Memory Management

Advanced Operating Systems and Virtualization

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Memory Management

- During the boot, the Kernel relies on a temporary memory manager
  - It's compact and not very efficient
  - The rationale is that there are not many memory requests during the boot
- At steady state this is no longer the case
  - Allocations/deallocations are frequent
  - Memory must be used wisely, accounting for hardware performance
- We must also discover how much physical memory is available, and how it is organized

NUMA Nodes Organization

- A node is organized in a `struct pglist_data` (even in the case of UMA) typedef'd to `pg_data_t`
- Every node in the system is kept on a `NULL`-terminated list called `pgdat_list`
- Each node is linked to the next with the field `pg_data_t→node_next`
  - In UMA systems, only one static `pg_data_t` structure called `contig_page_data` is used (defined at `mm/numa.c`)

NUMA Nodes Organization

- From Linux 2.6.16 to 2.6.17 much of the codebase of this portion of the kernel has been rewritten
- Introduction of macros to iterate over node data (most in `include/linux/mmzone.h`) such as:
  - `for_each_online_pgdat()`
  - `first_online_pgdat()`
  - `next_online_pgdat(pgdat)`
- Global `pgdat_list` has since then been removed
- Macros rely on the global `struct pglist_data *node_data[];`

pg_data_t

- Defined in `include/linux/mmzone.h`

```
typedef struct pglist_data {
        zone_t node_zones[MAX_NR_ZONES];
        zonelist_t node_zonelists[GFP_ZONEMASK+1];
        int nr_zones;
        struct page *node_mem_map;
        unsigned long *valid_addr_bitmap;
        struct bootmem_data *bdata;
        unsigned long node_start_paddr;
        unsigned long node_start_mapnr;
        unsigned long node_size;
        int node_id;
        struct pglist_data *node_next;
} pg_data_t;
```

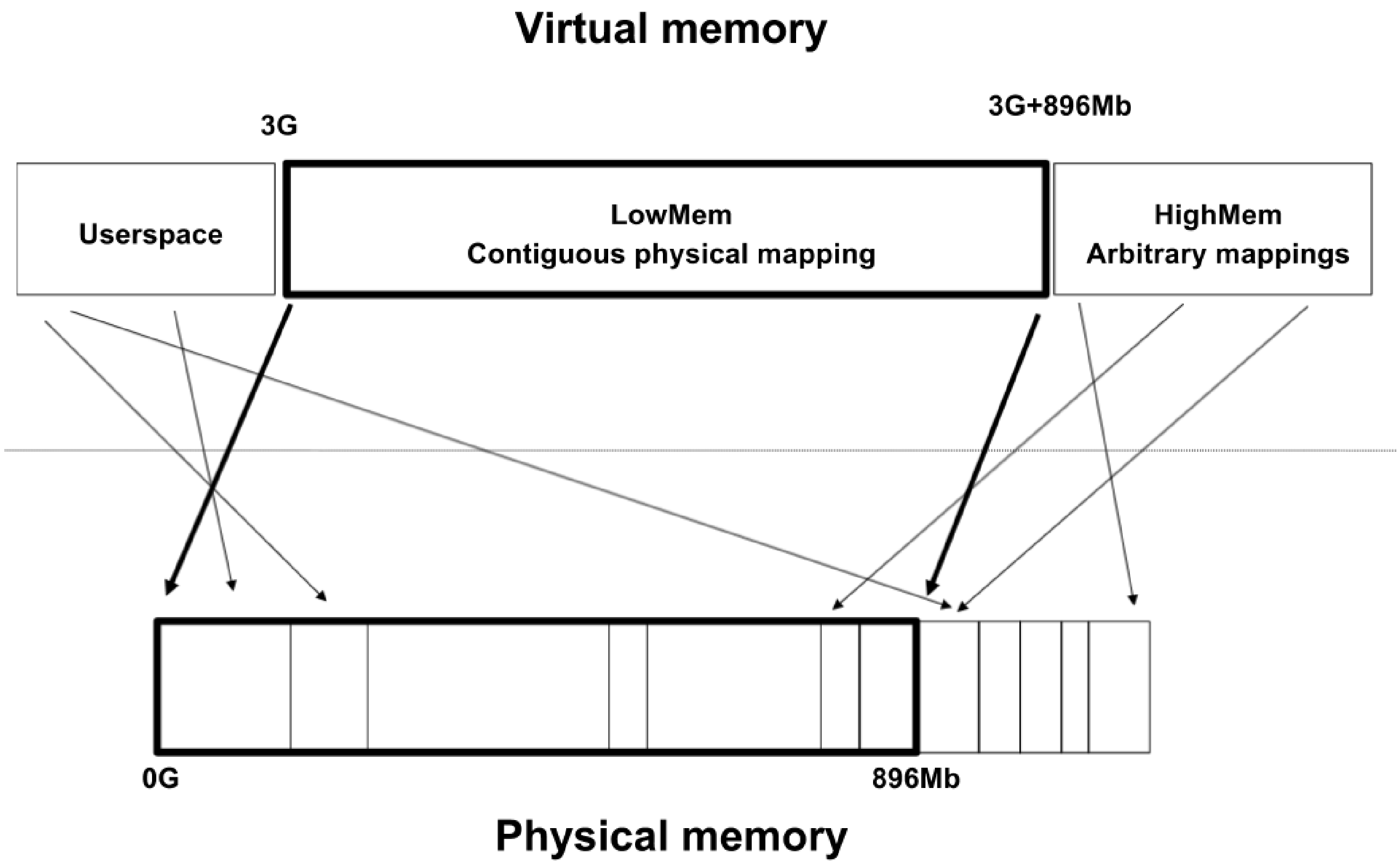
Zones

- Nodes are divided into zones:

```
#define ZONE_DMA        0
#define ZONE_NORMAL     1
#define ZONE_HIGHMEM    2
#define MAX_NR_ZONES    3
```

- They target specific physical memory areas:
  - `ZONE_DMA`: < 16 MB
  - `ZONE_NORMAL`: 16-896 MB ← Limited in size and high contention. Linux also has the notion of *high memory*
  - `ZONE_HIGHMEM`: > 896 MB

