Linux Memory Management

COMS W4118

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References: Operating Systems Concepts (9e), Understanding the Linux Kernel (3rd edition) by Bovet and Cesati, previous W4118s

Why aren't Page Tables Sufficient?

- How to device if a memory region unallocated vs. unloaded?
  - Virtual memory areas (VMAs)
- How to manage physical memory allocation?
  - Page descriptors
  - Page allocators (e.g., buddy algorithm, SLOB, SLUB, SLAB)
- Where to read a demand fetched page from?
  - Radix trees (page_tree)
- How to identify which PTEs map a physical page when evicting?
  - Reverse mappings
  - anon vmas (anon_vma), and radix priority trees (i_mmap)
- How to unify file accesses and swapping?
  - Page Cache

Linux Memory Subsystem Outline

- Memory data structures
- Virtual Memory Areas (VMA)
- Page Mappings and Page Fault Management
- Reverse Mappings
- Page Cache and Swapping
- Physical Page Management

Linux MM Objects Glossary

- struct mm: memory descriptor (mm_types.h)
- struct vm_area_struct mmap: vma (mm_types.h)
- struct page: page descriptor (mm_types.h)
- pgd, pud, pmd, pte: pgtable entries (arch/x86/include/asm/page.h, page_32.h, pgtable.h, pgtable_32.h)
  - pgd: page global directory
  - pud page upper directory
  - pmd: page middle directory
  - pte: page table entry
- struct anon_vma: anon vma reverse map (rmap.h)
- struct prio_tree_root i_mmap: priority tree reverse map (fs.h)
- struct radix_tree_root page_tree: page cache radix tree (fs.h)

The mm_struct Structure

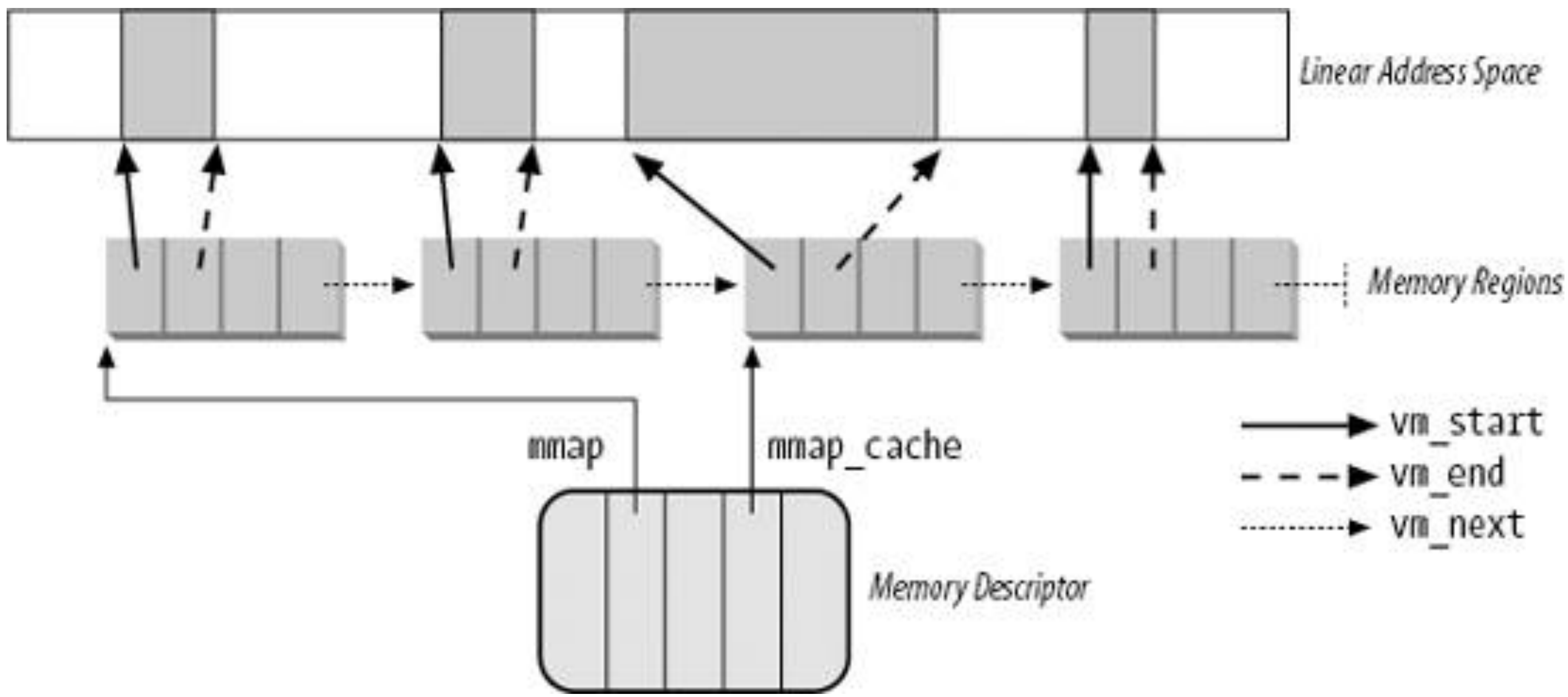
- Main memory descriptor
  - One per address space
  - Each task_struct has a pointer to one
  - May be shared between tasks (e.g., threads)
- Contains two main substructures
  - Memory map of virtual memory areas (vma)
  - Pointer to arch specific page tables
  - Other data, e.g., locks, reference counts, accounting information

