CAB-Fuzz: Practical Concolic Testing Techniques for COTS Operating Systems

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Why Microsoft can’t detect a driver with a bug (NDProxy)?

```
bool flag_table[125] = {false};
void (*fn_table[36])();

int dispatch_device_io_control(ulong ctrl_code, ulong *buf) {
  switch (ctrl_code) {
  case 0x8fff23c4:
    …
  case 0x8fff23cc:
    if (buf[0]>246 || buf[1]>124 || buf[2]>36)
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    for (int i=1; i<=buf[0]; ++i) {…}
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```

* https://www.offensive-security.com/vulndev/ndproxy-local-system-exploit-cve-2013-5065/

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buf[2]>35

buf[2] == 36 -> Out-of-bound execution

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Microsoft's large-scale fuzzing tools couldn't this bug

buf[2]>35

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Challenge 1: Path explosion because of array and loop

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Symbolic variables

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Symbolic variables

Symbolic memories

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Symbolic variables

Symbolic memories

Loop controlled by a symbolic variable

Challenge 1: Path explosion because of array and loop

```
bool flag_table[125] = {false};
void (*fn_table[36])();
```

More than million paths (124 x 36 x 246) to explore because of two arrays and a single loop

```
  case 0x8fff23cc:
    if (buf[0]>246 || buf[1]>124 || buf[2]>36)
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    if (flag_table[buf[1]])
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    for (int i=1; i<=buf[0]; ++i) {…}
}
```

Symbolic memories

Loop controlled by a symbolic variable

Challenge 1: Path explosion because of array and loop

- The number of feasible program paths to test **exponentially** increases according to its size
- COTS OS is complex and huge
- **Almost infinite number of paths to test**

Challenge 2: Difficulty in constructing pre-contexts to test targets

```
bool flag_table[125] = {false}; // default: false
void (*fn_table[36])();

int dispatch_device_io_control(ulong ctrl_code, ulong *buf)
{
  switch (ctrl_code) {
  case 0x8fff23c4:
    for (int i=0; i<125; ++i)
      flag_table[i] = true;
  case 0x8fff23cc:
    …
    if (flag_table[buf[1]])
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    if (flag_table[buf[1]])
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}
```

should be executed to trigger the bug

Challenge 2: Difficulty in constructing pre-contexts to test targets

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bool flag_table[125] = {false}; // default: false
void (*fn_table[36])();
```

Difficult to construct pre-contexts to trigger bugs

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    for (int i=0; i<125; ++i)
      flag_table[i] = true;
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should be executed to trigger the bug

Challenge 2: Difficulty in constructing pre-contexts to test targets

- Many functions and code blocks have **pre-contexts** to execute them correctly
  - Execution order to set up states (open before read), input validation (checksum), …
- **Difficult to construct or guess pre-contexts**

Challenge 2: Difficulty in constructing pre-contexts to test targets

- Many functions and code blocks have **pre-contexts** to execute them correctly
  - Execution order to set up states (open before read), input validation (checksum), …

Research goal: Can we make a concolic testing tool that
1) *avoids path explosion and*
2) *constructs pre-contexts automatically*?

Idea 1: Test paths likely having bugs first

- Prioritize **array and loop boundary states**
- Detect bugs due to a lack of proper boundary checks

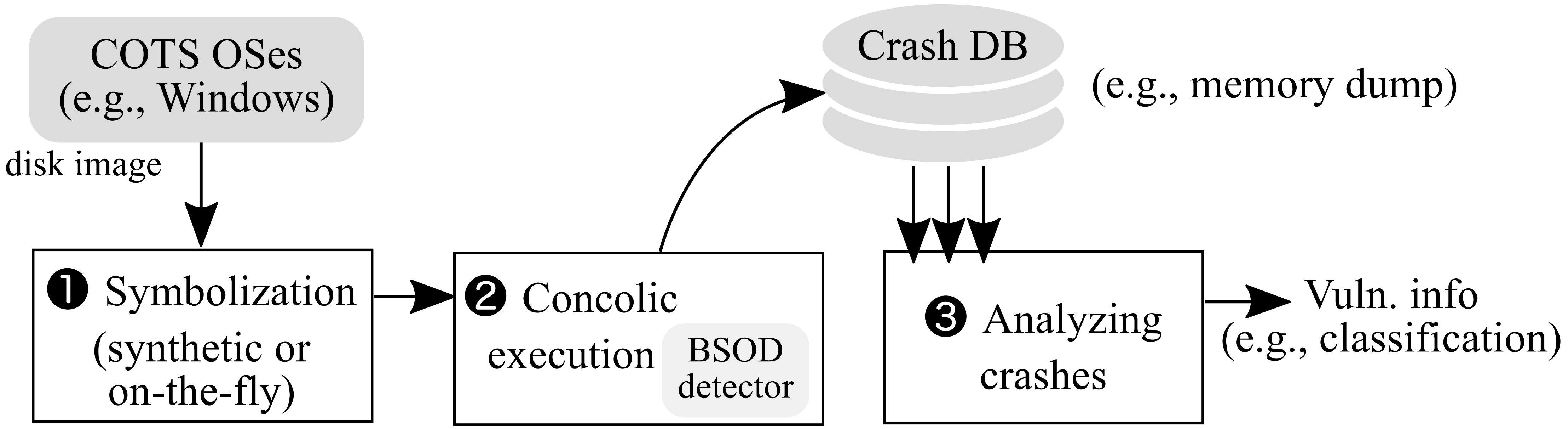
Idea 2: Construct pre-contexts using real programs

- Let real programs run until they call target OS APIs
  - Would have prepared necessary conditions before calling the APIs (they will call open syscall before read syscall)
- Hook the API calls and initiate concolic testing

Promising results

- Implemented by modifiying S2E and evaluated with Windows 7 and Windows Server 2008
- Found 21 unique crashes in six device drivers
  - Two **local privilege escalation** vulnerabilities
  - **Information disclosure** in **a crypto driver**

Overview of CAB-Fuzz



Synthetic symbolization with S2E

```
ulong ctrl_code = 0; ulong in_buf[IN_BUF_SIZE] = {0};

NtCreateFile(&device_handle,…, &object_attributes,…);

s2e_make_symbolic(&ctrl_code, sizeof(ctrl_code), “code”);
s2e_make_symbolic(&in_buf, sizeof(in_buf), “buf”);

NtDeviceIoControlFile(
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Specify target API

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Specify target drivers

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Symbolize two arguments

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Specify target API

Don't symbolize the size to avoid path explosion

Array-boundary prioritization

- Concretize the **lowest** and **highest** addresses of symbolic memory first
- Compute the boundary addresses using KLEE solver’s getRange function
  - For symbolic memory triggering a state fork at least twice

Loop-boundary prioritization

- Concretize a loop as **no loop execution**, a **single** execution, and the **maximum** executions
- Use a fork-and-kill approach to deal with unclear loop conditions and structures
  - Let a loop execute until it forks no more states (maximum)
  - Kill or pause uninteresting loop states

Prioritization reduces # of state forks to detect a bug

