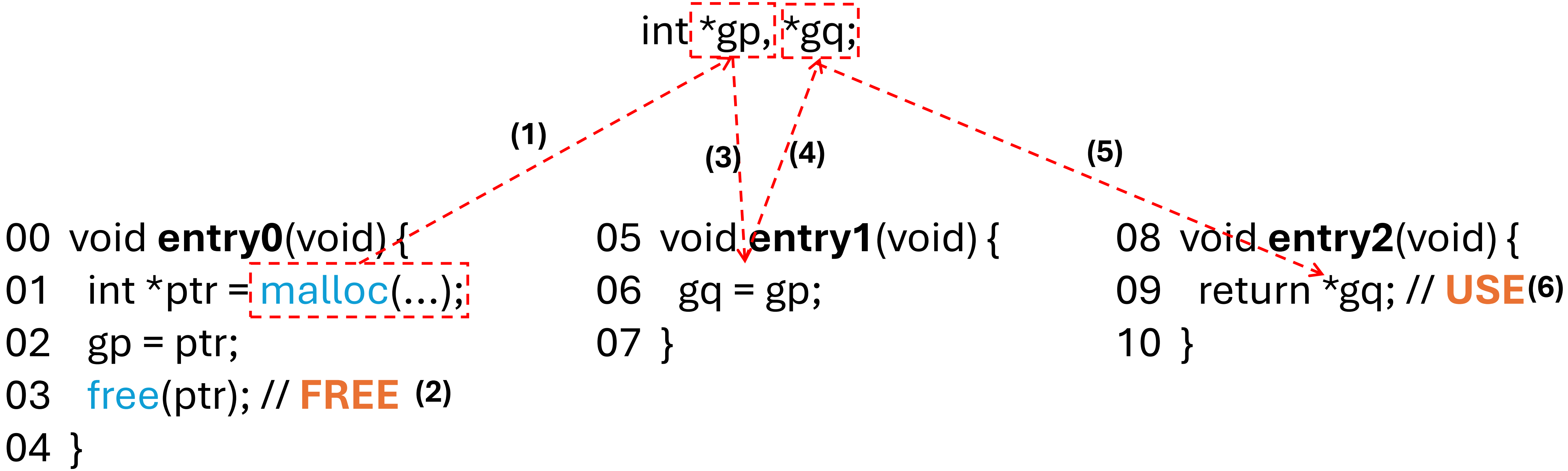

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- *Accurate*: *Interprocedural, flow-, context-, field-, and opportunistically path-sensitive.*

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- *Efficient:* ***On-demand*** *summary query.*

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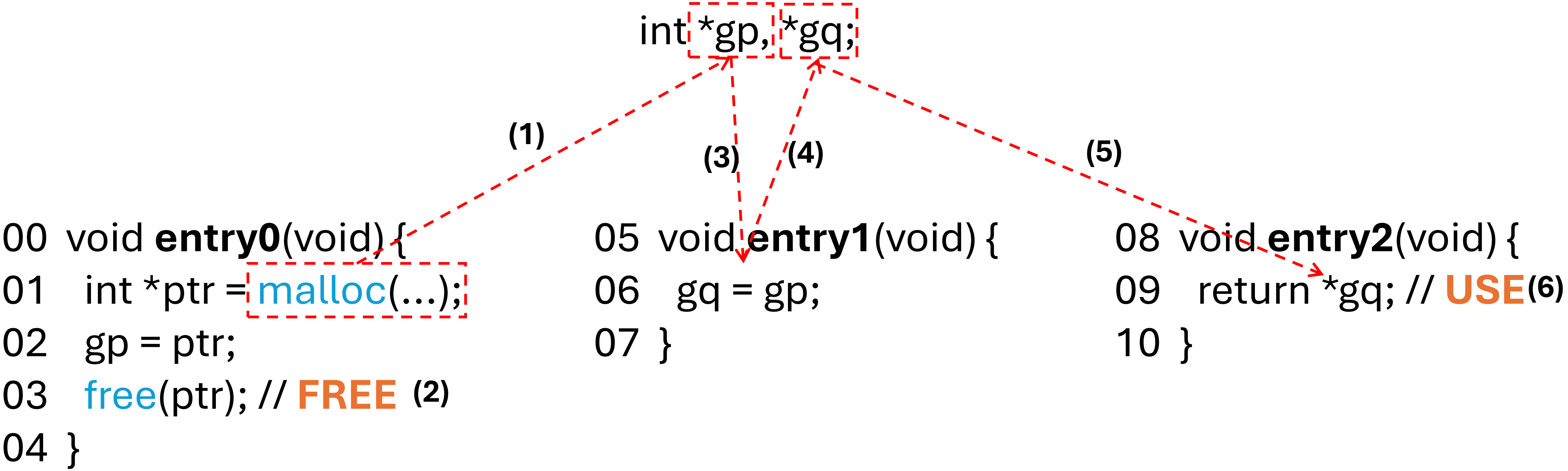