Zones



Virtual memory
3G
3G+896Mb
Userspace
LowMem
Contiguous physical mapping
HighMem
Arbitrary mappings
0G
896Mb
Physical memory

Zones Initialization

- Zones are initialized after the kernel page tables have been fully set up by `paging_init()`
- The goal is to determine what parameters to send to:
  - `free_area_init()` for UMA machines
  - `free_area_init_node()` for NUMA machines
- The initialization grounds on PFNs
- max PFN is read from BIOS e820 table

e820 dump in dmesg

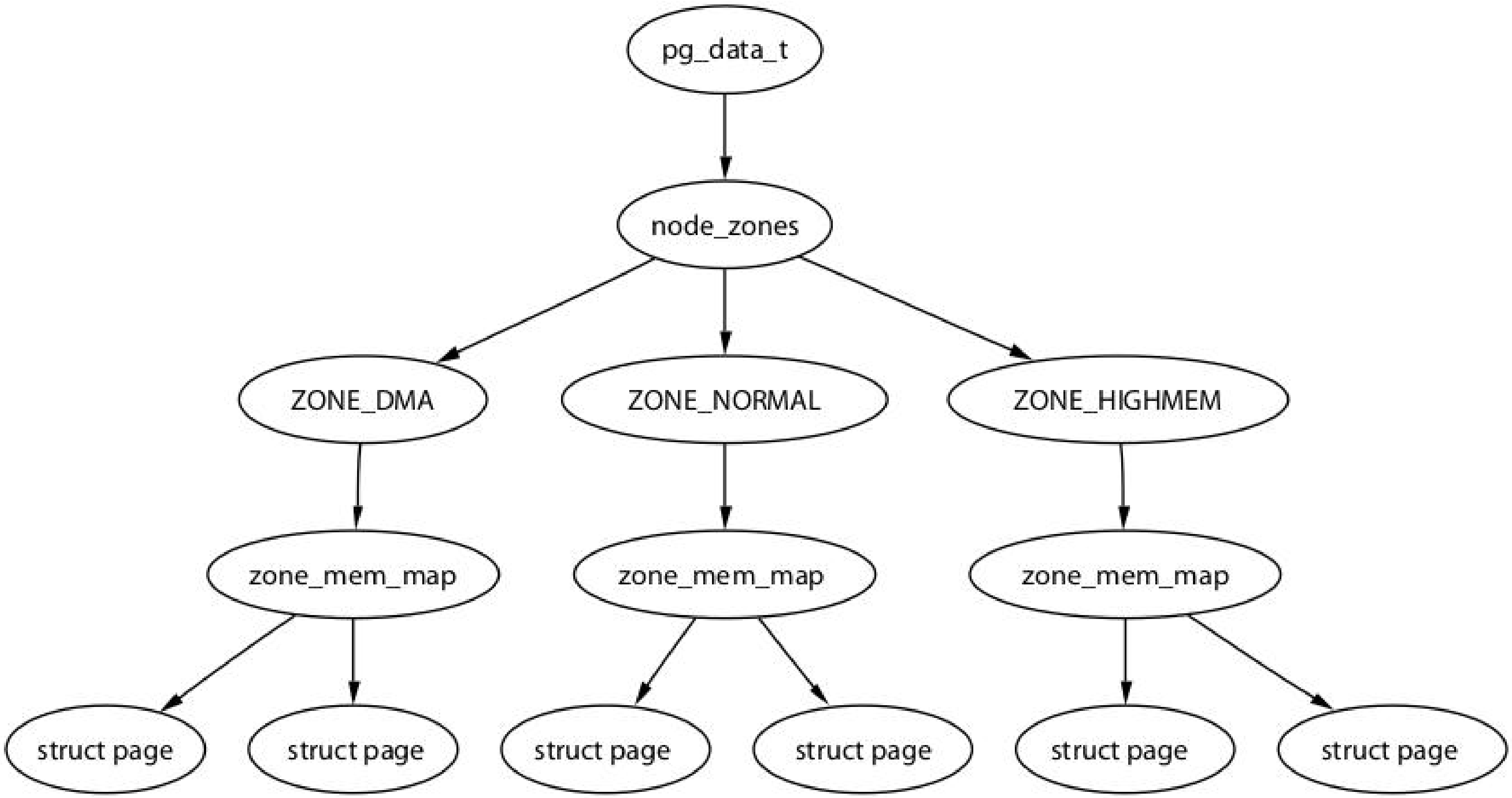
```
[0.000000] e820: BIOS-provided physical RAM map:
[0.000000] BIOS-e820: [mem 0x0000000000000000-0x000000000009fbff] usable
[0.000000] BIOS-e820: [mem 0x00000000000f0000-0x00000000000fffff] reserved
[0.000000] BIOS-e820: [mem 0x0000000000100000-0x000000007dc08bff] usable
[0.000000] BIOS-e820: [mem 0x000000007dc08c00-0x000000007dc5cbff] ACPI NVS
[0.000000] BIOS-e820: [mem 0x000000007dc5cc00-0x000000007dc5ebff] ACPI data
[0.000000] BIOS-e820: [mem 0x000000007dc5ec00-0x000000007fffffff] reserved
[0.000000] BIOS-e820: [mem 0x00000000e0000000-0x00000000efffffff] reserved
[0.000000] BIOS-e820: [mem 0x00000000fec00000-0x00000000fed003ff] reserved
[0.000000] BIOS-e820: [mem 0x00000000fed20000-0x00000000fed9ffff] reserved
[0.000000] BIOS-e820: [mem 0x00000000fee00000-0x00000000feefffff] reserved
[0.000000] BIOS-e820: [mem 0x00000000ffb00000-0x00000000ffffffff] reserved
```

zone_t

```
typedef struct zone_struct {
        spinlock_t                  lock;
        unsigned                    long   free_pages;
        zone_watermarks_t           watermarks[MAX_NR_ZONES];
        unsigned long               need_balance;
        unsigned long          nr_active_pages,nr_inactive_pages;
        unsigned long               nr_cache_pages;
        free_area_t                 free_area[MAX_ORDER];
        wait_queue_head_t           * wait_table;
        unsigned long               wait_table_size;
        unsigned long               wait_table_shift;
        struct pglist_data          *zone_pgdat;
        struct page                 *zone_mem_map;
        unsigned long               zone_start_paddr;
        unsigned long               zone_start_mapnr;
        char                        *name;
        unsigned long               size;
        unsigned long               realsize;
} zone_t;
```

