A Heap of Trouble

Exploiting the Linux Kernel SLOB Allocator

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Who am I?

- Security consultant and vulnerability researcher at VSR in Boston
  - App/net pentesting, code review, etc.
  - Published some bugs
  - Focus on Linux kernel
  - Bad habit of rooting Android phones
  - Research on kernel exploitation and mitigation

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Agenda

- What is SLOB?
- How does SLOB work?
- Evaluating exploitability
- SLOB exploitation techniques
- Demo
- Conclusion

Intro to SLOB

What is SLOB?

- Linux kernel supports three heap allocators:
  - SLAB, SLUB, and SLOB
  - Service dynamic allocations for kernel

- Implement `kmalloc()` and `kfree()` interfaces

- Sits on top of page frame allocator

Where is SLOB Used?

- Primarily embedded systems (low memory footprint)
  - Embedded Gentoo
  - OpenEmbedded
  - OpenWrt
  - Commercial embedded devices

- Mobile?
  - Not yet, maybe soon

Why is SLOB Interesting?

- Different allocation behavior and metadata from SLAB/SLUB
- No existing work on SLOB
- Who doesn't like crushing weak heaps?

Where Can I Use These Techniques?

- CVE-2009-1046: off-by-two heap overflow
- CVE-2010-2959: integer overflow leading to heap overflow in Controller Area Network (CAN)
- CVE-2010-3874: heap overflow on 64-bit platforms in Controller Area Network (CAN)
    - Not exploitable on any allocator but SLOB :-)
- CVE-2011-0699: heap overflow in btrfs
- CVE-2012-0038: heap overflow in XFS

How Does SLOB Work?

- Three singly-linked lists of partially-full pages
  - Less than 256 bytes
  - Less than 1024 bytes
  - Less than 4096 bytes

- Multiple sizes within same page

- `slob_page` struct
  - Metadata at base of actual SLOB page
  - Free units
  - Pointer to first free chunk within page
  - Linked list of free pages

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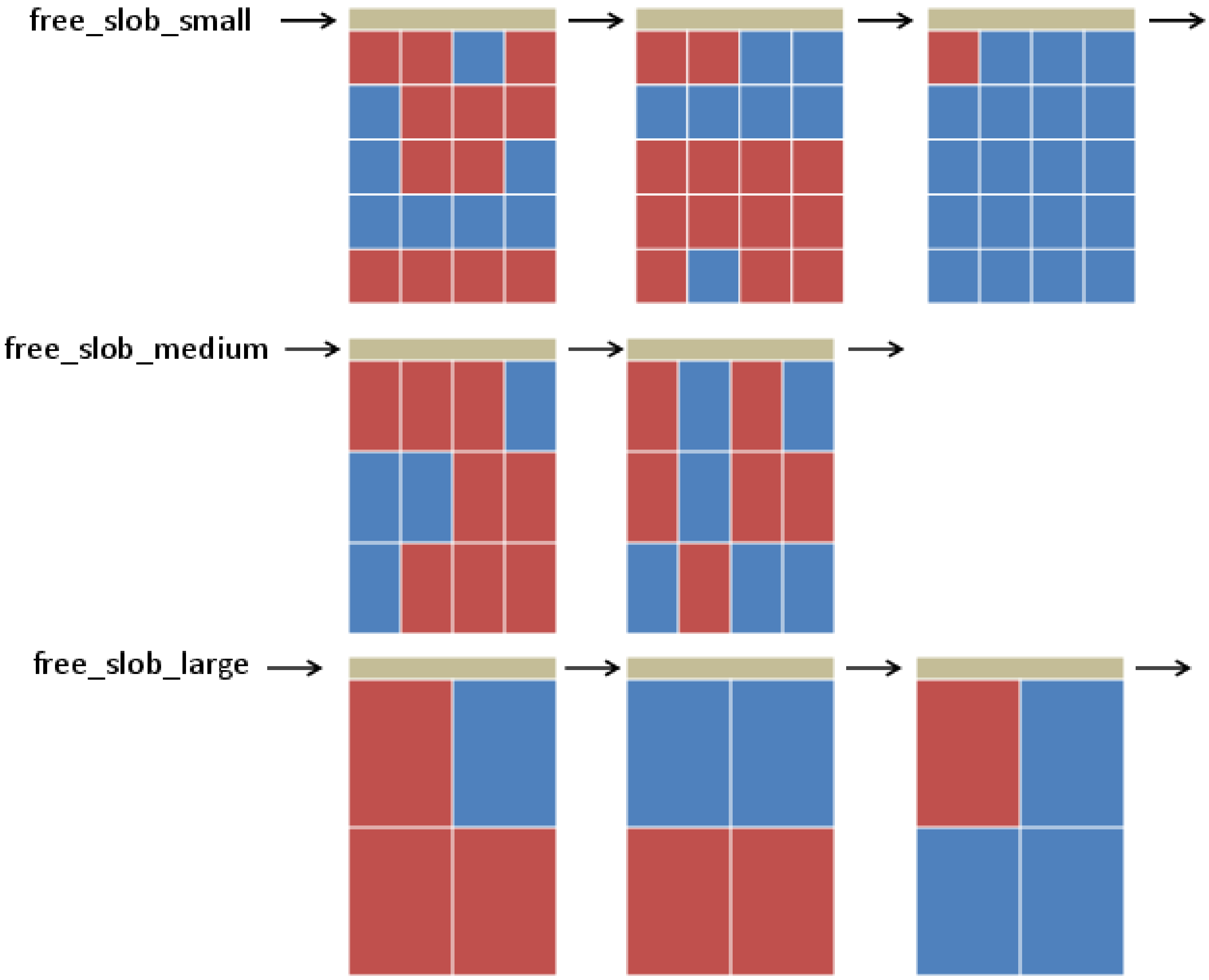
Blocks