```
…
if (buf[0]>246 &&
    buf[1]>124 &&
    buf[2]>36)
  return -1;
if (flag_table[buf[1])
  (*fn_table[buf[2]])();
for (int i=1; i<=buf[0];
     ++i) {…}
…
```

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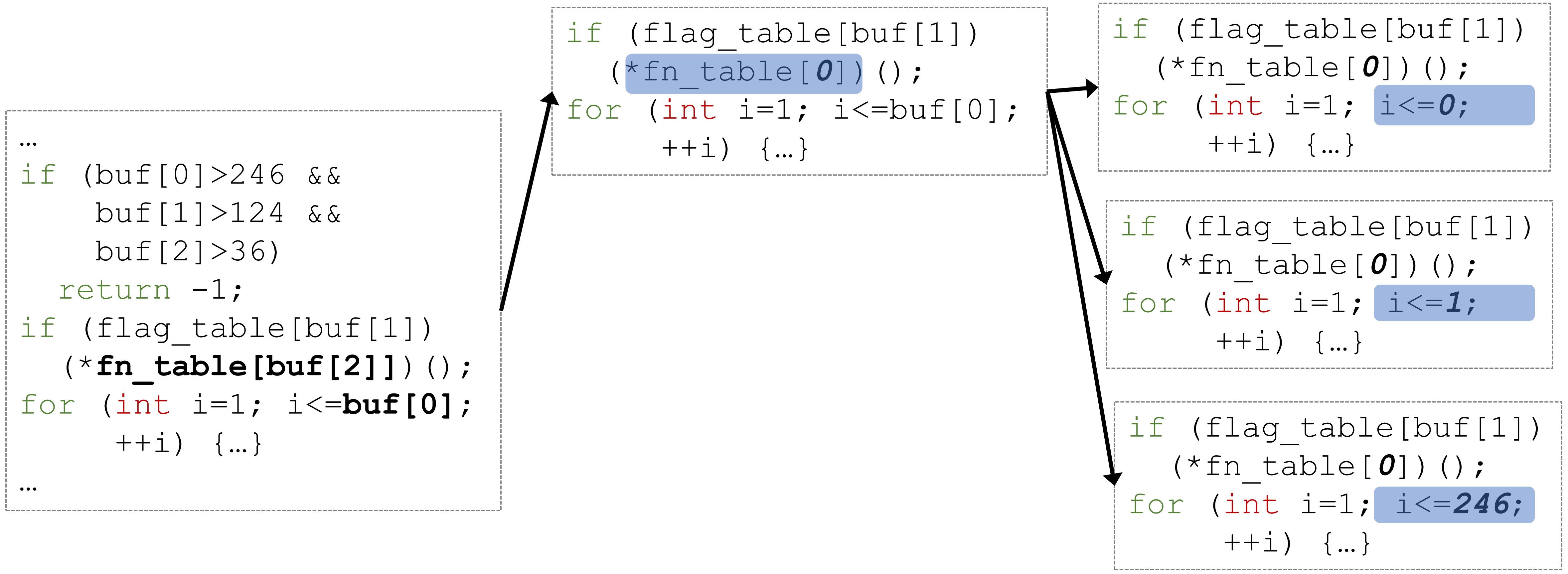

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```

```
if (flag_table[buf[1]])
   (*fn_table[0])();
for (int i=1; i<=buf[0];
      ++i) {…}
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if (flag_table[buf[1]])
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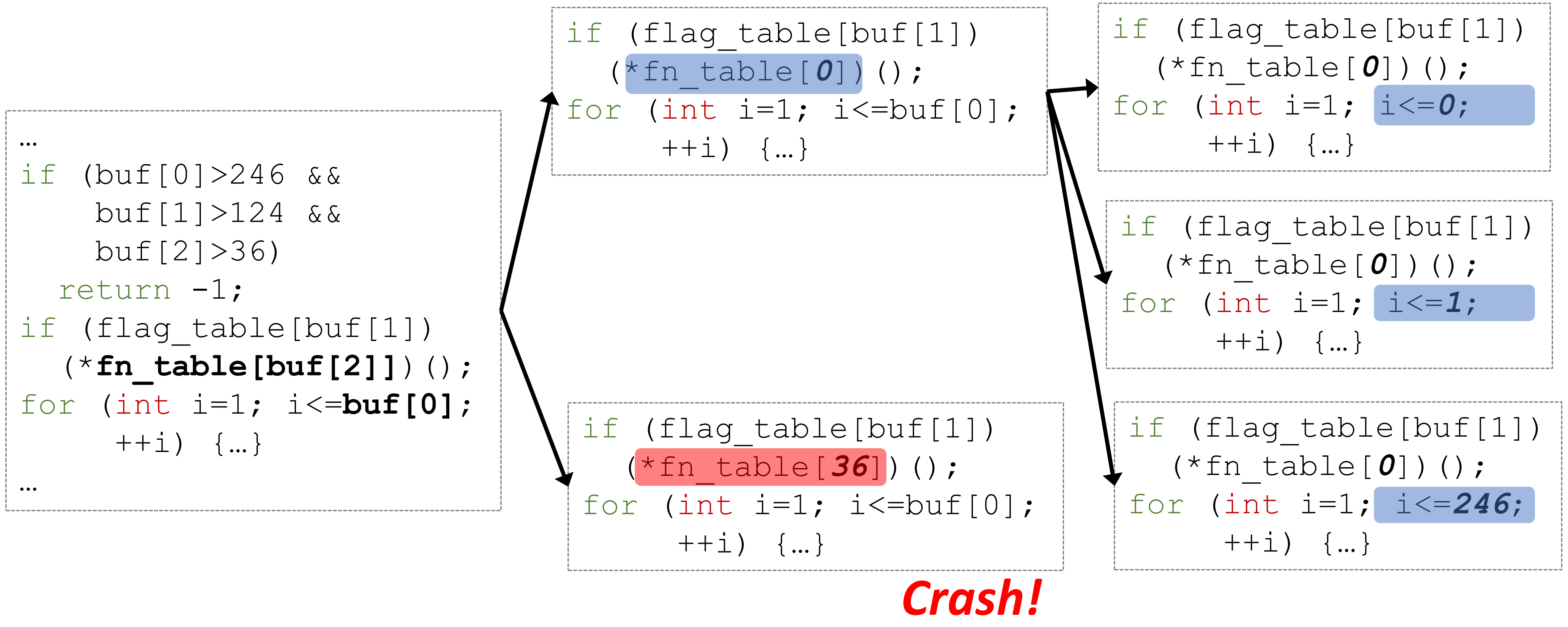
if (flag_table[buf[1]])
   (*fn_table[0])();
for (int i=1; i<=1;
      ++i) {…}
```