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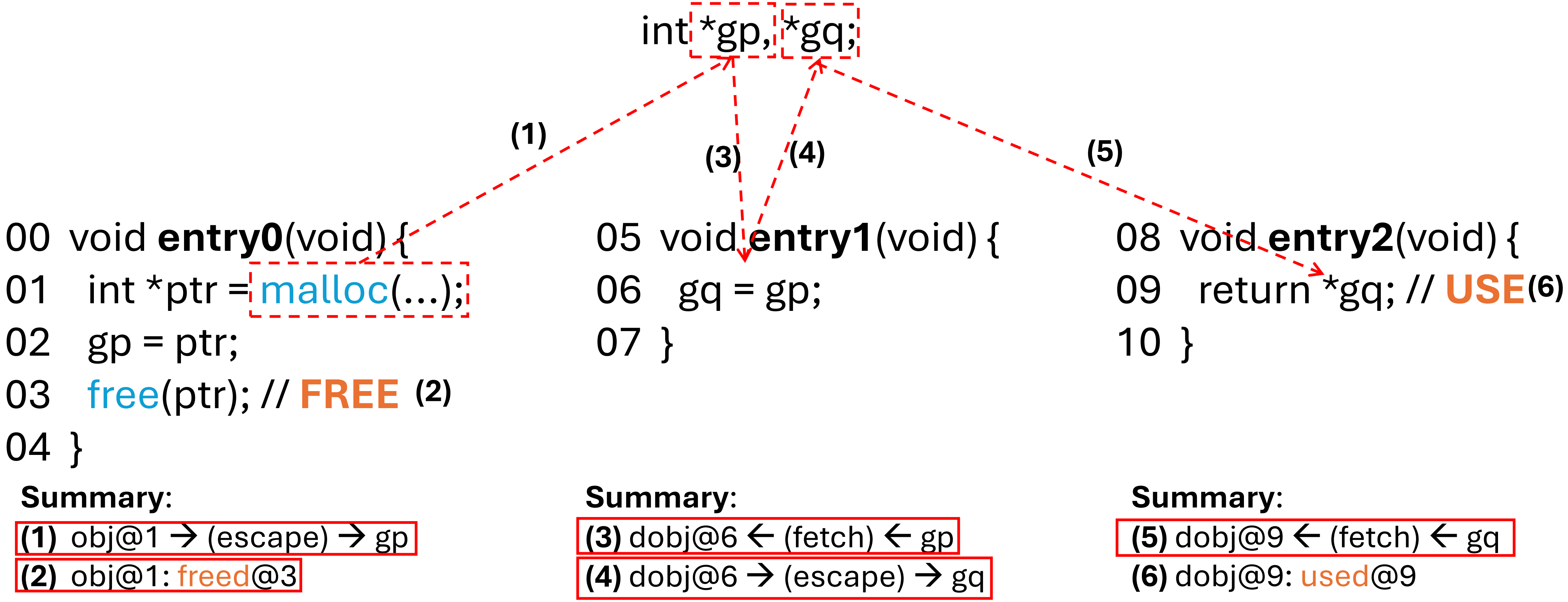

