Kernel Memory Corruption Debug

Based On SLAB Implementation

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Agenda

- Basic concepts
- Debugging methods
- Case study
- Potential improvements

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Memory corruption causes

- Hardware bugs
  - X86 Machine Check errors
    - CPU
    - DIMM
    - QPI
  - PCIe errors
- Some legacy or low end x86 box's RAS protection had the big gaps
  - Lots of CFDs caused by DIMM UEs and CPU errors
  - Platform SEL logs might not have debug information

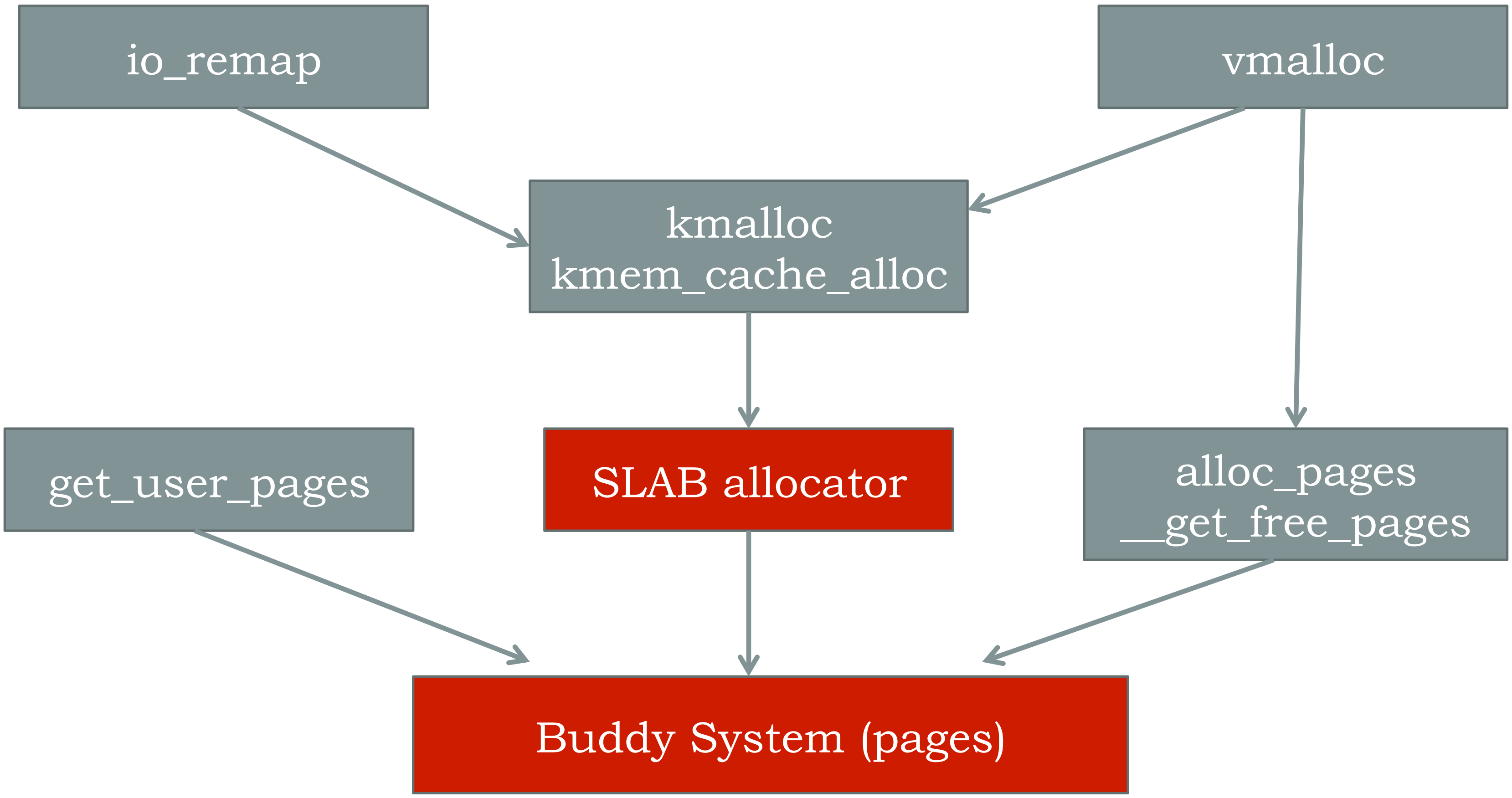
Memory corruption causes

- Software bugs
  - Use before initilaization
  - Use after free on heap, stack, global
    - Reference invalid memory
    - Double free
  - Out of bound memory access
    - Heap overflow
    - Stack overflow