Currently 11

Nodes, Zones and Pages Relations



Core Map

- It is an array of `mem_map_t` structures defined in `include/linux/mm.h` and kept in `ZONE_NORMAL`

```
typedef struct page {
    struct list_head list;              /* ->mapping has some page lists. */
    struct address_space *mapping;      /* The inode (or ...) we belong to. */
    unsigned long index;                /* Our offset within mapping. */
    struct page *next_hash;             /* Next page sharing our hash bucket in
                                           the pagecache hash table. */
    atomic_t count;                     /* Usage count, see below. */
    unsigned long flags;                /* atomic flags, some possibly
                                           updated asynchronously */
    struct list_head lru;               /* Pageout list, eg. active_list;
                                           protected by pagemap_lru_lock !! */
    struct page **pprev_hash; /* Complement to *next_hash. */
    struct buffer_head * buffers;       /* Buffer maps us to a disk block. */

    #if defined(CONFIG_HIGHMEM) || defined(WANT_PAGE_VIRTUAL)
    void *virtual;                      /* Kernel virtual address (NULL if
                                           not kmapped, ie. highmem) */
    #endif /* CONFIG_HIGMEM || WANT_PAGE_VIRTUAL */
} mem_map_t;
```

Core Map Members

- Struct members are used to keep track of the interactions between MM and other kernel sub-systems
- `struct list_head list`: used to organize the frames into free lists
- `atomic_t count`: counts the virtual references mapped onto the frame
- `unsigned long flags`: status bits for the frame

```
#define PG_locked      0
#define PG_referenced  2
#define PG_uptodate    3
#define PG_dirty       4
#define PG_lru         6
#define PG_reserved   14
```

How to manage `flags`

Bit Name	Set	Test	Clear
PG_active	SetPageActive()	PageActive()	ClearPageActive()
PG_arch_1	None	None	None
PG_checked	SetPageChecked()	PageChecked()	None
PG_dirty	SetPageDirty()	PageDirty()	ClearPageDirty()
PG_error	SetPageError()	PageError()	ClearPageError()
PG_highmem	None	PageHighMem()	None
PG_launder	SetPageLaunder()	PageLaunder()	ClearPageLaunder()
PG_locked	LockPage()	PageLocked()	UnlockPage()
PG_lru	TestSetPageLRU()	PageLRU()	TestClearPageLRU()
PG_referenced	SetPageReferenced()	PageReferenced()	ClearPageReferenced()
PG_reserved	SetPageReserved()	PageReserved()	ClearPageReserved()
PG_skip	None	None	None
PG_slab	PageSetSlab()	PageSlab()	PageClearSlab()
PG_unused	None	None	None
PG_uptodate	SetPageUptodate()	PageUptodate()	ClearPageUptodate()

Core Map on UMA

- Initially we only have the core map pointer
- This is `mem_map` and is declared in `mm/memory.c`
- Pointer initialization and corresponding memory allocation occur within `free_area_init()`
- After initializing, each entry will keep the value 0 within the `count` field and the value 1 into the `PG_reserved` flag within the `flags` field
- Hence no virtual reference exists for that frame and the frame is reserved
- Frame un-reserving will take place later via the function `mem_init()` in `arch/i386/mm/init.c` (by resetting the bit `PG_reserved`)

Core Map on NUMA

- There is not a global `mem_map` array
- Every node keeps its own map in its own memory
- This map is referenced by `pg_data_t→node_mem_map`
- The rest of the organization of the map does not change