```
if (flag_table[buf[1]])
   (*fn_table[0])();
for (int i=1; i<=246;
      ++i) {…}
```

Prioritization reduces # of state forks to detect a bug



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      ++i) {…}
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if (flag_table[buf[1])
  (*fn_table[0])();
for (int i=1; i<=1;
      ++i) {…}
```
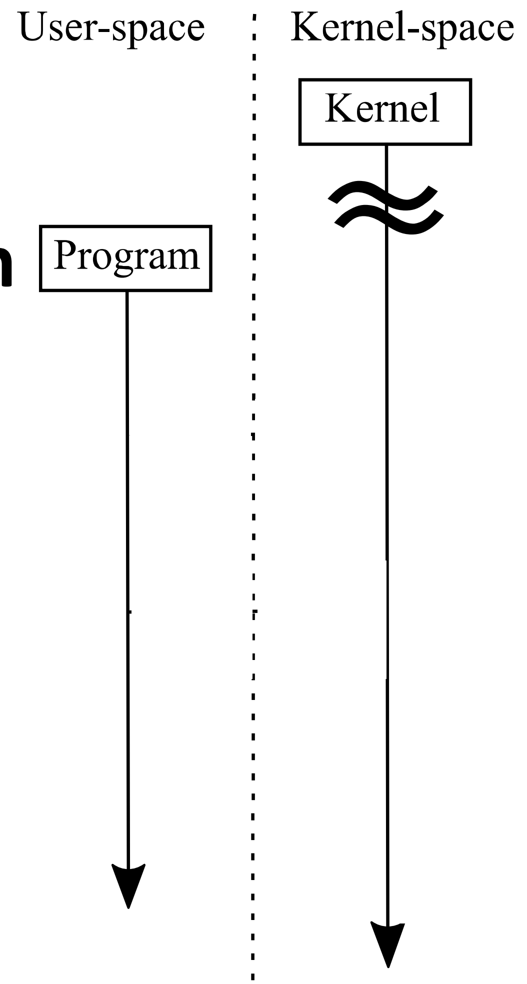

```
if (flag_table[buf[1])
  (*fn_table[0])();
for (int i=1; i<=246;
      ++i) {…}
```