    - Global overflow
  - Data race
    - Race conditions on memory modifications

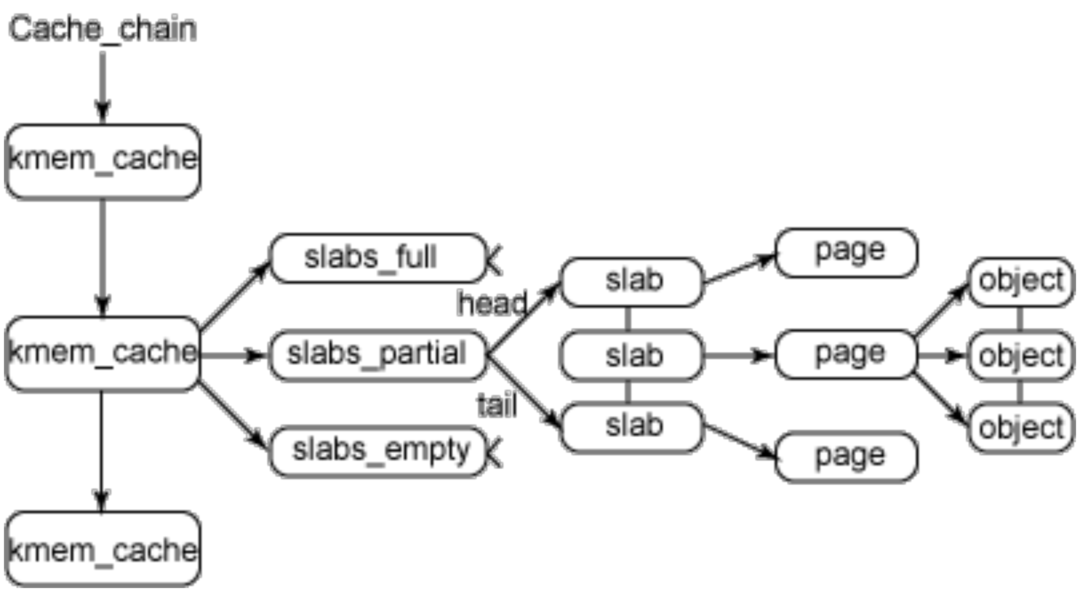
Challenges

- Memory corruption: one of most intractable issues
  - Hard to get root causes by a core dump file
    - The source of the memory corruption and its manifestation may be far apart, making it hard to correlate the cause and the effect.
  - Difficult to reproduce
    - Symptoms appear under unusual conditions, making it hard to consistently reproduce the error
- Kernel memory debugging is more difficulty
  - Difficult to triage due to cross component boundary
  - Lack of debugging facilities and tools

Kernel memory APIs



SLAB Intro



Cache_chain
kmem_cache
kmem_cache
kmem_cache
slabs_full
slabs_partial
slabs_empty
head
tail
slab
slab
slab
page
page
page
object
object
object