- Pages are broken into blocks (chunks)
- Size measured in SLOB_UNITS (2 bytes)
- Initially, each page is one big block
- Fragmented as necessary

SLOB Partially-Free Page Lists



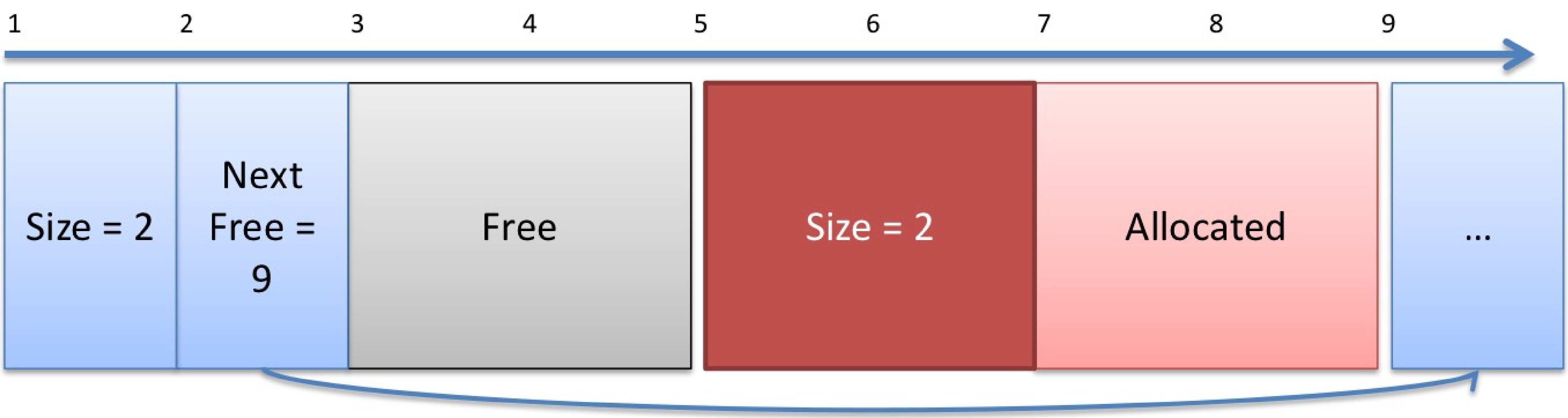
Metadata

- Allocated blocks have 4-byte size header

- Free blocks have packed header
  - If first two bytes are positive:
    - First two bytes are size
    - Second two bytes are index (in SLOB_UNITs) from base of page to next free block