On-the-fly symbolization

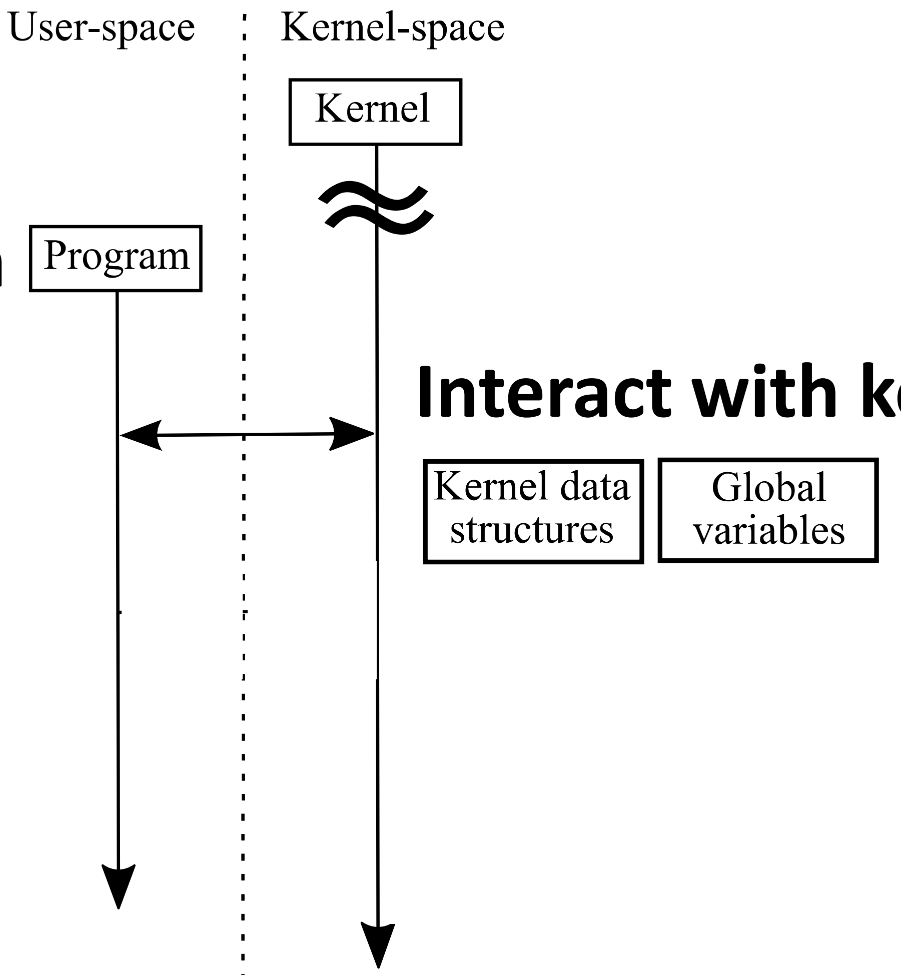
Run a real program



On-the-fly symbolization

Run a real program

Interact with kernel

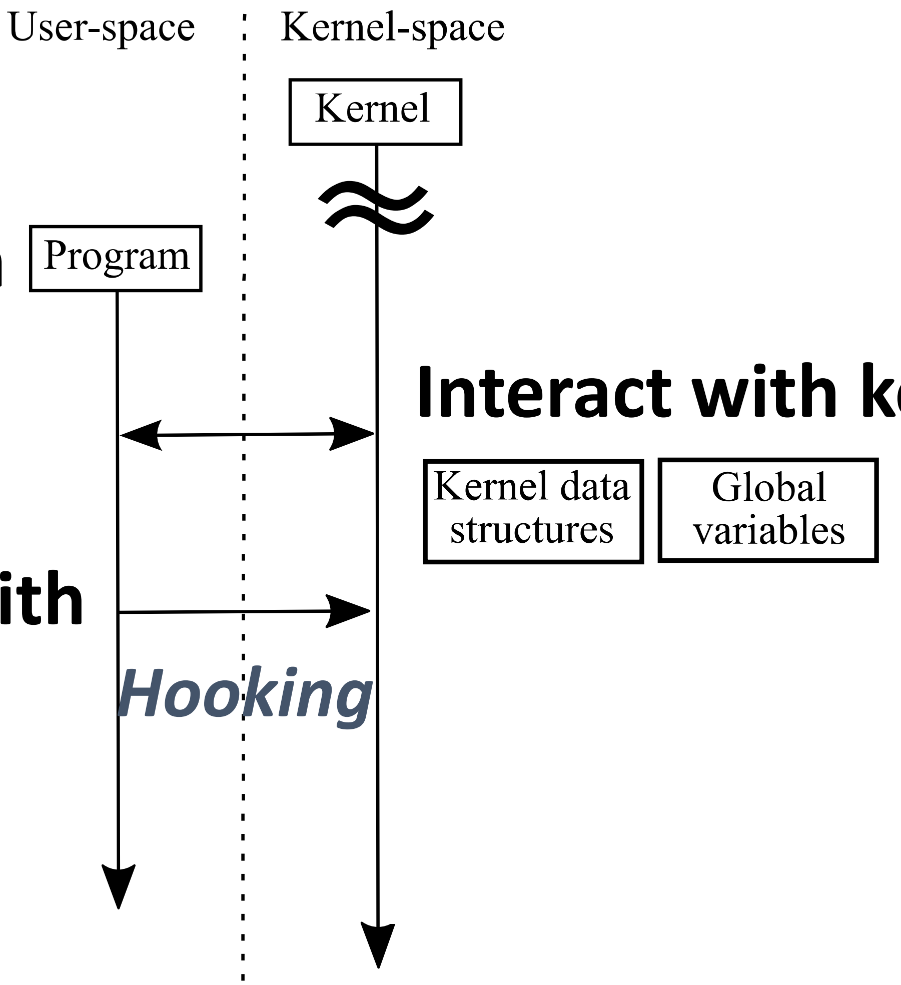


On-the-fly symbolization

Run a real program

Interact with kernel

Call a target function with valid arguments



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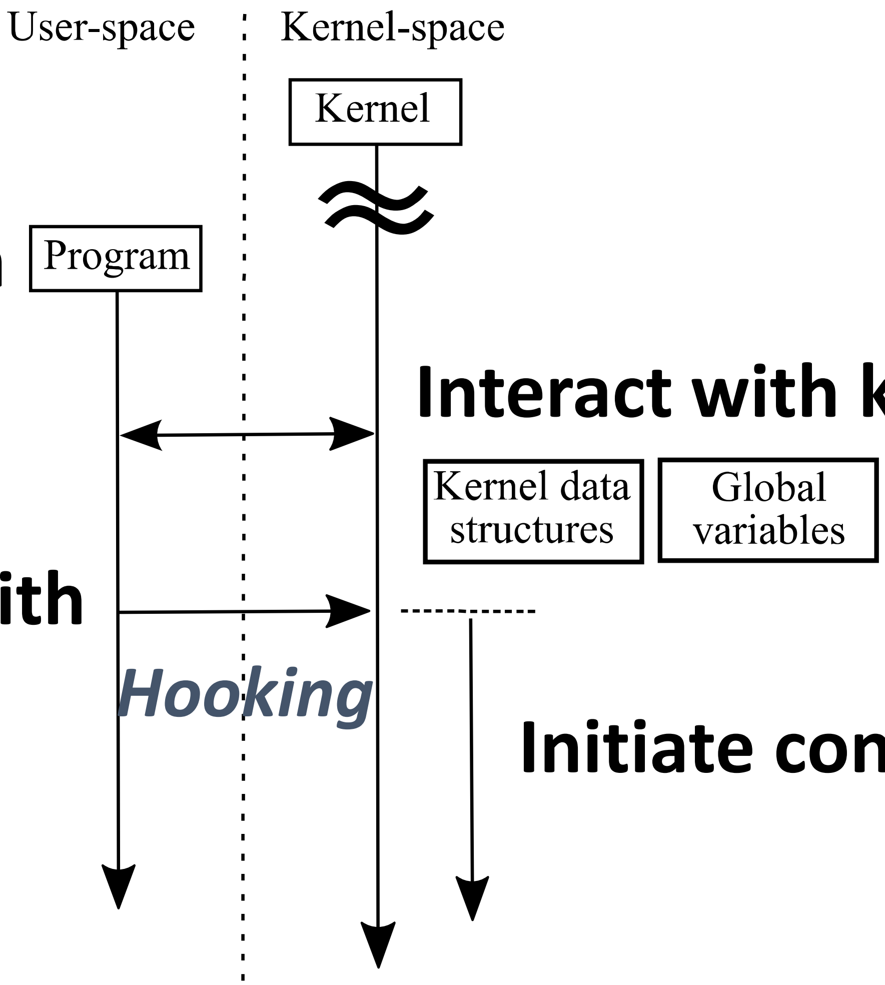


Run a real program

Interact with kernel

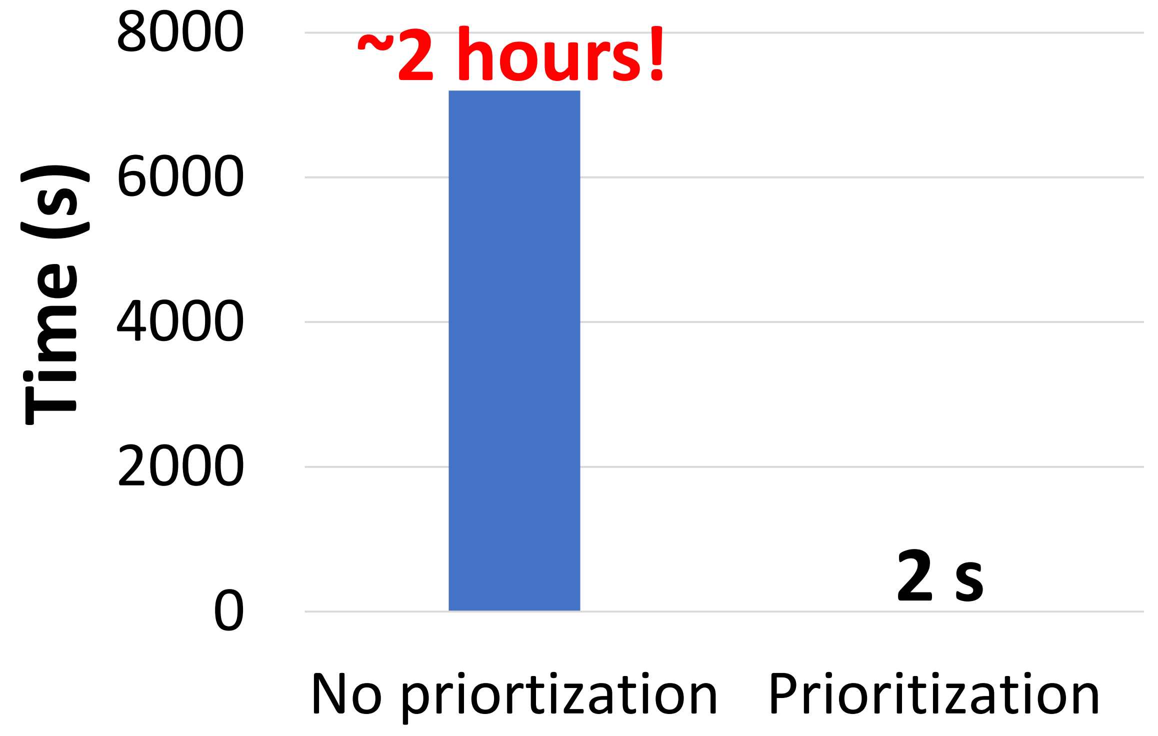
Call a target function with valid arguments