Slab Structure

Per-CPU local cache

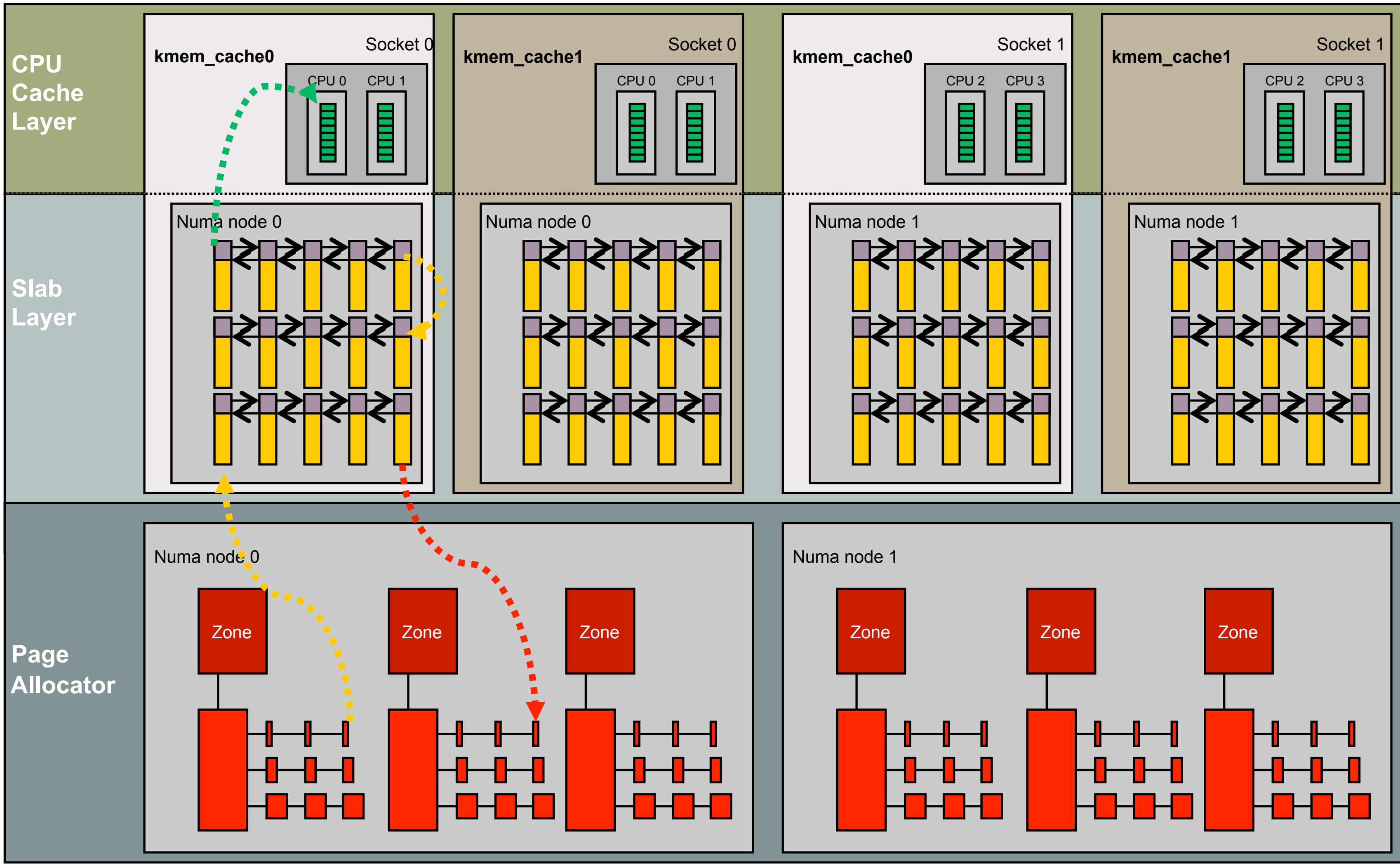
kmem_cache

- array_cache[N_CPUS]
  - array_cache *shared
  - array_cache *alien
- kmem_list3[N_NODES]
  - slabs_partial
  - slabs_full
  - slabs_free