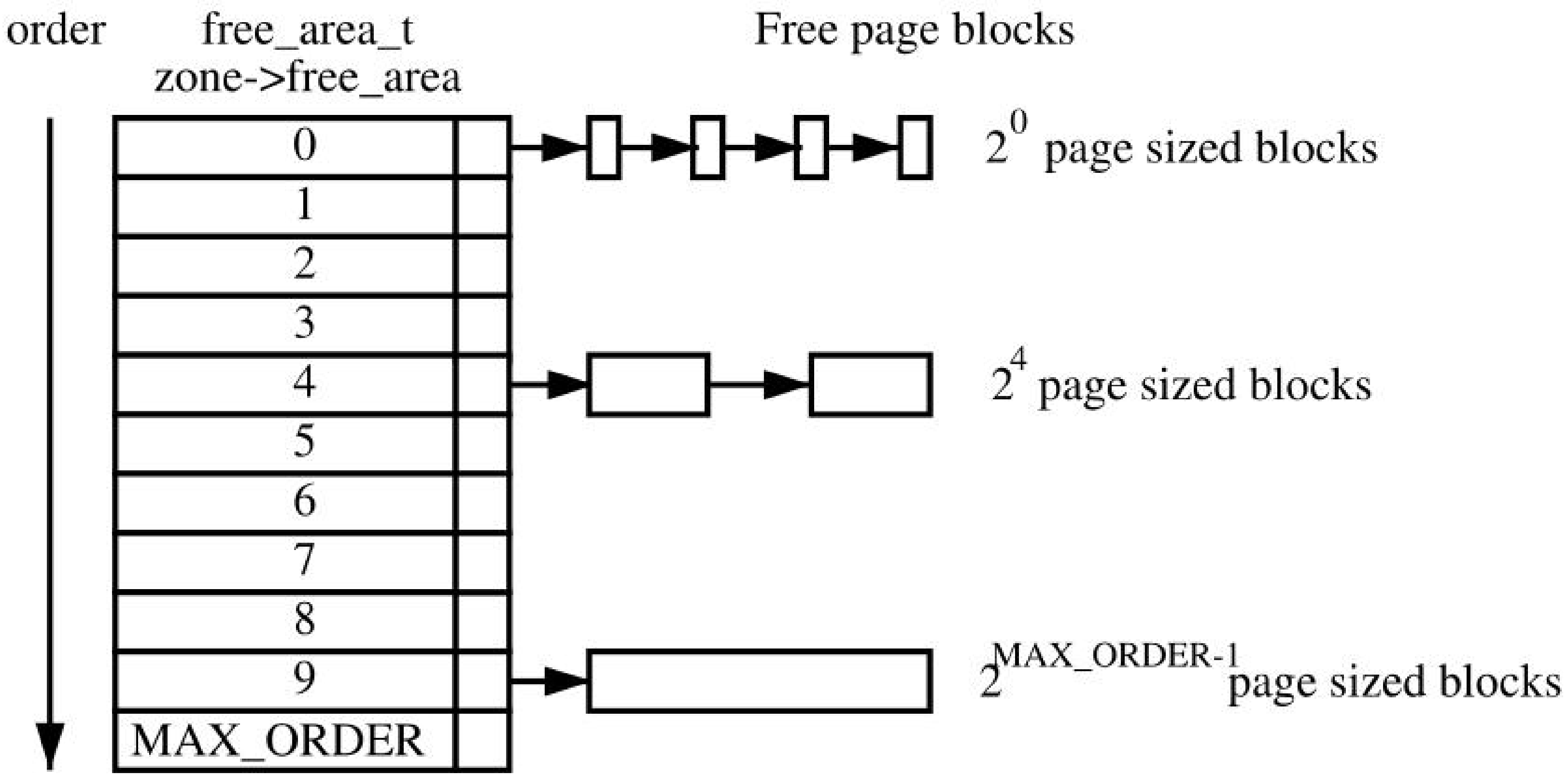
Buddy System: Frame Allocator

- By Knowlton (1965) and Knuth (1968)
- It has been experimentally shown to be quite fast

- Based on two main data structures:

```
typedef struct free_area_struct {
    struct list_head list;
    unsigned int *map;
} free_area_t

struct list_head {
    struct list_head *next, *prev;
}
```

`free_area_t` organization



Bitmap `*map` semantic

- Linux saves memory by using one bit for a pair of buddies
- It's a "fragmentation" bit
- Each time a buddy is allocated or free'd, the bit representing the pair is toggled
  - 0: if the pages are both free or allocated
  - 1: only one buddy is in use

Index in the global mem_map array

```
#define MARK_USED(index, order, area) \
__change_bit((index) >> (1+(order)), (area)->map)
```

High Memory

- When the size of physical memory approaches/ exceeds the maximum size of virtual memory, it is impossible for the kernel to keep all of the available physical memory mapped
- "Highmem" is the memory not covered by a permanent mapping
- The Kernel has an API to allow "temporary mappings"
- This is where userspace memory comes from

High Memory

- `vmap()`: used to make a long-duration mapping of multiple physical pages
- `kmap()`: it permits a short-duration mapping of a single page.
  - It needs global synchronization, but is amortized somewhat.
- `kmap_atomic()`: This permits a very short duration mapping of a single page.
  - It is restricted to the CPU that issued it
  - the issuing task is required to stay on that CPU until it has finished

- In general: nowadays, it *really* makes sense to use 64-bit systems!

High Memory Deallocation

- Kernel maintains an array of counters:

```
static int pkmap_count[ LAST_PKMAP ];
```

- One counter for each 'high memory' page
- Counter values are 0, 1, or more than 1:
  - =0: page is not mapped
  - =1: page not mapped now, but used to be
  - =n >1: page was mapped (n-1) times

`kunmap()`

- `kunmap(page)` decrements the associated reference counter
- When the counter is 1, mapping is not needed anymore
- But CPU still has “cached” that mapping
- So the mapping must be “invalidated”
- With multiple CPUs, all of them must do it
  - `__flush_tlb_all()`

Reclaiming Boot Memory

- The finalization of memory management init is done via `mem_init()` which destroys the bootmem allocator
- This function will release the frames, by resetting the `PG_RESERVED` bit
- For each free'd frame, the function `__free_page()` is invoked
  - This gives all the pages in `ZONE_NORMAL` to the buddy allocator
- At this point the reference `count` within the corresponding entry gets set to 1 since the kernel maps that frame anyway within its page table

Finalizing Memory Initialization

```
static unsigned long __init
free_all_bootmem_core(pg_data_t *pgdat) {
        ……………
        // Loop through all pages in the current node
        for (i = 0; i < idx; i++, page++) {
                if (!test_bit(i, bdata->node_bootmem_map)) {
                        count++;
                        ClearPageReserved(page);
                        // Fake the buddy into thinking it's an
                        // actual free
                        set_page_count(page, 1);
                        __free_page(page);
                }
        }
        total += count;
        ……………
        return total;
}
```

Allocation Contexts

- Process context: allocation due to a system call
  - If it cannot be served: wait along the current execution trace
  - Priority-based approach
- Interrupt: allocation due to an interrupt handler
  - If it cannot be served: no actual waiting time
  - Priority independent schemes

- This approach is general to most Kernel subsystems

Basic Kernel Internal MM API

- At steady state, the MM subsystem exposes API to other kernel subsystems
- Prototypes in `#include <linux/malloc.h>`
- Basic API: page allocation
  - `unsigned long get_zeroed_page(int flags)`: take a frame from the free list, zero the content and return its virtual address
  - `unsigned long __get_free_page(int flags)`: take a frame from the free list and return its virtual address
  - `unsigned long __get_free_pages(int flags, unsigned long order)`: take a block of contiguous frames of given `order` from the free list

Basic Kernel Internal MM API

- Basic API: page allocation
  - `void free_page(unsigned long addr)`: put a frame back into the free list
  - `void free_pages(unsigned long addr, unsigned long order)`: put a block of frames of given order back into the free list
- Warning: passing a wrong `addr` or `order` might corrupt the Kernel!