  - If first two bytes are negative:
    - First two bytes are negative index to next free block
    - Total size (including header) is assumed to be two SLOB_UNITs

Metadata Example



Allocation

- Choose appropriate linked list for size
- Walk list until page reporting enough room
  - Not guaranteed, could be non-contiguous
  - If no sufficiently free pages, allocate new page

Allocation

- Attempt allocation of `size + 4` bytes (room for header)
  - Walk free chunks checking sizes
  - If exact fit, unlink
  - If too big, fragment and unlink
  - On failure, continue to next page

- Insert size metadata, return chunk

- Rotate linked list of pages
  - Most recently used page is checked first

Freeing

- Freelist maintains address order
- Find freelist head for chunk (apply page mask to chunk address)
- Walk freelist until insertion point (address order)
- Adjust freelist metadata
  - Prev->next => Chunk
  - Chunk->size => size
  - Chunk->next => Next

Evaluating Exploitability

Exploitability Criteria

- What makes a heap “exploitable”?
- Criteria would be useful in evaluating heaps besides SLOB
- Can compare different heap implementations

Allocation behavior

"To what degree can attackers predict and control locality of allocations and frees?"

Allocation Behavior in SLOB

- No randomness in allocations
- Once a fresh page is allocated, all allocations are guaranteed to be consecutive within page
- Objects are freed predictably
  - Inserted into list in address order

Object Co-Residency

"Do multiple types of objects exist in the same memory region?"

Object Co-Residency in SLOB

- Unlike SLAB/SLUB, all objects share same cache
- Size is only factor in determining where to allocate
- Unlike SLUB, no per-cpu caches

Object Metadata

"Do free or allocated objects contain inline metadata that can be exploited?"

Object Metadata in SLOB

- SLAB/SLUB have minimal inline metadata (next free pointer), but SLOB has:
  - Allocated chunk size field
  - Free chunk size field
  - Free chunk list index field

Exploitation Mitigation

"Are any hardening measures in place to deter exploitation of heap vulnerabilities?"

Exploitation Mitigation in SLOB

Heap Comparison

Pre-Exploitation

Goals of Pre-Exploitation

- Cause heap to be in state conducive to exploitation
- Requires knowledge of allocation behavior
- Usually requires knowledge of specific allocation primitives
  - Can trigger allocation and/or freeing of objects of specific sizes

Pre-Exploitation on SLOB

- In classic heap overflow, goal is usually adjacent blocks
- In SLOB, once fresh page is used, allocations will be contiguous (for the short term)
- Basic approach:
  - Find allocation primitive for appropriate list size
  - Trigger enough allocations to cause fresh page
  - Trigger allocations and frees to cause vulnerable object to be placed appropriately

How Much Should I Allocate?

- No `/proc/slabinfo` on SLOB

- Have to make a reasonable guess
  - Depends on system uptime and load
  - No real penalty for allocating too much

- Experimentally, a few hundred allocations is plenty

Pre-Exploitation on SLOB

- Rotation of partially-free page list is helpful
  - Can fill partially free pages with larger objects
  - Subsequent smaller allocations will be in fresh page, even though they might have fit in other partially full pages

Exploitation

Assumptions

- We have some heap overflow vulnerability
  - Can write data past the end of a heap chunk into the next chunk
- Degree of control over length and contents will vary
- Can find appropriate allocation primitives
  - Structures with function pointers, etc.