Global Slab Layer

Page allocator

Slab - Layered Design



Slab memory layout

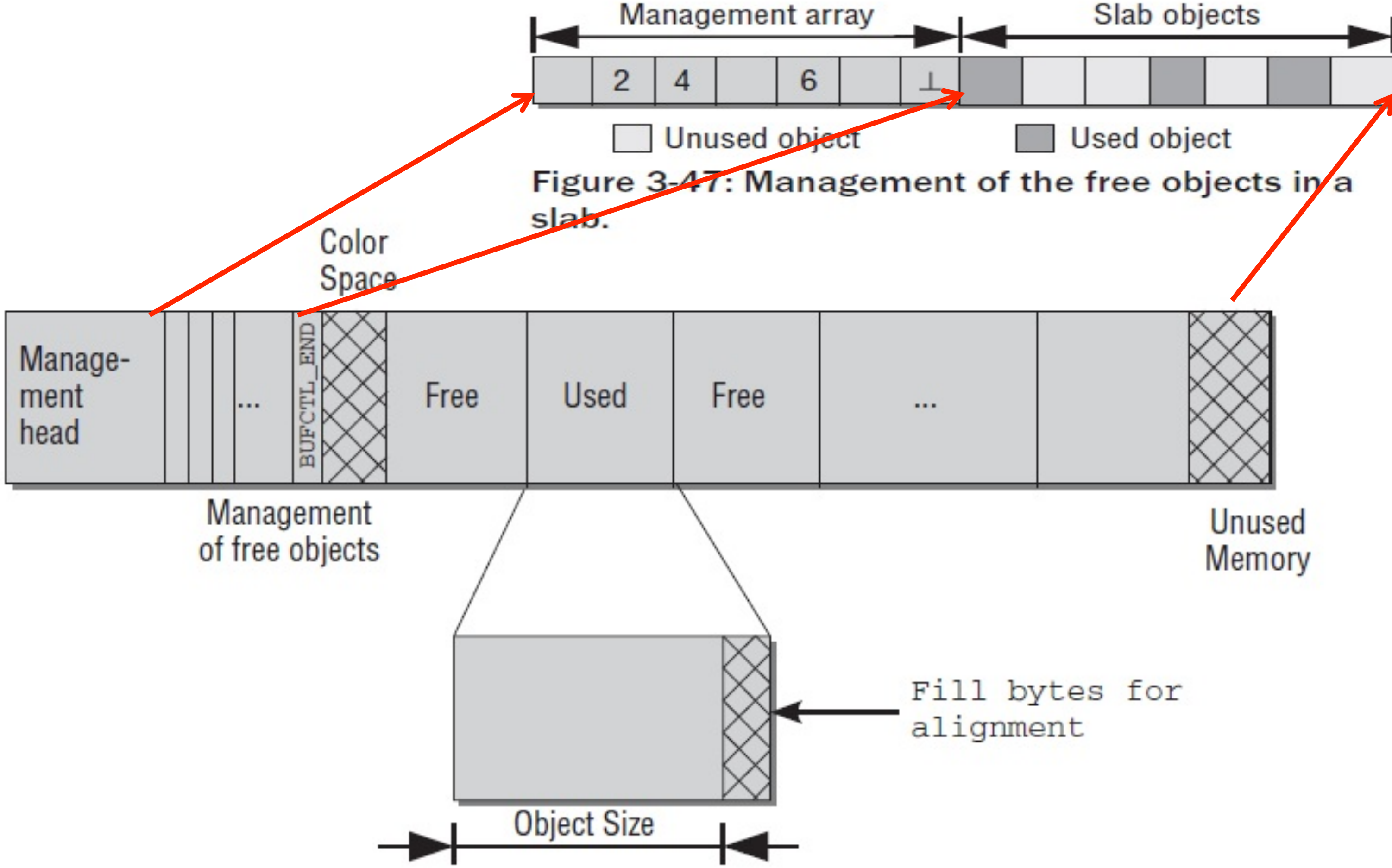


Figure 3-47: Management of the free objects in a slab.

Figure 3-46: Fine structure of a slab.

