Understanding and Detecting Disordered Error Handling with Precise Function Pairing

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Two parts of error related code

Error related code == cleaning up + error handling

- Cleanup operations
  - In the error code, programs often perform “cleanup” operations

```
/* drivers/media/platform/s5p-g2d/g2d.c */
static int g2d_probe (struct platform_device *pdev) {
        …
        ret = v4l2_device_register(&pdev->dev, &dev->v4l2_dev);
        if (ret)
                goto unprep_clk_gate;
        vfd = video_device_alloc();
        if (!vfd) {
                ret = -ENOMEM;
                goto unreg_v4l2_dev;
        }
        ...
unreg_v4l2_dev:
        v4l2_device_unregister(&dev->v4l2_dev);
unprep_clk_gate:
        clk_unprepare(dev->gate);
        return ret;
}
```

Cleanup operations

Error related code == cleaning up + error handling

- Cleanup operations
- Handling the errors
  - Besides cleanup operations, the program will handle the error through return error, print out error-message, stop the execution ...

```
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}
```

Handling the errors

Previous works

- Most research focused on “handling” but not “cleanup”
  - Error-propagation related bugs
  - Error check related bugs
  - Error-handling severity level

Previous works

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- Some attempted to detect only missing cleanup operations
  - Missing release, missing refcount decrease, ...

Previous works

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- Some research attempted to detect only missing cleanup operations

Limitations:

1.Could only handle obvious cleanup operations

- Commonly used release functions
- Function name based approach

2.None of them can comprehensively and systematically detect wrong cleanup operations .

Critical issues with cleanup operations

- Calling cleanup operations inadequately
  - Missing release, missing refcount decrease …

Critical issues with cleanup operations

- Calling cleanup operations inadequately
- Calling cleanup operations redundantly
    - Double-free, double-unlock, ...

Critical issues with cleanup operations

- Calling cleanup operations inadequately
- Calling cleanup operations redundantly
- Calling cleanup operations in an incorrect order
    - Use-after-free, double-free, ...

Critical issues with cleanup operations

- Calling cleanup operations inadequately
- Calling cleanup operations redundantly
- Calling cleanup operations in an incorrect order

We refer to such bugs that caused by incorrect cleanup operations as ***Disordered Error Handling*** (DiEH).

Our goal:

Systematically study and detect the DiEH bugs

How to clean up correctly?

Clean up correctly == Correctly use function pairs

Function pair = leader function + follower function

- Leader function
  - initiates an operation against some resources
- Follower function: typically used as cleanup operations
  - recovers the resources that are initiated by leader functions

Cleanup correctly == Correctly use function pairs

```
1  static int foo() {
2    // allocate memory
3    mem = kmalloc(...);
4    if (!mem)
5        return -1;
6    …
7    if (err) {
8        // free previously allocated memory
9        kfree(mem);
10       …
11   }
12   ...
13 }
```

Function pairs

	Leader	Follower	
③	kmalloc	kfree	⑨

Cleanup correctly == Correctly use function pairs

```
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  // allocate memory
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  if (!mem)
        return -1;
  …
  if (err) {
        // free previously allocated memory
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        …
  }
  ...
}
```

Function pairs

Leader	Follower
③ kmalloc	kfree ⑨

The follower functions typically perform the cleanup operation.

The first step and the key step of identifying DiEH bugs is correctly pairing function.

How to collect function pairs?

Intuitive approaches

- Name-based approach
  - e.g., “alloc” --- ‘free’, “inc” -- “dec”
- NLP based approach
  - Checking the function description
- Pattern-mining based approach

Limitations:

1. High FPs & FNs
2. Cannot handling customized functions well

The incremental error-handling structure --- EH stacks

```c
1 /* drivers/media/platform/s5p-g2d/g2d.c */
2 static int g2d_probe (struct platform_device *pdev) {
3         …
4         ret = v4l2_device_register(&pdev->dev, &dev->v4l2_dev);
5         if (ret)
6                 goto unprep_clk_gate;
7         vfd = video_device_alloc();
8         if (!vfd) {
9                 ret = -ENOMEM;
10                goto unreg_v4l2_dev;
11        }
12        …
13        ret = video_register_device(vfd, VFL_TYPE_VID, 0);
14        if (ret)
15                goto rel_vdev;
16        …
17        dev->m2m_dev = v4l2_m2m_init(&g2d_m2m_ops);
18        if (IS_ERR(dev->m2m_dev))
19                goto unreg_video_dev;
20        ...
21 unreg_video_dev:
22        video_unregister_device(dev->vfd);
23 rel_vdev:
24        video_device_release(vfd);
25 unreg_v4l2_dev:
26        v4l2_device_unregister(&dev->v4l2_dev);
27 unprep_clk_gate:
28        clk_unprepare(dev->gate);
29        ...
30 }
```

Function pairs

	Leader	Follower	
4	v4l2_device_register	v4l2_device_unregister	26
7	video_device_alloc	video_device_release	24
13	video_register_device	video_unregister_device	22
	...	...	