struct mm_struct

```
struct mm_struct {
	struct vm_area_struct * mmap;		/* list of VMAs */
	struct rb_root mm_rb;
	struct vm_area_struct * mmap_cache;	/* last find_vma result */
	unsigned long mmap_base;		/* base of mmap area */
	unsigned long task_size;		/* size of task vm space */
	pgd_t * pgd;
	atomic_t mm_users;			/* How many users with user space? */
	atomic_t mm_count;			/* How many references to "struct mm_struct */
	int map_count;				/* number of VMAs */
	struct rw_semaphore mmap_sem;
	spinlock_t page_table_lock;		/* Protects page tables and some counters */
	unsigned long hiwater_rss;	/* High-watermark of RSS usage */
	unsigned long hiwater_vm;	/* High-water virtual memory usage */
	unsigned long total_vm, locked_vm, shared_vm, exec_vm;
	unsigned long stack_vm, reserved_vm, def_flags, nr_ptes;
	cpumask_t cpu_vm_mask;
	unsigned long flags; /* Must use atomic bitops to access the bits */
};
```

Virtual Memory Areas (vma)

Access to memory map is protected by mmap_sem read/write semaphore

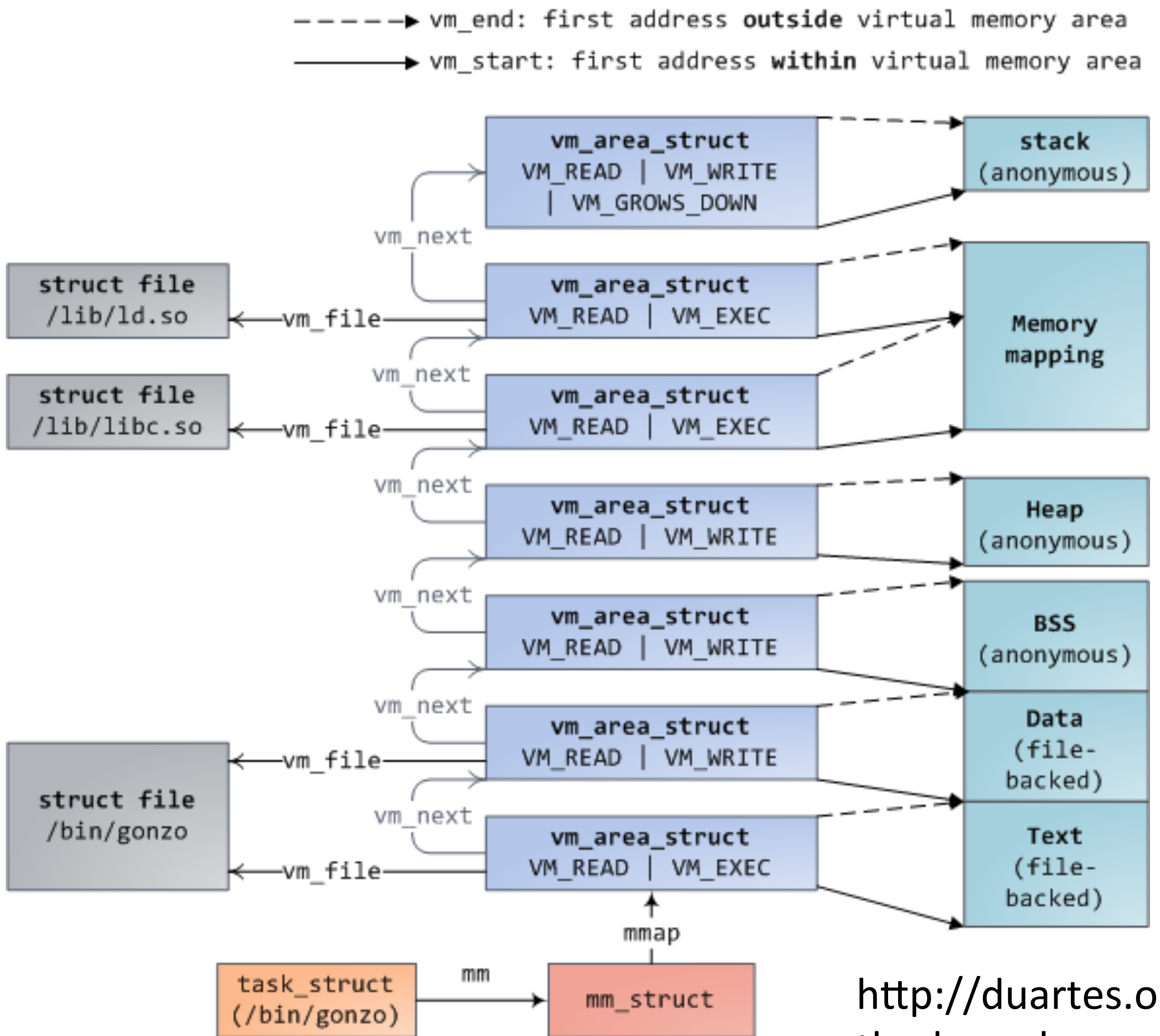


Reference: http://www.makelinux.net/books/ulk3/understandlk-CHP-9-SECT-3

Types of VMA Mappings

- File based mappings (mmap):
  - Code pages (binaries), libraries
  - Data files
  - Shared memory
  - Devices
- Anonymous mappings:
  - Stack
  - Heap
  - CoW pages
- Use different mechanisms for reverse mapping, demand fetching, swapping