Basic Kernel Internal MM API

- `flags`: used to specify the allocation context
  - `GFP_ATOMIC`: interrupt context. The call cannot lead to sleep
  - `GFP_USER`: Used to allocate memory for userspace-related activities. The call can lead to sleep
  - `GFP_BUFFER`: Used to allocate a buffer. The call can lead to sleep
  - `GFP_KERNEL`: Used to allocate Kernel memory. The call can lead to sleep

NUMA Allocation

- On NUMA systems, we have multiple nodes
- UMA systems eventually invoke NUMA API, but the system is configured to have a single node
- Core memory allocation API:
  - `struct page *alloc_pages_node(int nid, unsigned int flags, unsigned int order);`
  - `__get_free_pages()` calls `alloc_pages_node()` specifying a *NUMA policy*

NUMA Policies

- NUMA policies determine what NUMA node is involved in a memory operation
- Since Kernel 2.6.18, userspace can tell the Kernel what policy to use:

```
#include <numaif.h>
int set_mempolicy(int mode, unsigned long
*nodemask, unsigned long maxnode);
```

- `mode` can be: `MPOL_DEFAULT`, `MPOL_BIND`, `MPOL_INTERLEAVE` or `MPOL_PREFERRED`

NUMA Policies

```
#include <numaif.h>
int mbind(void *addr, unsigned long len,
int mode, unsigned long *nodemask,
unsigned long maxnode, unsigned flags);
```

Sets the NUMA memory policy, which consists of a policy mode and zero or more nodes, for the memory range starting with *addr* and continuing for *len* bytes. The memory policy defines from which node memory is allocated.

Moving Pages Around

```
#include <numaif.h>
long move_pages(int pid, unsigned long
count, void **pages, const int *nodes,
int *status, int flags);
```

Moves the specified *pages* of the process *pid* to the memory nodes specified by *nodes*. The result of the move is reflected in *status*. The *flags* indicate constraints on the pages to be moved.

Frequent Allocations/Deallocations

- Consider fixed-size data structures which are frequently allocated/released
- The buddy system here does not scale
  - This is a classical case of frequent logical contention
  - The Buddy System on each NUMA node is protected by a spinlock
  - The internal fragmentation might rise too much

Classical Examples

- Allocation/release of page tables, at any level, is very frequent
- We want to perform these operations quickly
- For paging we have:
  - `pgd_alloc()`,`pmd_alloc()` and `pte_alloc()`
  - `pgd_free()`,`pmd_free()` and `pte_free()`
- They rely on one of Kernel-level *fast allocators*

Fast Allocation

- There are several fast allocators in the Kernel
- For paging, there are the *quicklists*
- For other buffers, there is the *slab allocator*
- There are three implementations of the slab allocator in Linux:
  - the SLAB: Implemented around 1994
  - the SLUB: The Unqueued Slab Allocator, default since Kernel 2.6.23
  - the SLOB: Simple List of Blocks. If the SLAB is disabled at compile time, Linux reverts to this

Quicklist

- Defined in `include/linux/quicklist.h`
- They are implemented as a list of per-core page lists
- There is no need for synchronization
- If allocation fails, they revert to `__get_free_page()`

Quicklist Allocation

```
static inline void *quicklist_alloc(int nr, gfp_t flags, ...) {
	struct quicklist *q;
	void **p = NULL;

	q = &get_cpu_var(quicklist)[nr];
	p = q->page;
	if (likely(p)) {
		q->page = p[0];
		p[0] = NULL;
		q->nr_pages--;
	}
	put_cpu_var(quicklist);
	if (likely(p))
		return p;

	p = (void *)__get_free_page(flags | __GFP_ZERO);
	return p;
}
```

likely/unlikely

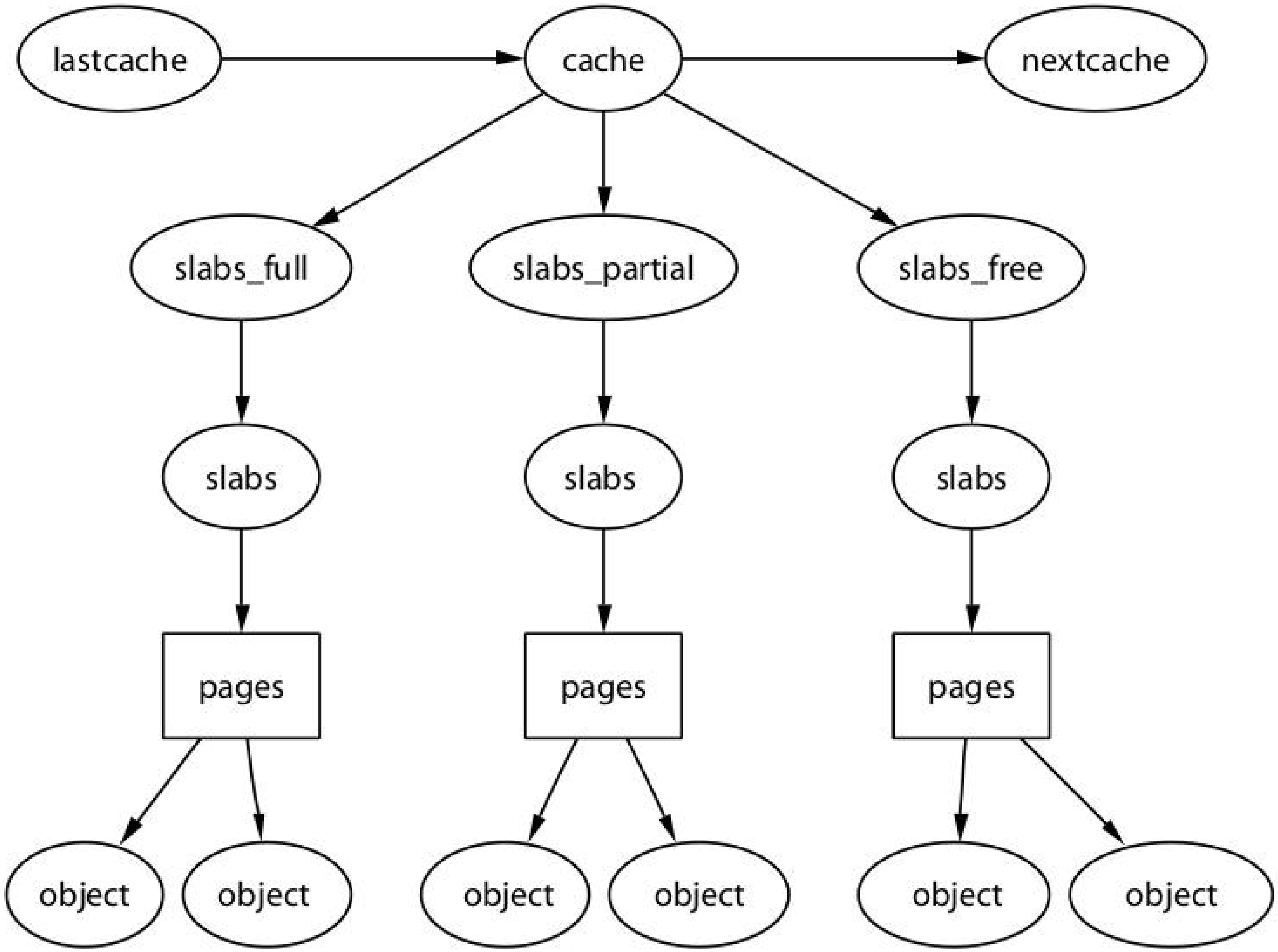
- Defined in `include/linux/compiler.h`

```
# define likely(x) __builtin_expect(!!(x), 1)
# define unlikely(x) __builtin_expect(!!(x), 0)
```