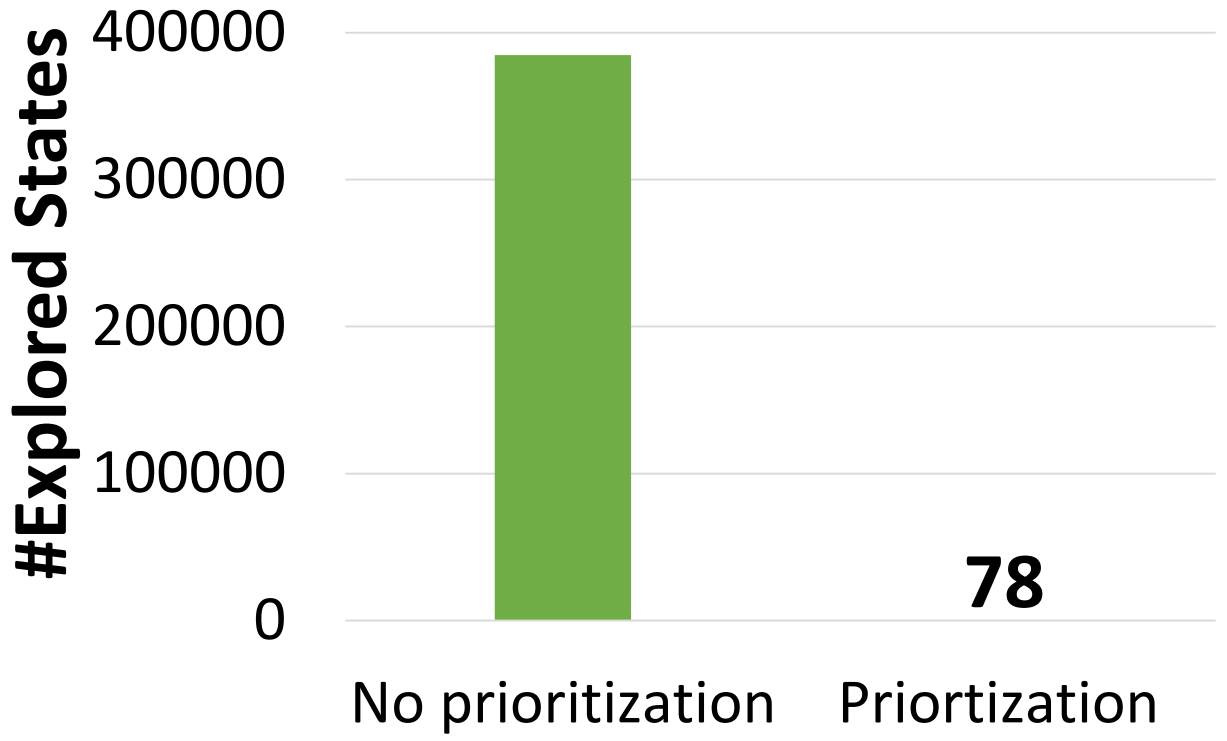
Initiate concolic testing

Evaluation

- How efficiently did CAB-Fuzz detect the known vulnerability (NDProxy)?
- How many new crashes did CAB-Fuzz discover?
- What particular characteristics did the newly discovered crashes exhibit?

CAB-Fuzz crashed NDProxy within two seconds



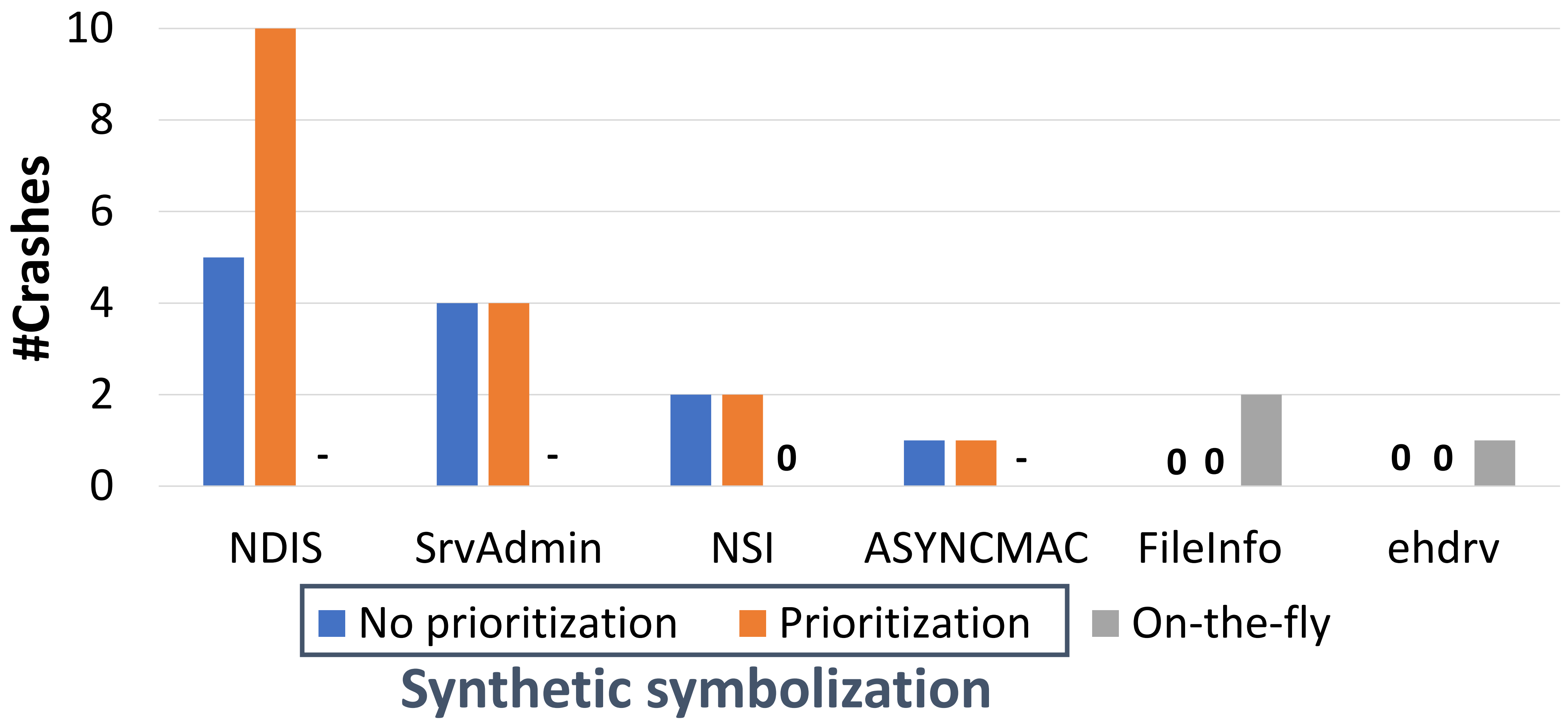


CAB-Fuzz found 21 new crashes

- Synthetic symbolization
  - 274 device drivers in Windows 7 and Windows Server 2008
- On-the-fly symbolization
  - 16 real programs and 15 drivers the programs used