SLAB debugging use cases

- Use-after-free
  - Poison, check at next alloc
  - If off_slab and nPAGEs, record the call stack of last free, then unmap the slab page
- Use-before-initialization
  - Poison, check at debugging time
- Double free, check the memory outside of object
  - Redzone, mark INACTIVE at free time
  - Bufctl, mark FREE at free time
- Buffer overflow
  - Redzone, check redzone at free
- Memory Leak
  - Traverse all the slab, and aggregate the callers (STORE_USER)

Object layout for debugging

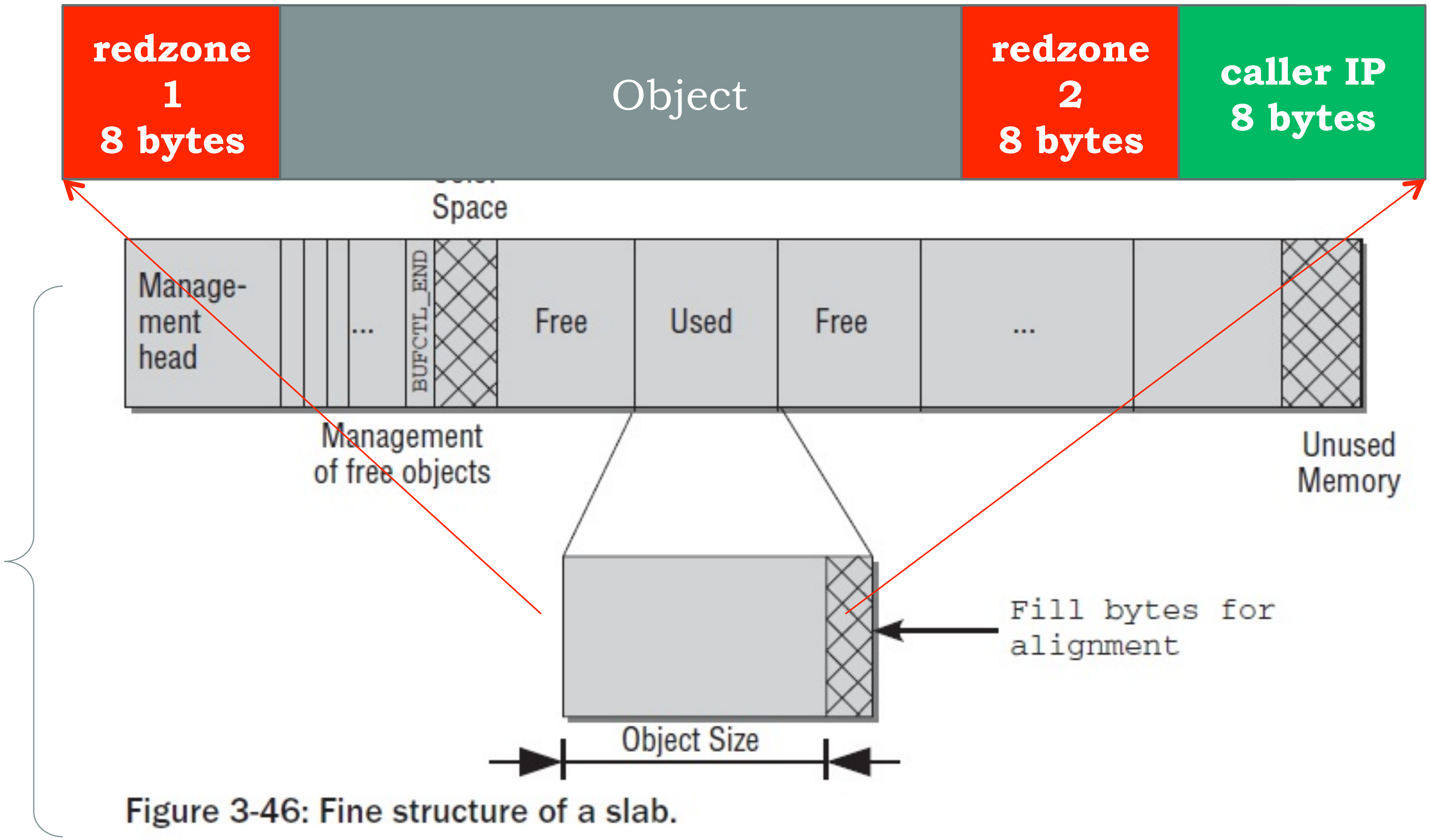


Figure 3-46: Fine structure of a slab.