Virtual Memory Areas



http://duartes.org/gustavo/blog/post/how-the-kernel-manages-your-memory

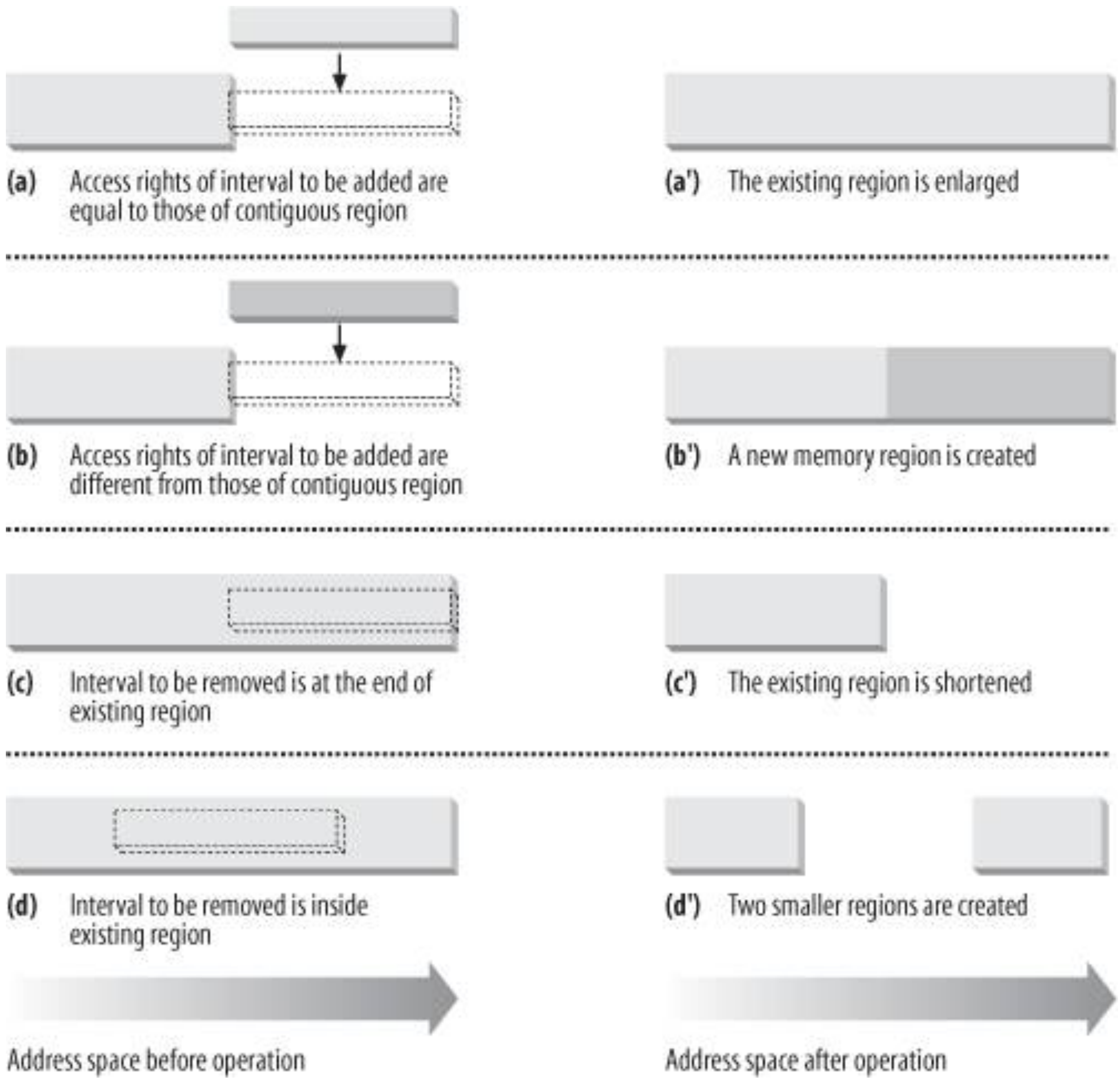
Anatomy of a VMA

- Pointer to start and end of region in address space (virtual addresses)
- Data structures to index vmas efficiently
- Page protection bits
- VMA protection bits/flags (superset of page bits)
- Reverse mapping data structures
- Which file this vma loaded from?
- Pointers to functions that implement vma operations
  - E.g., page fault, open, close, etc.