➢**Found 21 crashes in six among the drivers**

CAB-Fuzz found 21 new crashes



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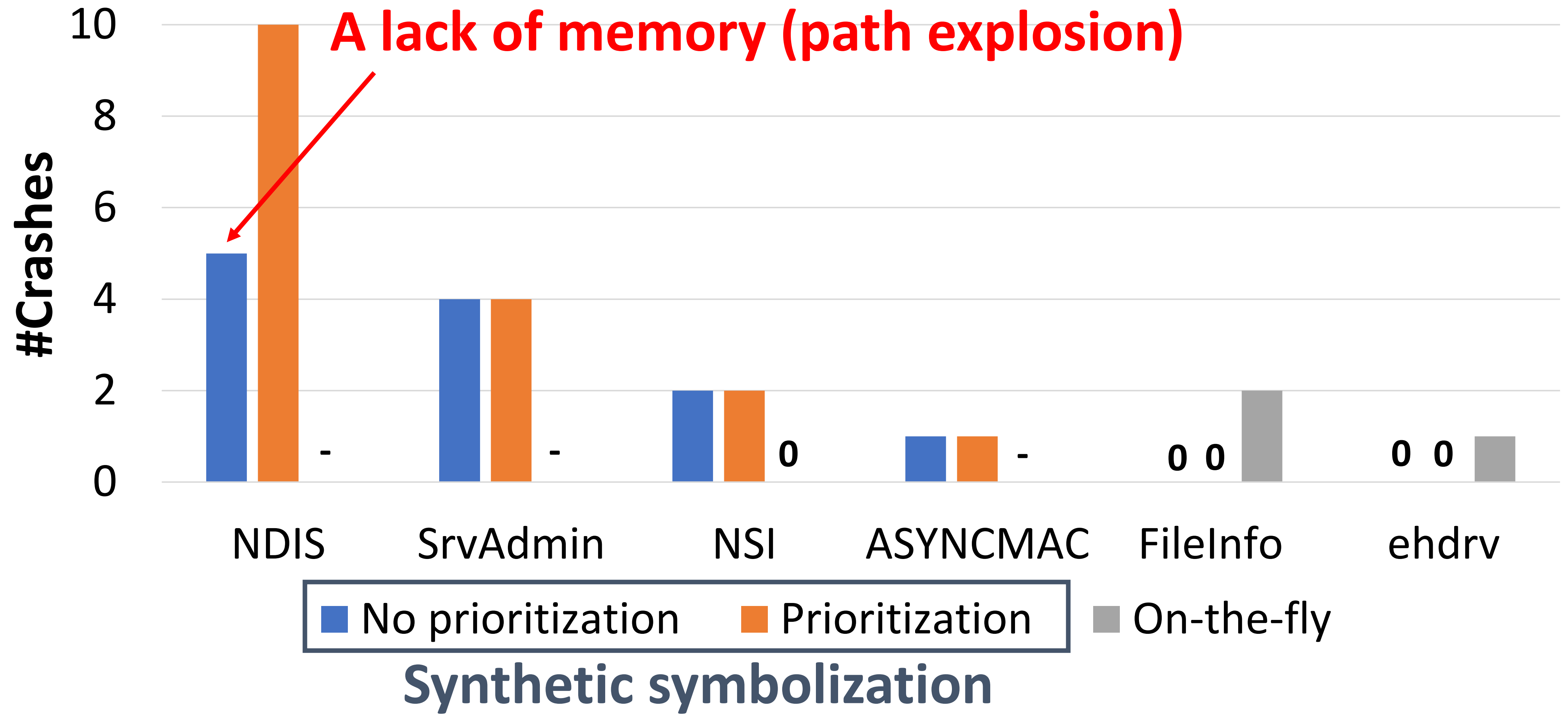

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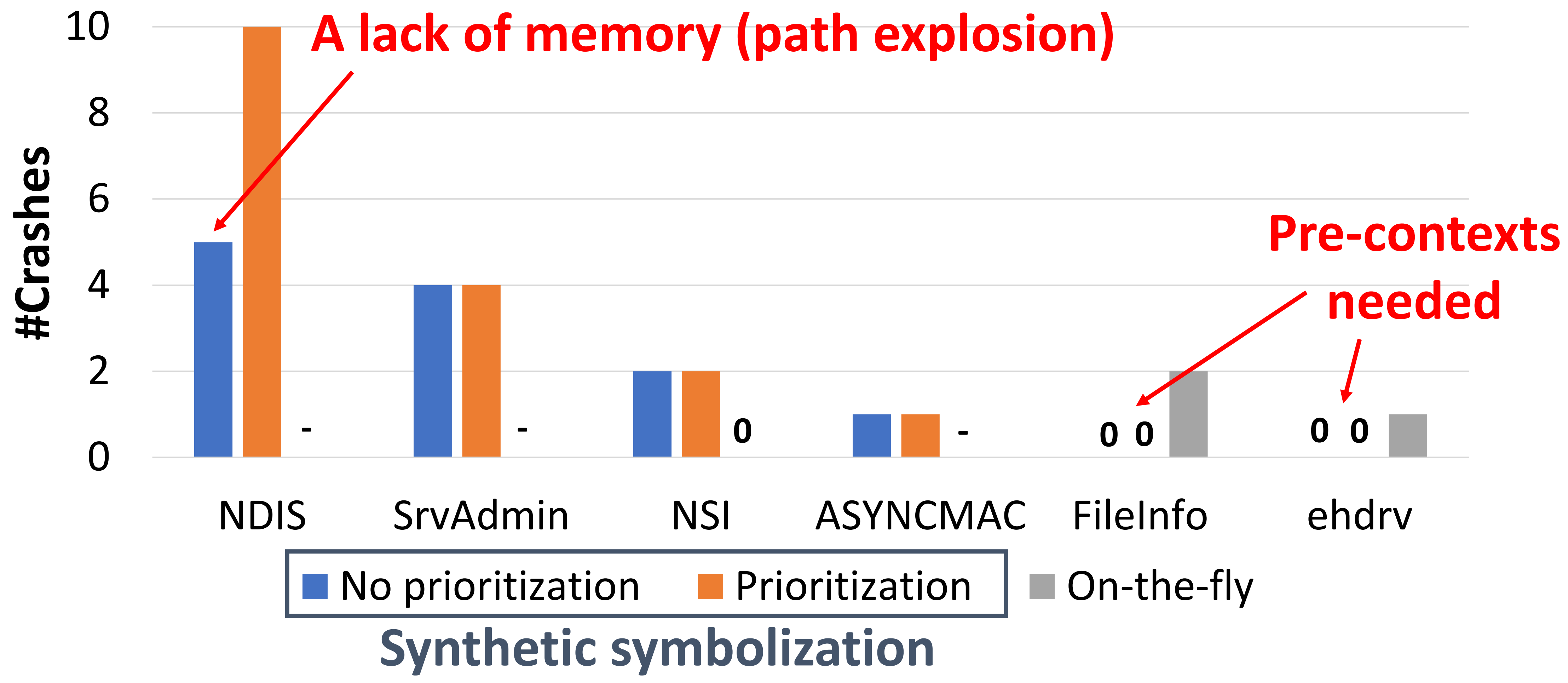