Redzone

#define RED_INACTIVE 0x09F911029D74E35BULL /* when obj is inactive */

#define RED_ACTIVE 0xD84156C5635688C0ULL /* when obj is active */

Allocation

1. ! INACTIVE. (X)
2. set redzone ACTIVE

Initialization

1. set redzone INACTIVE
2. ctor()
3. ! INACTIVE. (X)

Destroy

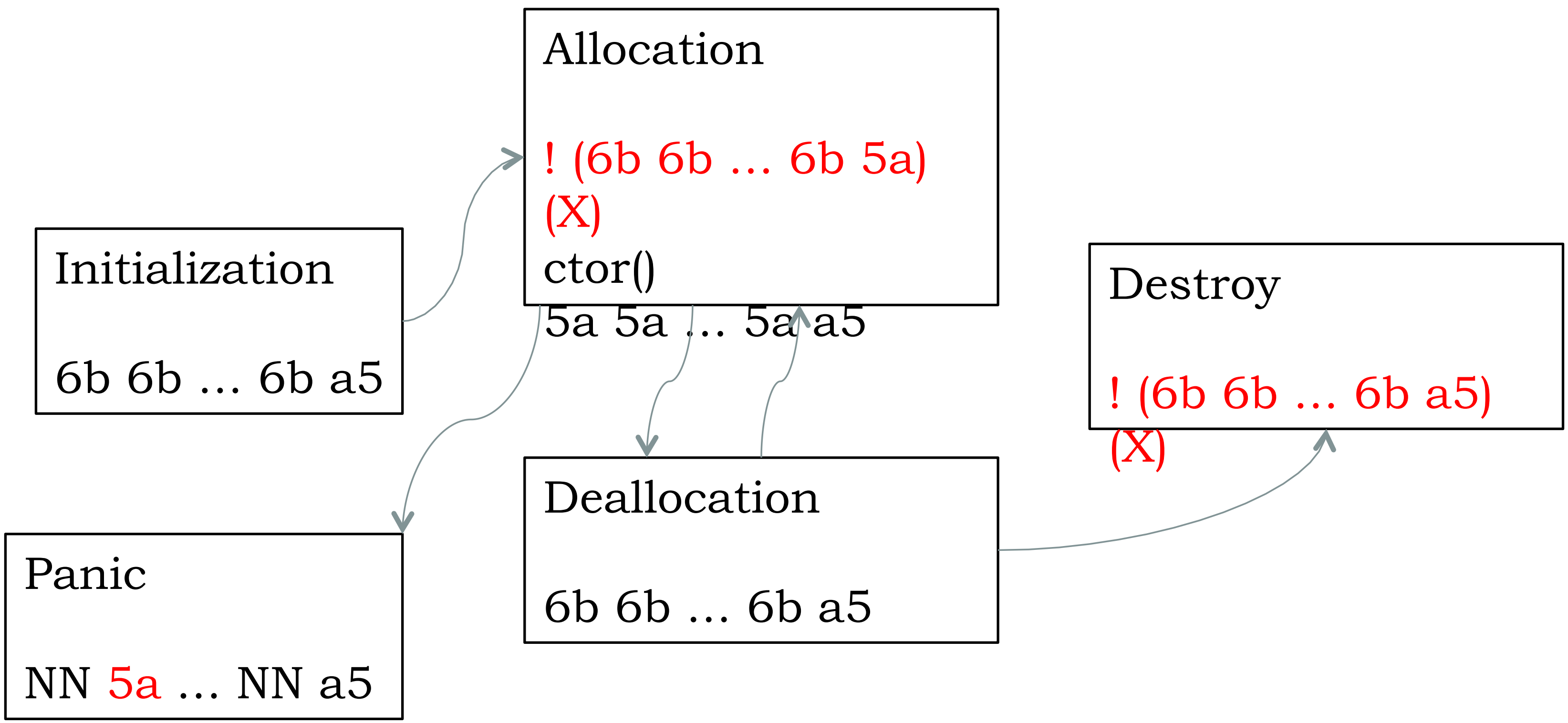
1. ! INACTIVE. (X)