- `!!` is used to convert any value to 1 or 0

- Up to Pentium 4:
  - `0x2e`: Branch Not Taken
  - `0x3e`: Branch Taken

The SLAB Allocator



SLAB Interfaces

- Prototypes are in `#include <linux/malloc.h>`
- `void *kmalloc(size_t size, int flags)`: allocation of contiguous memory (it returns the virtual address)
- `void kfree(void *obj)`: frees memory allocated via `kmalloc()`
- `void *kmalloc_node(size_t size, int flags, int node)`: NUMA-aware allocation

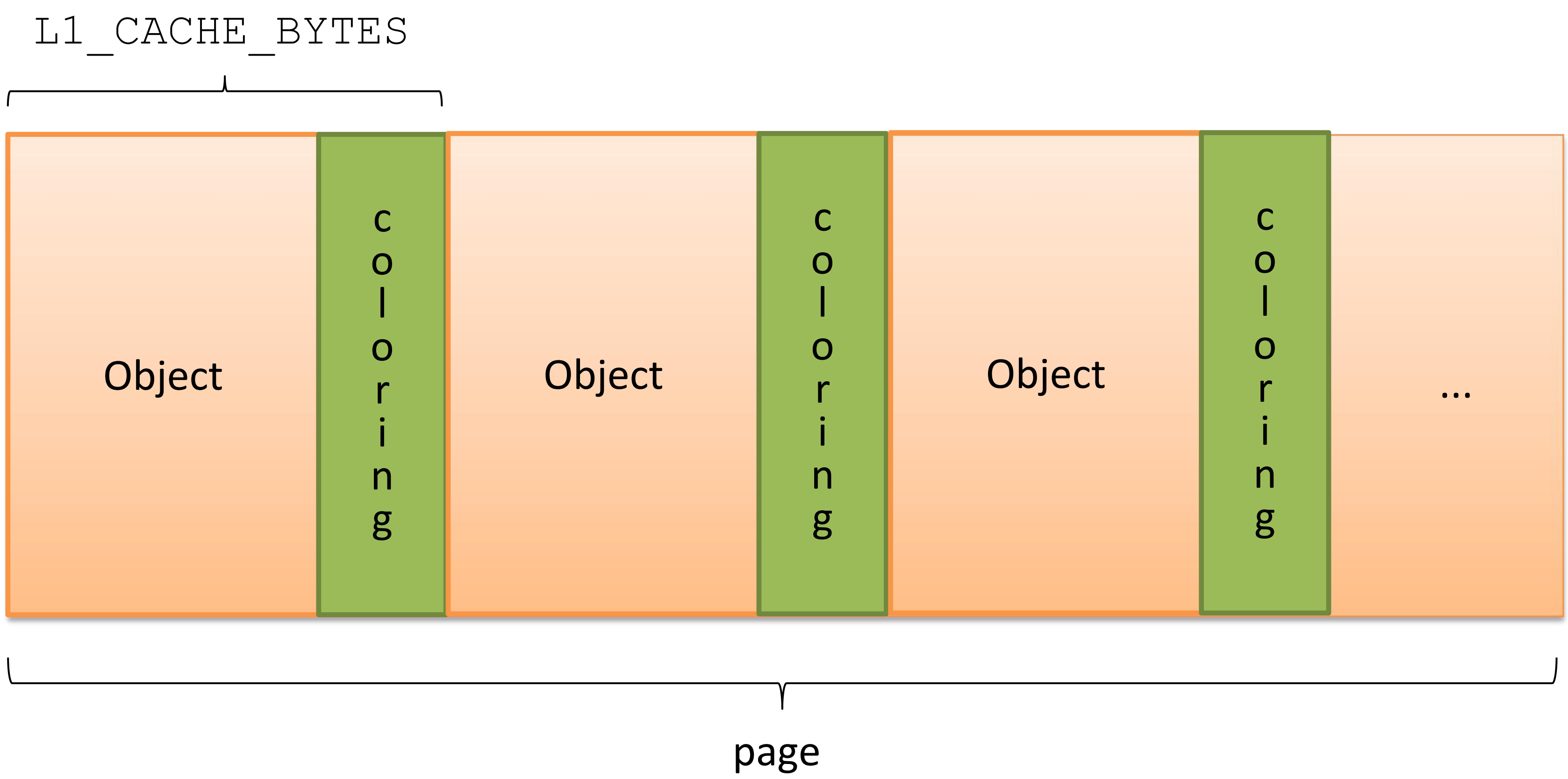
Available Caches (up to 3.9.11)

```
struct cache_sizes {
	size_t			cs_size;
	struct kmem_cache	*cs_cachep;
#ifdef CONFIG_ZONE_DMA
	struct kmem_cache	*cs_dmacachep;
#endif
}

static cache_sizes_t cache_sizes[] = {
	{32,		NULL,		NULL},
	{64,		NULL,		NULL},
	{128,		NULL,		NULL}
	...
	{65536,		NULL,		NULL},
	{131072,	NULL,		NULL},
}
```