Arbitrary Overflow

Full control over size of overflow and contents

Object Data Overwrite

- Fill partial pages and cause allocation of fresh page
  - We'll assume this from now on...
- Position target chunk after vulnerable chunk
- Trigger overflow
- Trigger function pointer call/write to pointer

Object Data Overflow Cleanup

- Unlike SLUB/SLAB, allocated chunks have 4-byte size header
  - Need to restore to avoid unwanted corruption
- If new size is less than old size, do nothing
  - No freelist corruption, shrinking causes no harm
- Otherwise, cleanup after gaining control
  - If function pointer call, base of chunk is almost guaranteed to be in a register

Off-by-Small Overflow

Some control over contents of three to four byte overflow

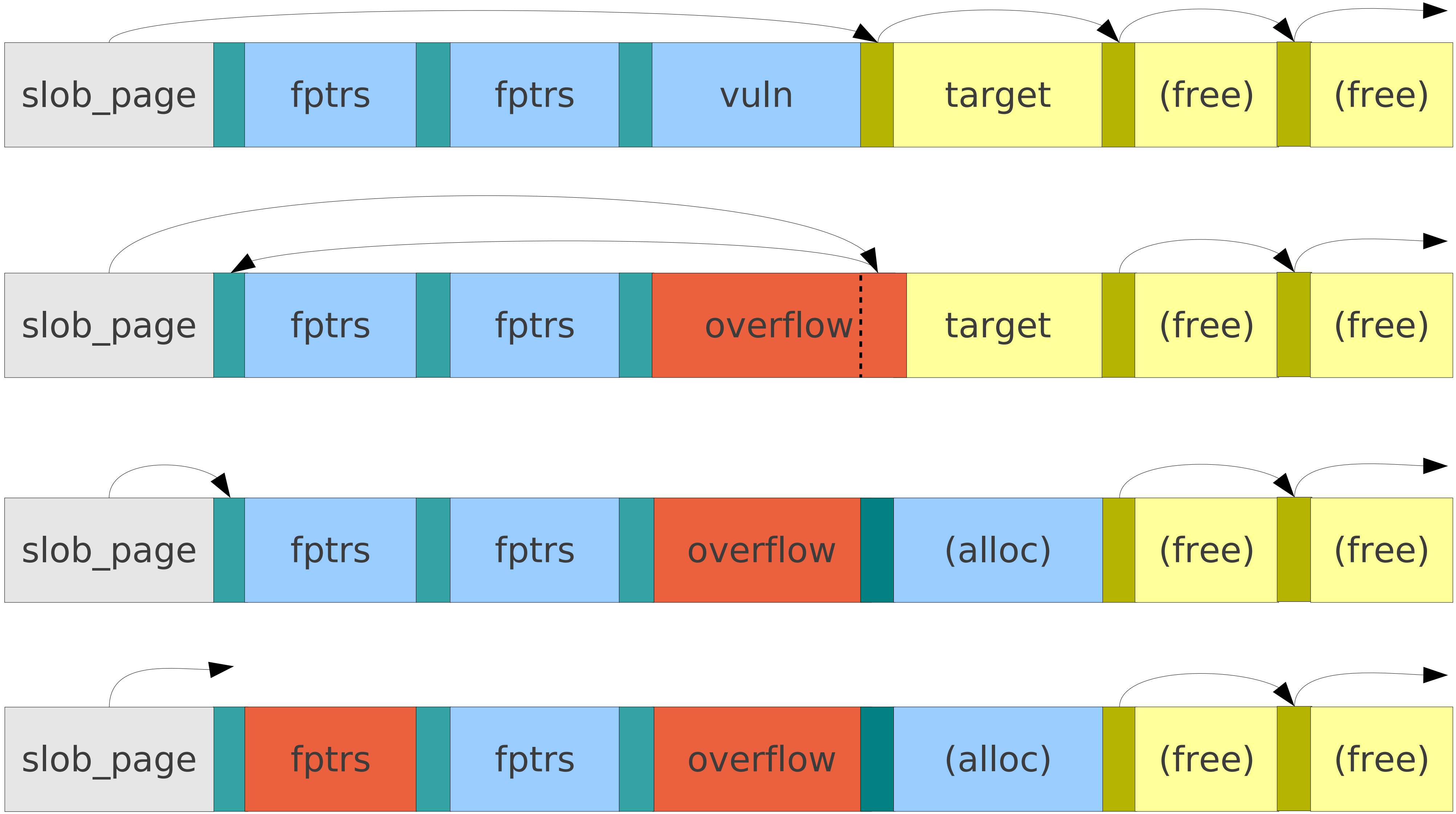
Free Pointer Overwrite Overview

- Modification of technique by sgrakkyu and twiz
- Basic approach: corrupt freelist to trigger chunk reuse
  - If we can trigger allocation of a useful target block on top of data we control (or vice versa) we can win
- Need to corrupt “next free” pointer in adjacent free block
- Remember: it's a two-byte index, not a pointer