Deallocation

1. check redzone
   - ACTIVE. Y
   - INACTIVE (double free)
   - else, overwritten
2. set redzone INACTIVE

Poison

```
#define POISON_INUSE    0x5a    /* for use-uninitialised poisoning */
#define POISON_FREE     0x6b    /* for use-after-free poisoning */
#define POISON_END      0xa5    /* end-byte of poisoning */
```



Other Debug Features

- Save caller IP
- State for management array tacking
  - BUFCTL_END
  - BUFCTL_FREE
  - BUFCTL_ACTIVE
  - SLAB_LIMIT

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Kernel Core Analysis

- Identify corruption location
- Confirm corruption pattern
- Search potential culprit
- Nail down issue by code

Identify corruption location

- Understand the scenario
- Study the source code
- Verified the scenario in kernel core files

Confirm Corruption Pattern

- Get to familiar with the corrupted data structure
  - Learn related data structure and source code
- Jump out the box - dump the raw memory pages
  - Basic knowledge of kernel memory allocators
    - Slab/Slub/vmalloc/ioremap/page allocators
- Are they similar with any known corruption patterns?
  - Is it a possible corruption pattern caused by HW error?
    - If yes, confirm from BIOS SEL logs
  - For patterns caused by SW bugs, please refer to page 5.

Search potential culprit

- Search the pointer if culprit owns the pointer
  - Per corruption pattern, determine possible pointer address
  - Run search -k <pointer address> to get all references
  - Using kmem and rd to determine the references owners
- Search the corruption data if culprit owns that pattern
  - Per corruption pattern, determine the basic corrupted data
  - Run search -k <data pattern> to get all references
  - Using kmem and rd to confirm the references owners

Nail down issue by code

- Narrow down the source code in possible culprit
  - Per corruption pattern, determine data structure
  - Per corruption pattern, determine the related memory API
  - Find the memory signature if possible
- Any debug code could be enabled for catching bugs?
  - Run the testing with debug code enabled

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A Slab corruption bug - 1

- Identify the corruption location
  - Get the back trace, and find the panic location
    - cache_alloc_refill+0x17b
  - Dump the corrupted memory

```
crash> slab ffff810262bf5040
struct slab {
  list = {
    next = 0x20a00150463, <====== bad pointer
    prev = 0xffff810c0ec002c0
  },
………………………………
```

  - Understand why the corruption cause the panic
    - Unable to handle kernel paging request at 0000020a0015046b

A Slab corruption bug - 2

- Confirm the corruption pattern
  - Get to familiar with the corrupted data structure
    - Slab struct is at or close to the page boundary
  - Jump out the box - dump the raw memory pages
    - Not only check the slab, but also dump the adjacent pages
  - Are they similar with any known corruption patterns?
    - Shouldn’t be HW bug, as the corruption pattern had the significant pattern
    - It looked like the buffer overflow bug.

A Slab corruption bug - 3

- Correlate corruption with potential culprit
  - Search the pointer if culprit owns the pointer
    - The pointer address might be ffff810262bf4000 because,
      - the corruption pattern seemed to start here.
      - the kmem ffff810262bf4000 indicated it is not allocated by slab
      - Search who reference the pointer?
        - crash> search -k ffff810262bf4000
        - ffff810262f03928: ffff810262bf4000
    - Who is the owner of ffff810262f03928?
      - crash> rd ffff810262f03920 -64 128
      - Found the signature: qla2xxx_ts_11 and QLE2562

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Improvements for memory corruption debug

- Using debug kernel in…
  - Kernel/Driver unit testing
  - Release testing
- Increase the debugability for kernel/driver
  - Avoid to use the page allocator if SLUB/SLAB allocation is possible
  - Consider to implement some debug features
    - Create module/driver unique memory signature
    - Introduce the redzone and posion code in module/driver
- Use kernel debug features
  - Replace Slab with Slub which enables SLUG_DEBUG
  - Debug page alloc
  - Kmemcheck
  - KASAN

Q&A

Thank you!