Available Caches (since 3.10)

```
struct kmem_cache_node {
        spinlock_t list_lock;

#ifdef CONFIG_SLAB
        struct list_head slabs_partial; /* partial list first, better
                                           asm code */
        struct list_head slabs_full;
        struct list_head slabs_free;
        unsigned long free_objects;
        unsigned int free_limit;
        unsigned int colour_next;     /* Per-node cache coloring */
        struct array_cache *shared;   /* shared per node */
        struct array_cache **alien;   /* on other nodes */
        unsigned long next_reap;      /* updated without locking */
        int free_touched;             /* updated without locking */
#endif
};
```

Slab Coloring



L1 data caches

- Cache lines are small (typically 32/64 bytes)
- `L1_CACHE_BYTES` is the configuration macro in Linux
- Independently of the mapping scheme, close addresses fall in the same line
- Cache-aligned addressess fall in different lines
- We need to cope with *cache performance issues at the level of kernel programming* (typically not of explicit concern for user level programming)

Cache Performance Aspects

- *Common members* access issues
  - Most-used members in a data structure should be placed at its head to maximize cache hits
  - This should happen provided that the slab-allocation (kmalloc()) system gives cache-line aligned addresses for dynamically allocated memory chunks
- *Loosely related fields* should be placed sufficiently distant in the data structure so as to avoid performance penalties due to *false cache sharing*
- The Kernel has also to deal with Aliasing

Cache flush operations

- Cache flushes automation can be partial (similar to TLB)
- Need for explicit cache flush operations
- In some cases, the flush operation uses the physical address of the cached data to support flushing ("strict caching systems", e.g. HyperSparc)
- Hence, TLB flushes should always be placed after the corresponding data cache flush calls

Flushing Full MM	Flushing Range	Flushing Page
flush_cache_mm() Change all page tables flush_tlb_mm()	flush_cache_range() Change page table range flush_tlb_range()	flush_cache_page() Change single PTE flush_tlb_page()

Cache flush operations

- `void flush_cache_all(void)`
  - Flushes the entire CPU cache system, which makes it the most severe flush operation to use
  - It is used when changes to the kernel page tables, which are global in nature, are to be performed

- `void flush_cache_mm(struct mm_struct *mm)`
  - Flushes all entries related to the address space
  - On completion, no cache lines will be associated with `mm`

Cache flush operations

```
void flush_cache_range(struct mm_struct *mm,
   unsigned long start, unsigned long end)
```

- This flushes lines related to a range of addresses
- Like its TLB equivalent, it is provided in case the architecture has an efficient way of flushing ranges instead of flushing each individual page

```
void flush_cache_page(struct vm_area_struct
*vma, unsigned long vmaddr)
```

- Flushes a single-page-sized region
- `vma` is supplied because the `mm_struct` is easily accessible through `vma->vm_mm`
- Additionally, by testing for the `VM_EXEC` flag, the architecture knows if the region is executable for caches that separate the instructions and data caches

User-/Kernel-Level Data Movement

```
unsigned long copy_from_user(void *to, const void *from,
   unsigned long n)
```

Copies n bytes from the user address(from) to the kernel address space(to).

```
unsigned long copy_to_user(void *to, const void *from,
   unsigned long n)
```

Copies n bytes from the kernel address(from) to the user address space(to).

```
void get_user(void *to, void *from)
```

Copies an integer value from userspace (from) to kernel space (to).

```
void put_user(void *from, void *to)
```

Copies an integer value from kernel space (from) to userspace (to).

```
long strncpy_from_user(char *dst, const char *src, long count)
```

Copies a null terminated string of at most count bytes long from userspace (src) to kernel space (dst)

```
int access_ok(int type, unsigned long addr, unsigned
   long size)
```

Returns nonzero if the userspace block of memory is valid and zero otherwise

Large-size Allocations

- Typically used when adding large-size data structures to the kernel in a stable way
- This is the case when, e.g., mounting external modules
- The main APIs are:
  - `void *vmalloc(unsigned long size)`

    allocates memory of a given size, which can be non-contiguous, and returns the virtual address (the corresponding frames are reserved)
  - `void vfree(void *addr)`