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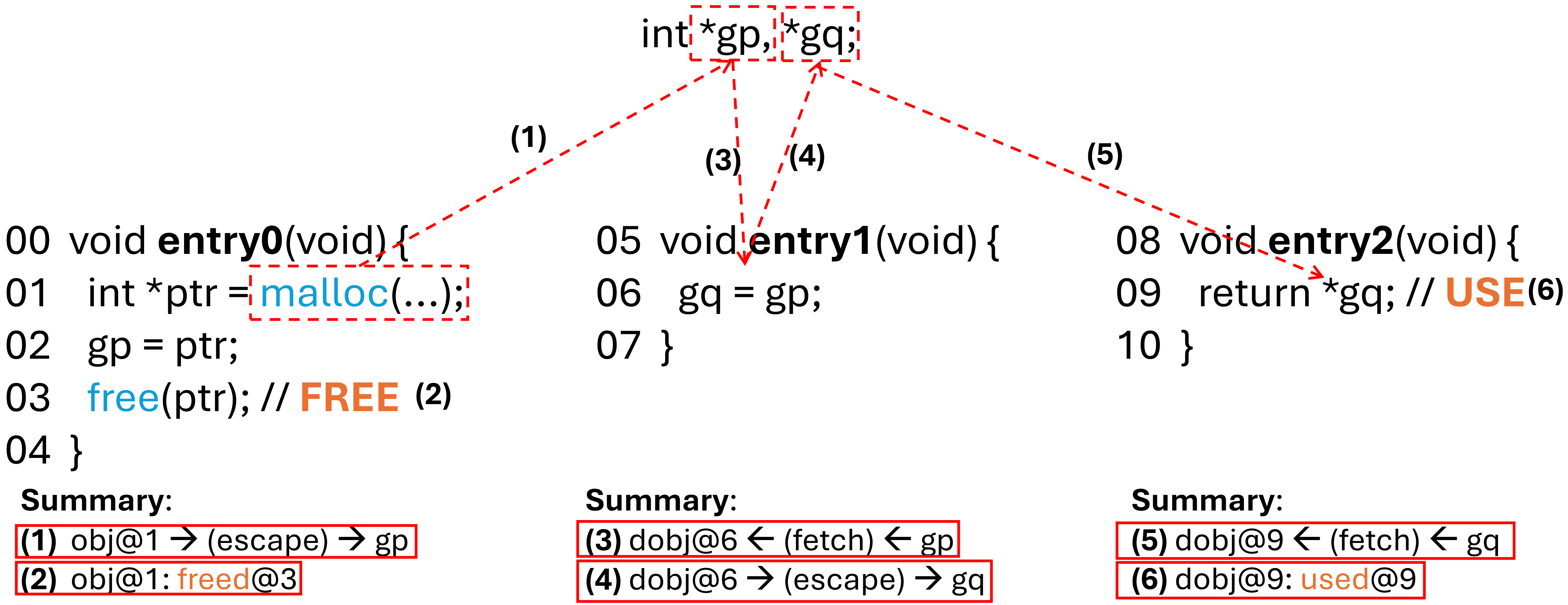

UAFX: Partial-Order-Based UAF Validation

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- **Step 1**: Identify relevant statements (e.g., lock/unlock, condition set/check) and perform the **cross-entry** match (e.g., lock objects, condition variables).

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Aliased lock pairs:
L01 (lock) - L03 (unlock),
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Aliased cond. set/check:
L04 (set) → (kill) → L08 (check)

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- Solution exists → the UAF is feasible.

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Lock semantics:

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Sequential order:

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L07 < L08 < L09 < L10

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Discover new UAFs

- **Subjects** : 34 Linux kernel device driver modules and 1 user-space program.
- UAFX issues **80** true positive warnings, where **37** have been confirmed (related to **10** independent UAF issues).

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Efficiency

- Running time **varies** for different targets, ranging from seconds to 30+ hours (for a large driver).
- More expensive than other tools due to analysis complexity.

Thank You!
Q & A