Free Pointer Overwrite #1

- Do the pre-exploitation dance
- Fill fresh page with target chunks
- Trigger overflow into free chunk, overwriting 3-4 bytes (size and one or two bytes of next free pointer)
- Trigger allocation of controlled chunk on top of some target block
- Win

Free Pointer Overwrite #1



Free Pointer Overwrite Cleanup

- Freelist has been corrupted
  - Subsequent allocations may panic the kernel

- Easiest option is to terminate the freelist early (thanks Nico) so corrupted free chunks never get traversed
  - Chunk is considered “final” when its next-free index returns a next chunk that is page aligned
  - Overwrite a free chunk's next pointer with NULL or any multiple of 0x800 to terminate the list

Off-by-Smaller Overflow

Some control over contents of one to two byte overflow

Free Pointer Overwrite #2

- Same as other free pointer overwrite, except:
  - Take advantage of special case
  - Negative value in first two bytes of free chunk is interpreted as negative index, not size

- Allows exploitation of controlled off-by-two overflow (need both bytes to overwrite with negative two-byte value)

- Remember to clean up the freelist

Off-by-One Overflow

Some control over contents of one byte overflow

Chunk Growth Attack

- Overwrite size field on adjacent free or allocated chunk to “grow” that chunk
  - Shrinking does nothing useful – no freelist corruption, so just causes wastage of memory
- If overflow into allocated block, cause that block to be freed
- Trigger allocation of chunk with size equal to “grown” size with data you control
- Second portion of this chunk will overlap with target chunk, allowing exploitation

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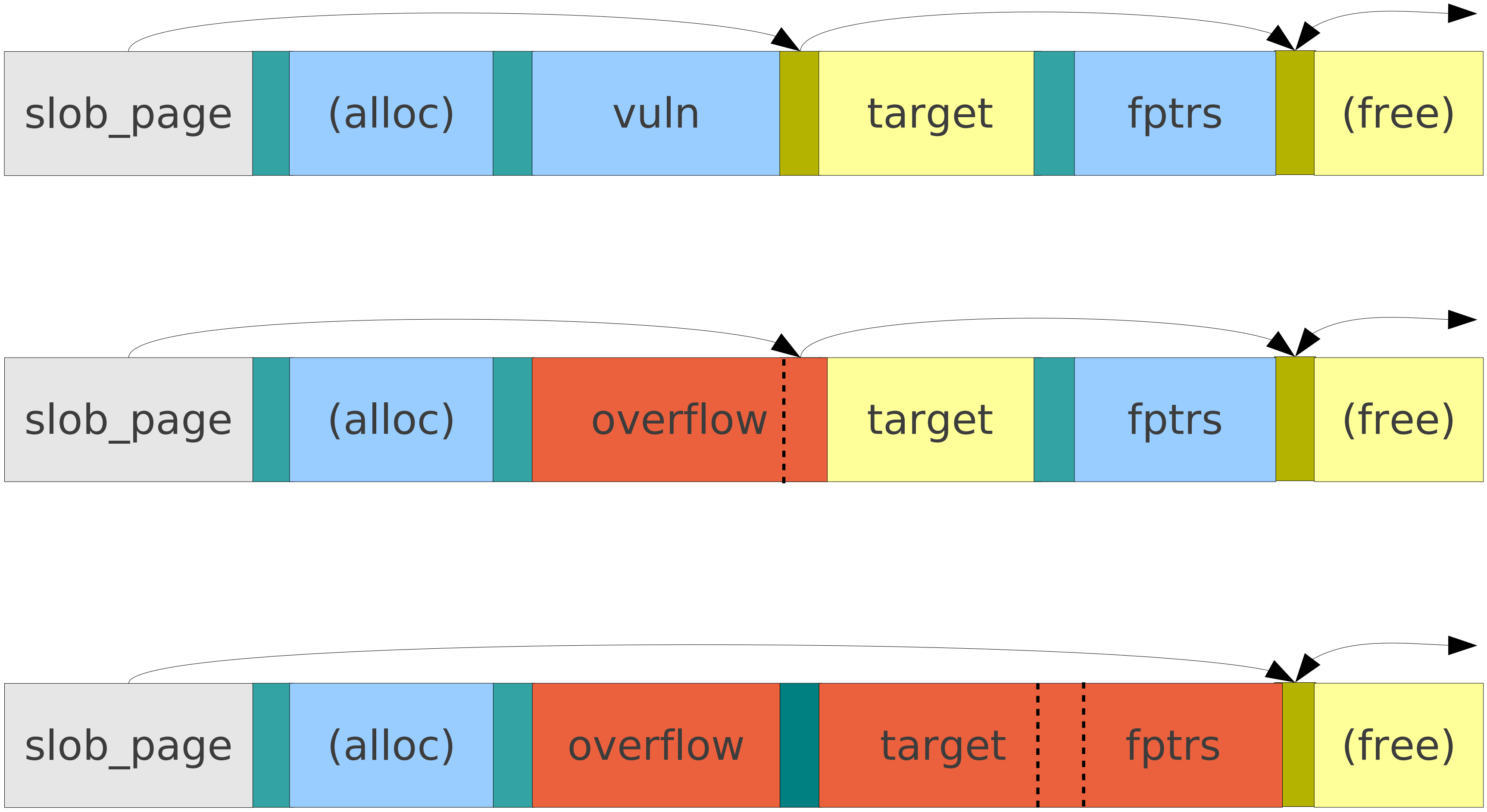
Chunk Growth Attack