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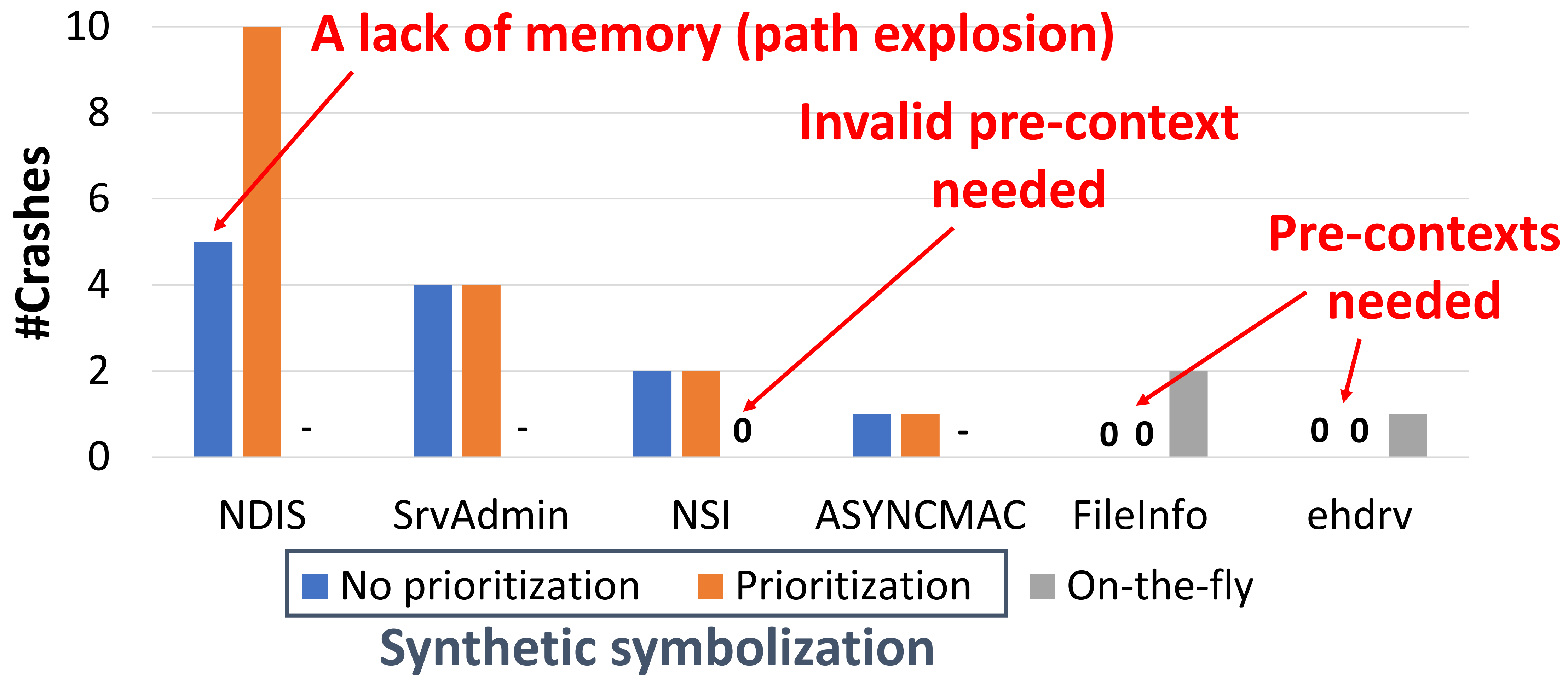

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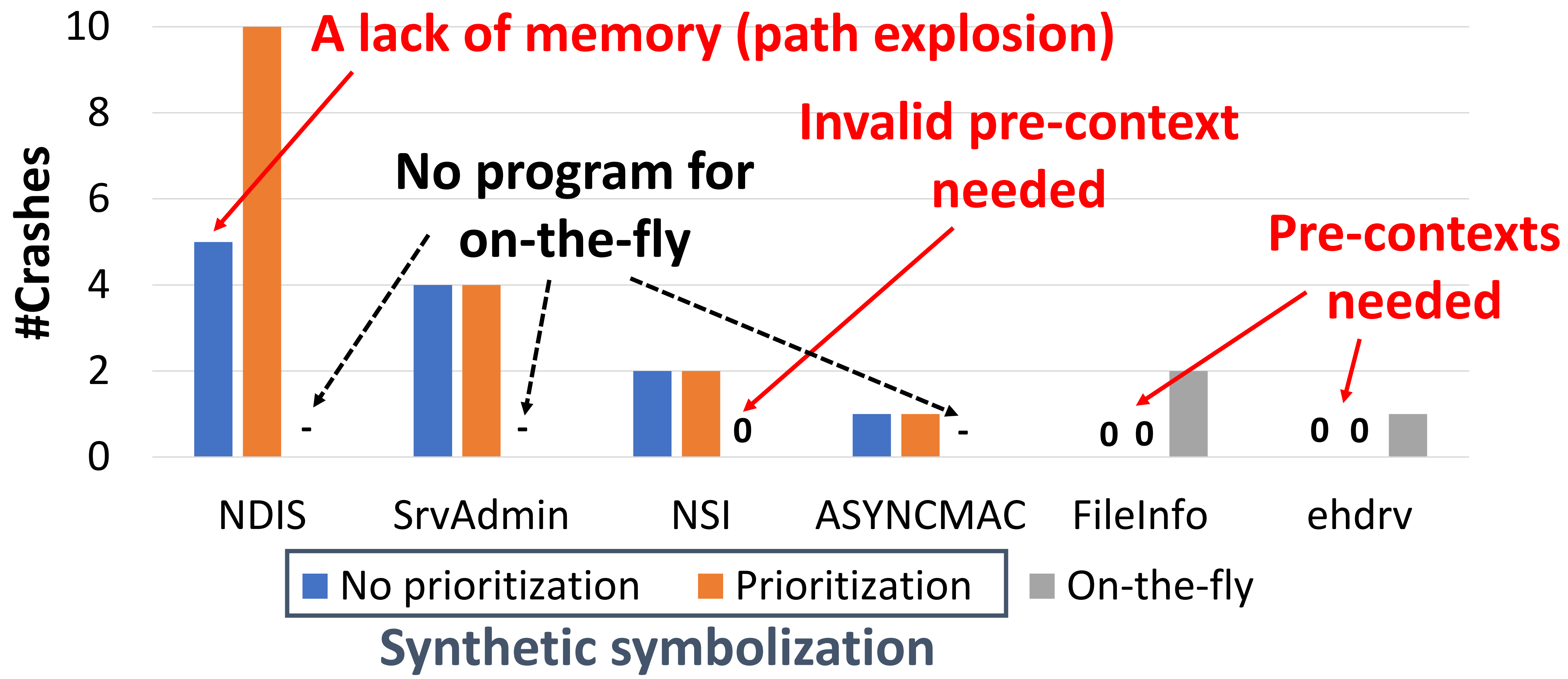