    frees the above mentioned memory

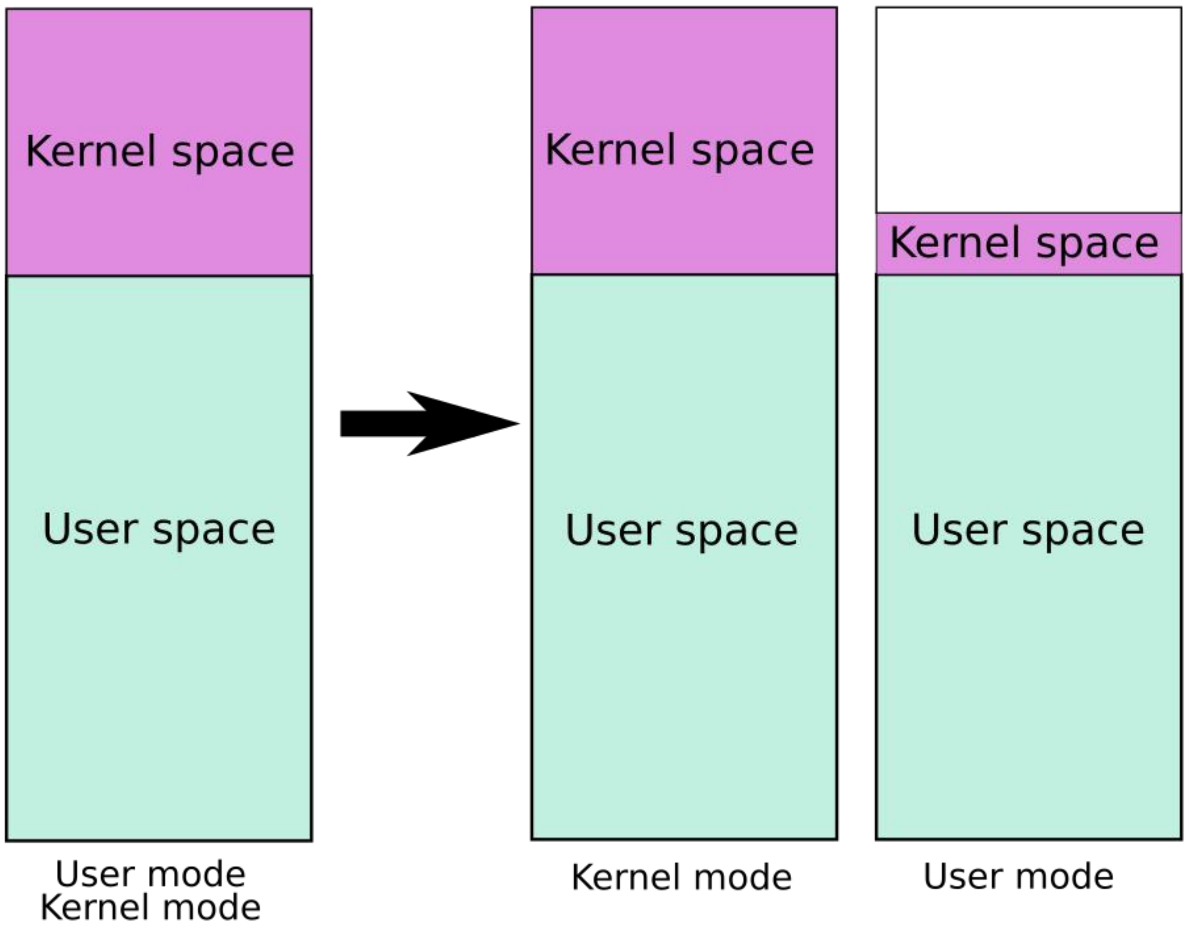
Logical/Physical Address Translation

- This is valid only for kernel directly mapped memory (not vmalloc'd memory)
- `virt_to_phys(unsigned int addr)` (in `include/x86/io.h`)
- `phys_to_virt(unsigned int addr)` (in `include/x86/io.h`)

`kmalloc()` **VS** `vmalloc()`

- Allocation size:
  - Bounded for kmalloc (cache aligned)
    - The boundary depends on the architecture and the Linux version. Current implementations handle up to 8KB
  - 64/128 MB for vmalloc
- Physical contiguousness
  - Yes for kmalloc
  - No for vmalloc
- Effects on TLB
  - None for kmalloc
  - Global for vmalloc (transparent to vmalloc users)

Kernel Page Table Isolation

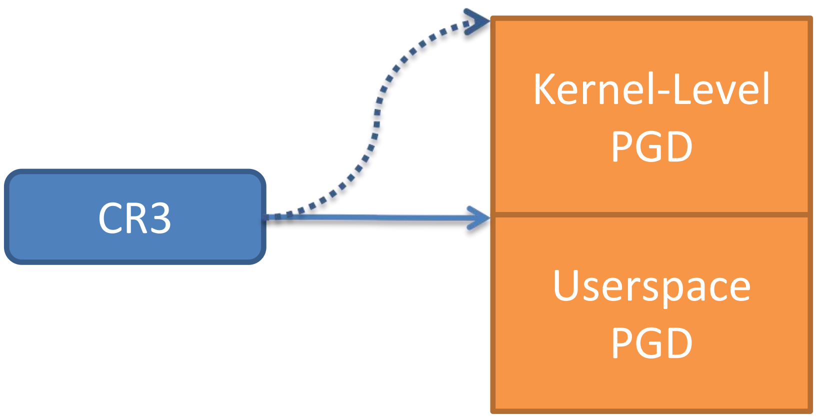


cpu_entry_area

```
struct cpu_entry_area {
   char gdt[PAGE_SIZE];

   struct entry_stack_page entry_stack_page;

   struct tss_struct tss;

   char exception_stacks[...];
};

DECLARE_PER_CPU(struct cpu_entry_area *,
                cpu_entry_area);
```

Double Page General Directory

- The first level of the page table is composed of a buffer of 8 KBs (two actual pages)
- One page is used to map the kernel-level memory view
- The other one is used to map the userspace memory view



CR3 is updated when transitioning to and from kernel mode

Switch CR3

```
/arch/x86/entry/entry_64.S:
SYM_CODE_START(entry_SYSCALL_64)
        ...
        SWITCH_TO_KERNEL_CR3 scratch_reg=%rsp
        ...
        SWITCH_TO_USER_CR3_STACK scratch_reg=%rdi
```

```
/arch/x86/entry/calling.h:
.macro SWITCH_TO_KERNEL_CR3 scratch_reg:req
        mov     %cr3, \scratch_reg
        andq     $(~PTI_USER_PGTABLE_AND_PCID_MASK), \scratch_reg
        mov     \scratch_reg, %cr3
.endm
```

Memory View Consistency

- When a minor fault occurs, the process transitions to kernel mode
- Any update in the page table is therefore reflected only in the kernel-view page table
- The userspace page table must be explicitly realigned by the fault handler
- This same behavior occurs when a clone of the page table is created (this aspect is related to the implementation of the `fork()`)

Memory View Consistency (5.5)

```
static noinline int vmalloc_fault(unsigned long address)
{
        pgd_t *pgd, *pgd_k;
        p4d_t *p4d, *p4d_k;
        pud_t *pud;
        pmd_t *pmd;
        pte_t *pte;

        pgd = (pgd_t *)__va(read_cr3_pa()) + pgd_index(address);

        if (pgd_none(*pgd)) {
                set_pgd(pgd, *pgd_k);
        }

        ...
}
```

Memory View Consistency (5.5)

```
/arch/x86/include/asm/pgtable_64.h:
static inline void native_set_pgd(pgd_t *pgdp, pgd_t pgd)
{
        WRITE_ONCE(*pgdp, pti_set_user_pgtbl(pgdp, pgd));
}

/arch/x86/mm/pti.c:
pgd_t __pti_set_user_pgtbl(pgd_t *pgdp, pgd_t pgd)
{
        if (!pgdp_maps_userspace(pgdp))
                return pgd;

        kernel_to_user_pgdp(pgdp)->pgd = pgd.pgd;

        if ((pgd.pgd & (_PAGE_USER|_PAGE_PRESENT)) == (_PAGE_USER|_PAGE_PRESENT) &&
            (__supported_pte_mask & _PAGE_NX))
                pgd.pgd |= _PAGE_NX;

        return pgd;
}
```