Off-by-One NULL Byte Overflow

Well, this sucks.

What Are Our Options?

- Allocated chunk size header
  - NULL byte means we can only shrink, not useful
- Free chunk size header
  - Same as above
- What was that special case again?

Special Case

- If first two bytes are negative:
  - Size is assumed to be one SLOB_UNIT (2 bytes)
  - First two bytes are negative index to next free block

- Great, overwriting LSB of free index could be a win
  - Trigger allocation on top of existing chunk

- All we need to do is cause a 2-byte block to be allocated!

- But…

:-(

mm/slob.c:

```
void *__kmalloc_node(size_t size, gfp_t gfp, int node)
{
    ...
    int align = max(ARCH_KMALLOC_MINALIGN, ARCH_SLAB_MINALIGN);
    ...
    m = slob_alloc(size + align, gfp, align, node);
    ...
}
```

include/linux/slab.h:

```
#define ARCH_SLAB_MINALIGN __alignof__(unsigned long long)
```

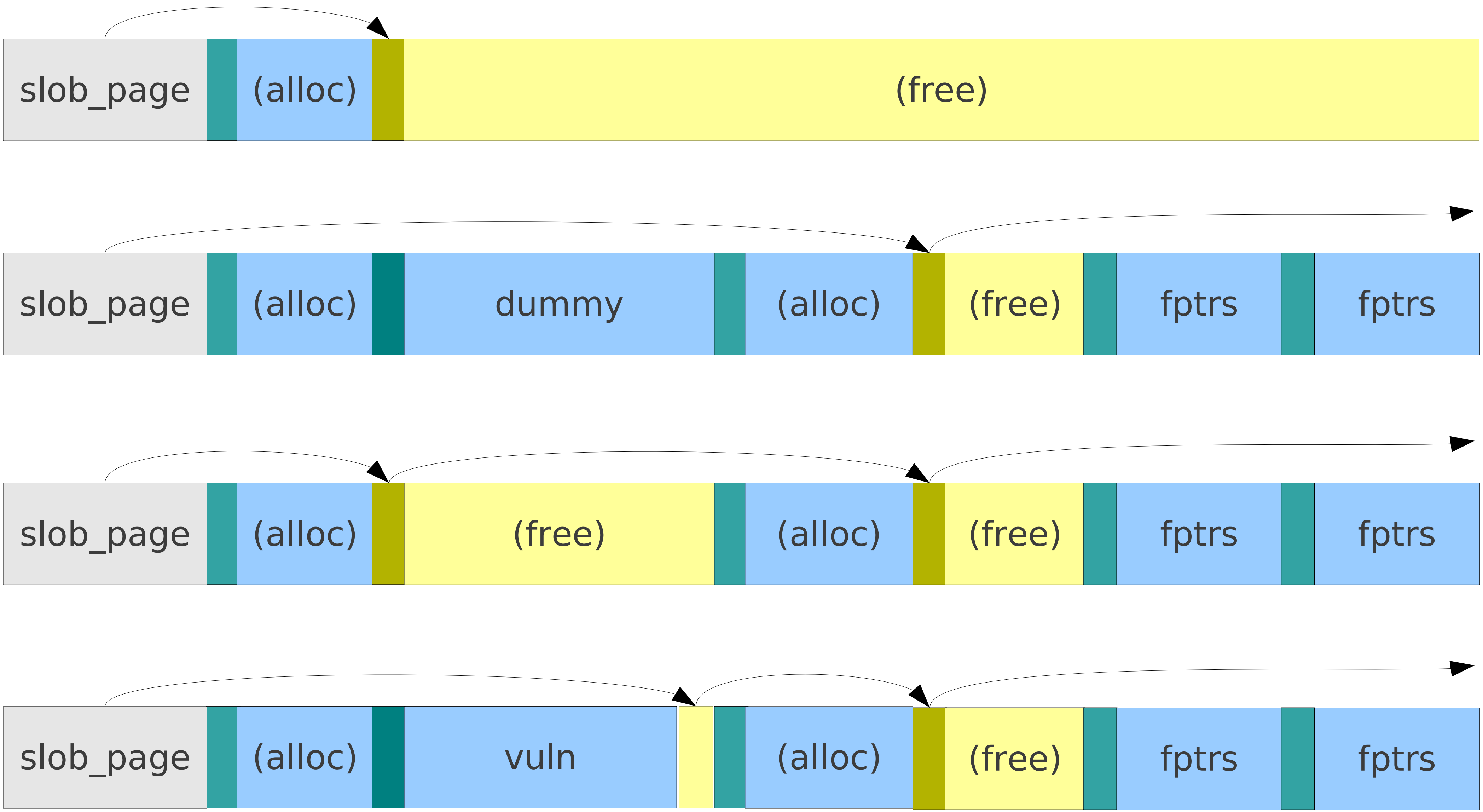
What Does This Mean?

- The only piece of metadata we can possibly exploit can't exist in any chunks we can allocate :-(
- Is all hope lost?
  - Hint: no.
- Remember how SLOB works: chunks of varying sizes exist in the same cache