struct vm_area_struct

```
struct vm_area_struct {
    struct mm_struct * vm_mm;     /* The address space we belong to. */
    unsigned long vm_start;       /* Our start address within vm_mm. */
    unsigned long vm_end;
    struct vm_area_struct *vm_next;
    pgprot_t vm_page_prot;        /* Access permissions of this VMA. */
    unsigned long vm_flags;       /* Flags, see mm.h. */
    struct rb_node vm_rb;
    struct raw_prio_tree_node prio_tree_node;
    struct list_head anon_vma_node;   /* Serialized by anon_vma->lock */
    struct anon_vma *anon_vma;  /* Serialized by page_table_lock */
    struct vm_operations_struct * vm_ops;
    unsigned long vm_pgoff;
    struct file * vm_file;        /* File we map to (can be NULL). */
    void * vm_private_data;       /* was vm_pte (shared mem) */
};
```

VMA Addition and Removal



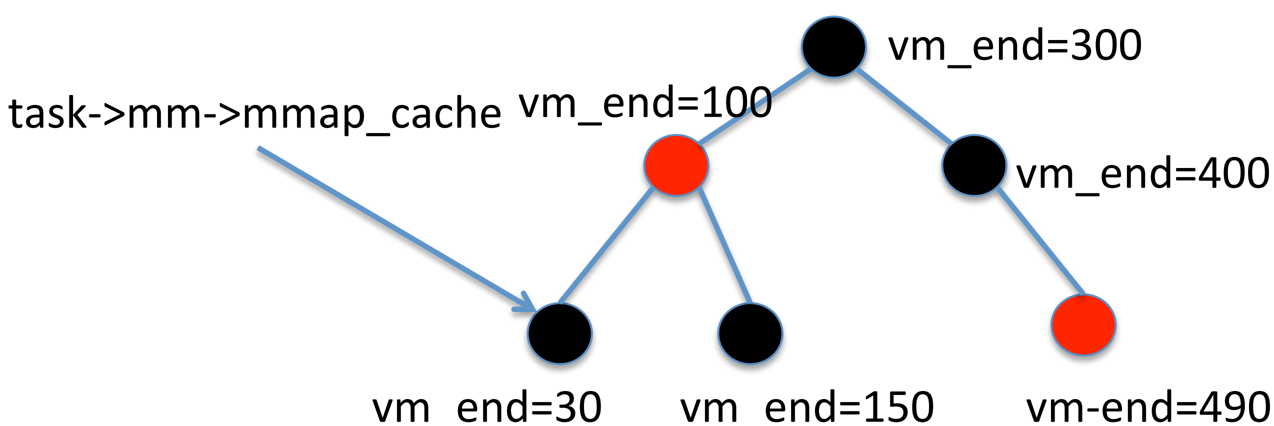
- Occurs whenever a new file is mmaped, a new shared memory segment is created, or a new section is created (e.g., library, code, heap, stack)
- Kernel tries to merge with adjacent sections

VMA Search

- VMA is very frequently accessed structure
  – Must often map virtual address to vma
  – Whenever we have a fault, mmap, etc.
  – Need efficient lookup
- Two Indexes for different uses
  – Linear linked list
    - Allows efficient traversal of entire address space
    - vma->vm_next
  – Red-black tree of vmas
    - Allows efficient search based on virtual address
    - vma->vm_rb

Efficient Search of VMAs

- Red-black trees allow O(lg n) search of vma based on virtual address
- Indexed by vm_end ending address