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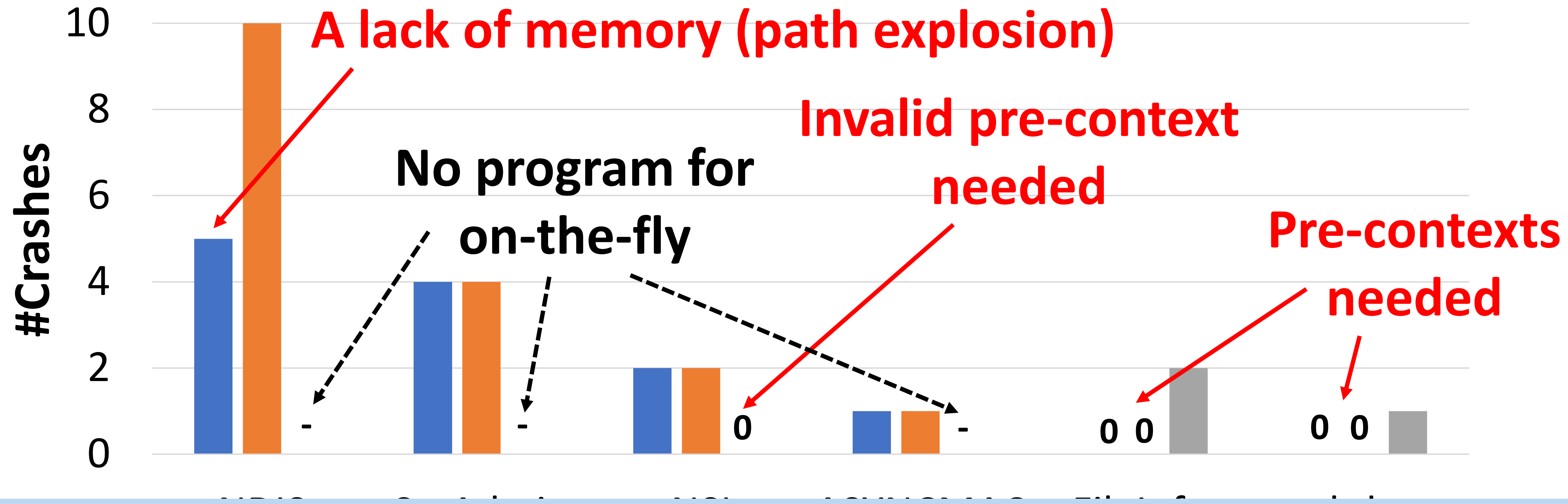
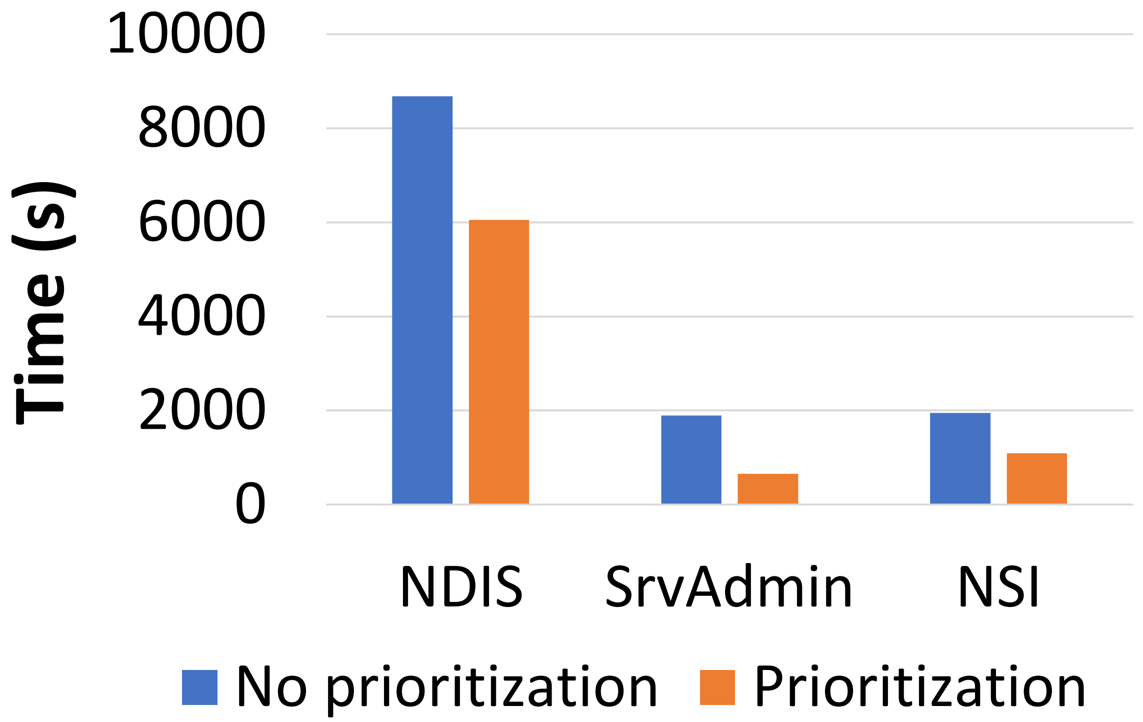


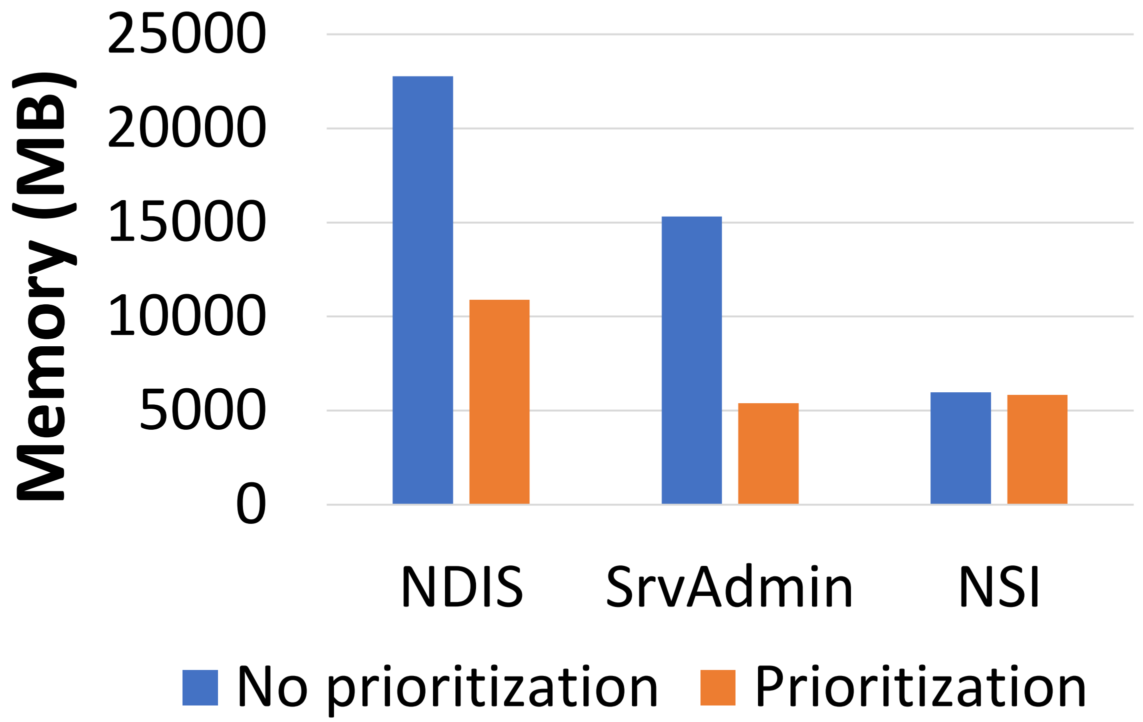
Synthetic and on-the-fly symbolizations are complementary to each other

What pre-contexts did drivers need?

- Selectively loaded (FileInfo)
  - Filesystem filter driver by Microsoft
  - **Loaded only when a certain program started**
- Access controlled (ehdrv)
  - Driver installed by antivirus software ESET Smart Security
  - **Only accessible by the antivirus software itself**

Prioritization reduced CPU time and memory usage





Limitations

- Reduce code coverage when prioritizing symbolic memory with instruction addresses (e.g., jump table)
- Cannot get boundary states from flexible data structures (e.g., linked list)

Limitations

- Have difficulties in regenerating on-the-fly-driven crashes
    - Lack of explicit control of pre-contexts construction
- Need to specify target APIs and programs

Conclusion

- CAB-Fuzz: A practical concolic testing tool for COTS OS
  - Check potentially vulnerable paths first
  - Analyze COTS OS without debug information and pre-contexts
- Found 21 crashes including three vulnerabilities with CVEs