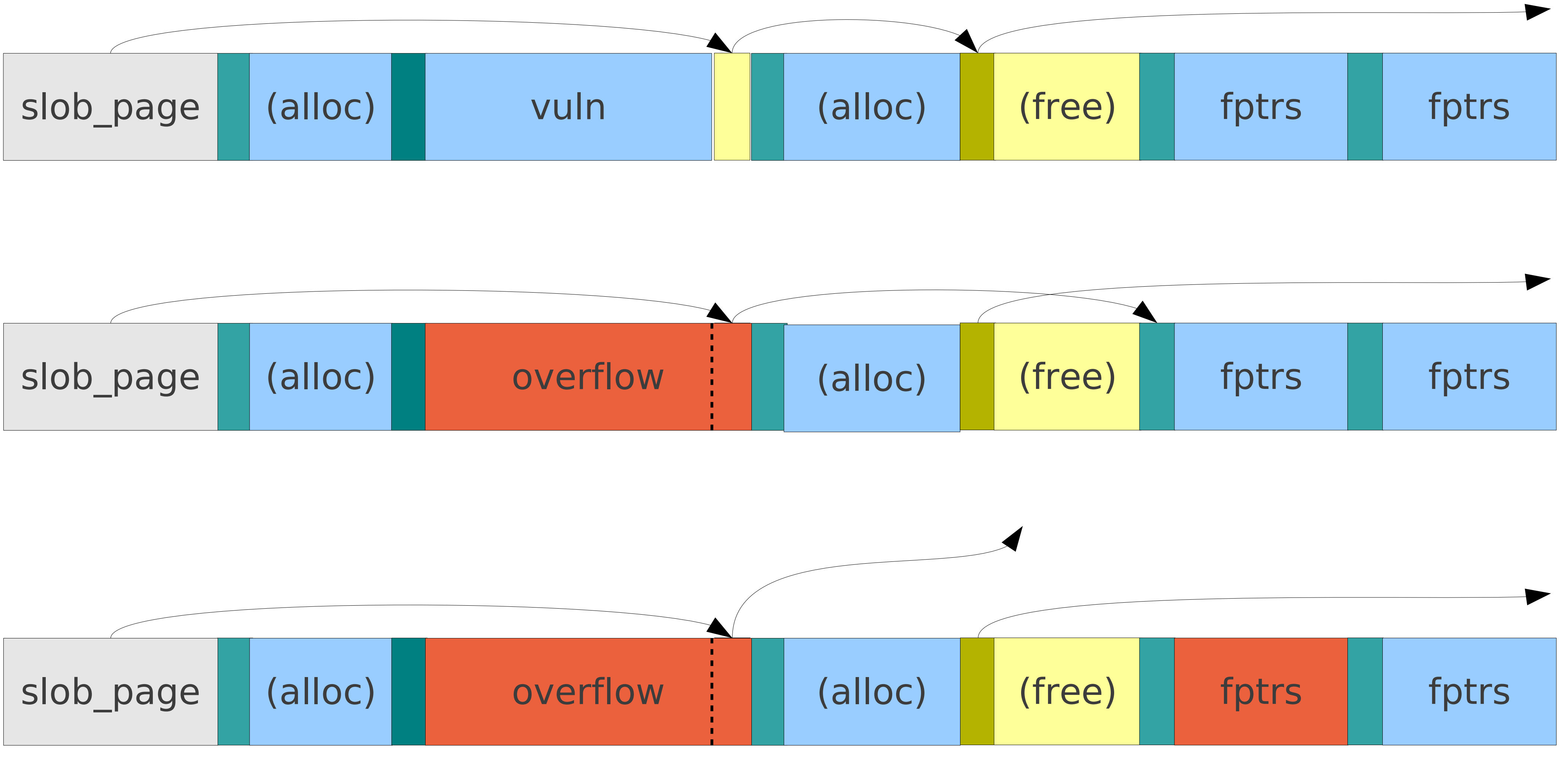
Fragmentation to the Rescue!

- Same old pre-exploitation phase, fill new page with targets
- Trigger allocation and freeing of block four bytes larger than size of vulnerable block
- Trigger allocation of vulnerable block
- SLOB will fragment previous block into vulnerable block and four-byte “special” chunk
- Trigger overflow, continue as if free pointer overwrite

Fragmentation Attack: Phase I



Fragmentation Attack: Phase 2



Demo

Setting up a Test Environment

- Wrote LKM “playground”
- Creates device file
- Can trigger heap primitives via `ioctl`
  - Allocate, free, overflow, function pointer call, etc.
- Develop techniques with theoretical primitives
  - Replace with real examples later

Chunk Growth Attack Demo

Conclusion

- SLOB's design allows easy exploitation
- SLOB has virtually no hardening
  - Basic freelist validation would be simple
    - Next chunk is after current chunk
    - Next chunk is before end of page
- See KERNHEAP for ideas

Future Work

- Harden the SLOB allocator?
  - I'm not going to do this

- Automated finding of heap primitives
  - I don't know anything about static analysis
    - Need to trace code paths, enumerate all heap activity, and determine which chunks remain allocated persistently
  - Jon Oberheide's kstructhunter is a start

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- twiz
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Questions?

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