A stack-like (LIFO) structure: The first called leader function will be handled at last.

The incremental error-handling structure --- EH stacks

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25 unreg_v4l2_dev:
26        v4l2_device_unregister(&dev->v4l2_dev);
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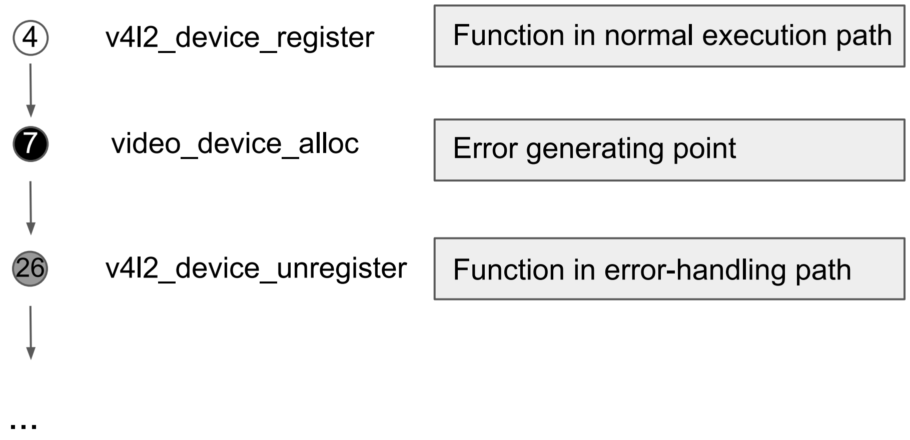
28        clk_unprepare(dev->gate);
29        ...
30 }
```

Error handling(EH) stack: represent the functions in one path.

E.g.,:



The functions in line 4 -> 7 -> 26 -> … form a EH stack

Collecting function pairs based on the EH deltas

```
1 /* drivers/media/platform/s5p-g2d/g2d.c */
2 static int g2d_probe (struct platform_device *pdev) {
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```

Consider two execution paths

EH Stack	
4->7->26->...	#1

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23 rel_vdev:
24        video_device_release(vfd);
25 unreg_v4l2_dev:
26        v4l2_device_unregister(&dev->v4l2_dev);
27 unprep_clk_gate:
28        clk_unprepare(dev->gate);
29        ...
30 }
```

Consider two execution paths

EH Stack	
4->7->26->...	#1
4->7->13->24->26->...	#2

Collecting function pairs based on the EH deltas

```
1 /* drivers/media/platform/s5p-g2d/g2d.c */
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```

Consider two execution paths

EH Stack	
4->7->26->...	#1
4->7->13->24->26->...	#2

EH delta : Subtract two EHs

(only consider successfully executed functions)

7(video_device_alloc)-24(video_device_release)

Collecting function pairs based on the EH deltas

```
1 /* drivers/media/platform/s5p-g2d/g2d.c */
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Consider two execution paths

EH Stack	
4->7->26->...	#1
4->7->13->24->26->...	#2

EH delta : Subtract two EHs
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7(video_device_alloc)-24(video_device_release)

EH deltas = Function pairs

Detecting DiEH bugs based on function pairs

Detecting DiEH bugs based on function pairs

- Detecting DiEH cases
  - Check leader and follower functions in every EH stacks
  - Detecting the disordered usages of the function pairs
  - E.g., [alloc1, aclloc2, free1, free2]

- Detecting DiEH bugs from DiEH cases
  - Eliminating infeasible paths
  - Eliminating harmless DiEH cases by dependency reasoning
  - Ranking reported bugs through cross-validation

Evaluation

Performance

Target programs	Lines of code	Num of IR files	Time for pairing	Time for detection
Linux kernel	17.7M	18071	48 min	10h16min
FreeBSD	4.8M	1483	10 min	2h28min
OpenSSL	450K	1903	53 sec	11min

Detected function pairs and DiEH bugs

Target programs	Num of func pairs	Num of DiEH bugs	Security impacts of DiEH bugs
Linux kernel	7.5K (precision > 90%, recall > 60%)	234 (48% FPR)	Double-free, use-after-free, refcount leak, memory leak, double unlock
FreeBSD	416	2	Memory leak
OpenSSL	323	3	Double-free, memory leak

Conclusions

- Cleanup operations are commonly misused.
- We proposed DiEH bugs that are caused by improper cleanup operations.
- We proposed an EH-delta based pairing mechanism.
- Identified a large number of function pairs, critical DiEH bugs (cause double-free, UAF, memory leak, …)