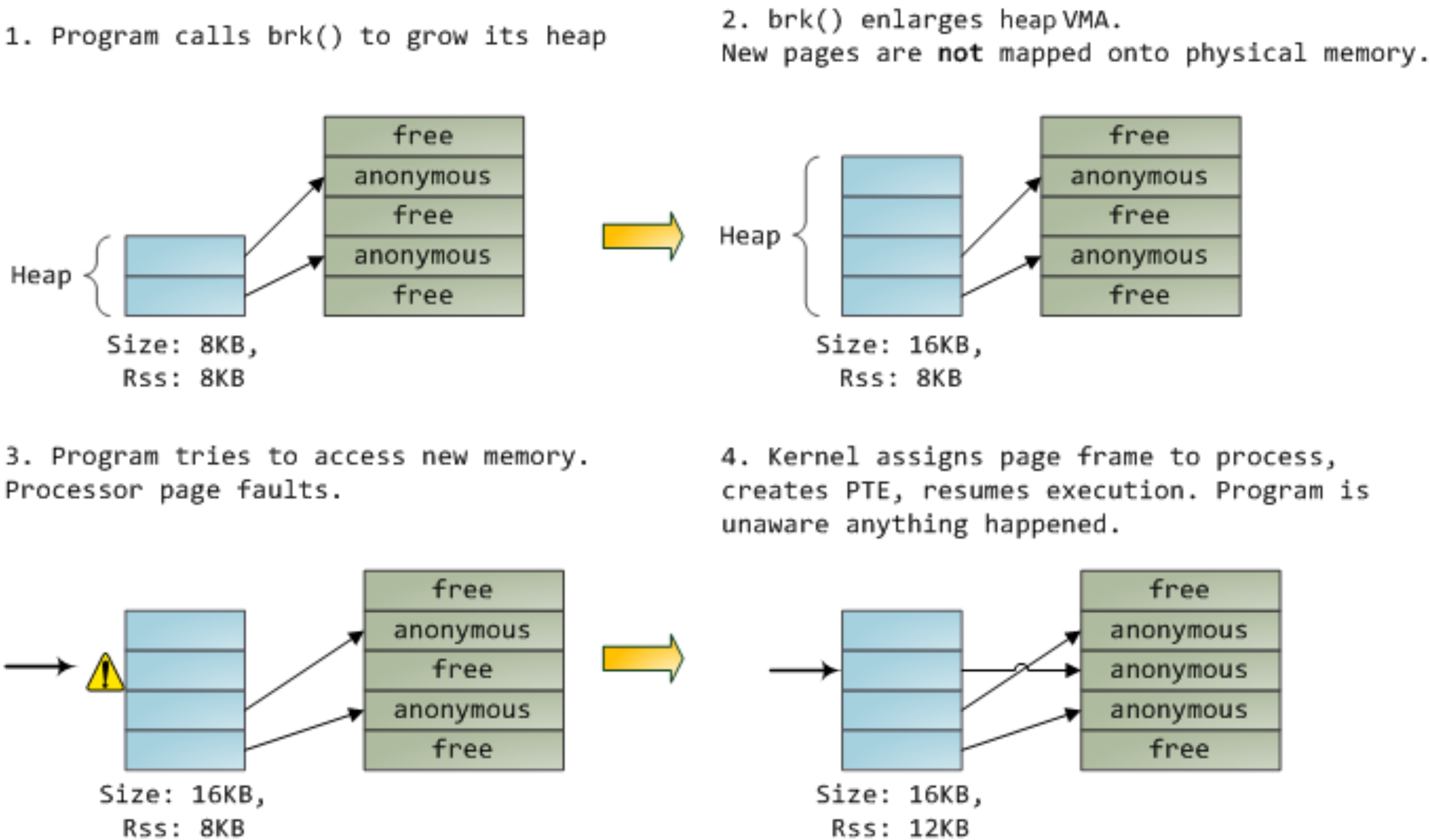
struct vm_operations_struct

```
struct vm_operations_struct {
	void (*open)(struct vm_area_struct * area);
	void (*close)(struct vm_area_struct * area);
	int (*fault)(struct vm_area_struct *vma, struct vm_fault *vmf);

	/* notification that a previously read-only page is about to become
	 * writable, if an error is returned it will cause a SIGBUS */
	int (*page_mkwrite)(struct vm_area_struct *vma, struct page *page);

	/* called by access_process_vm when get_user_pages() fails, typically
	 * for use by special VMAs that can switch between memory and hardware
	 */
	int (*access)(struct vm_area_struct *vma, unsigned long addr,
			void *buf, int len, int write);
};
```

Demand Fetching via Page Faults



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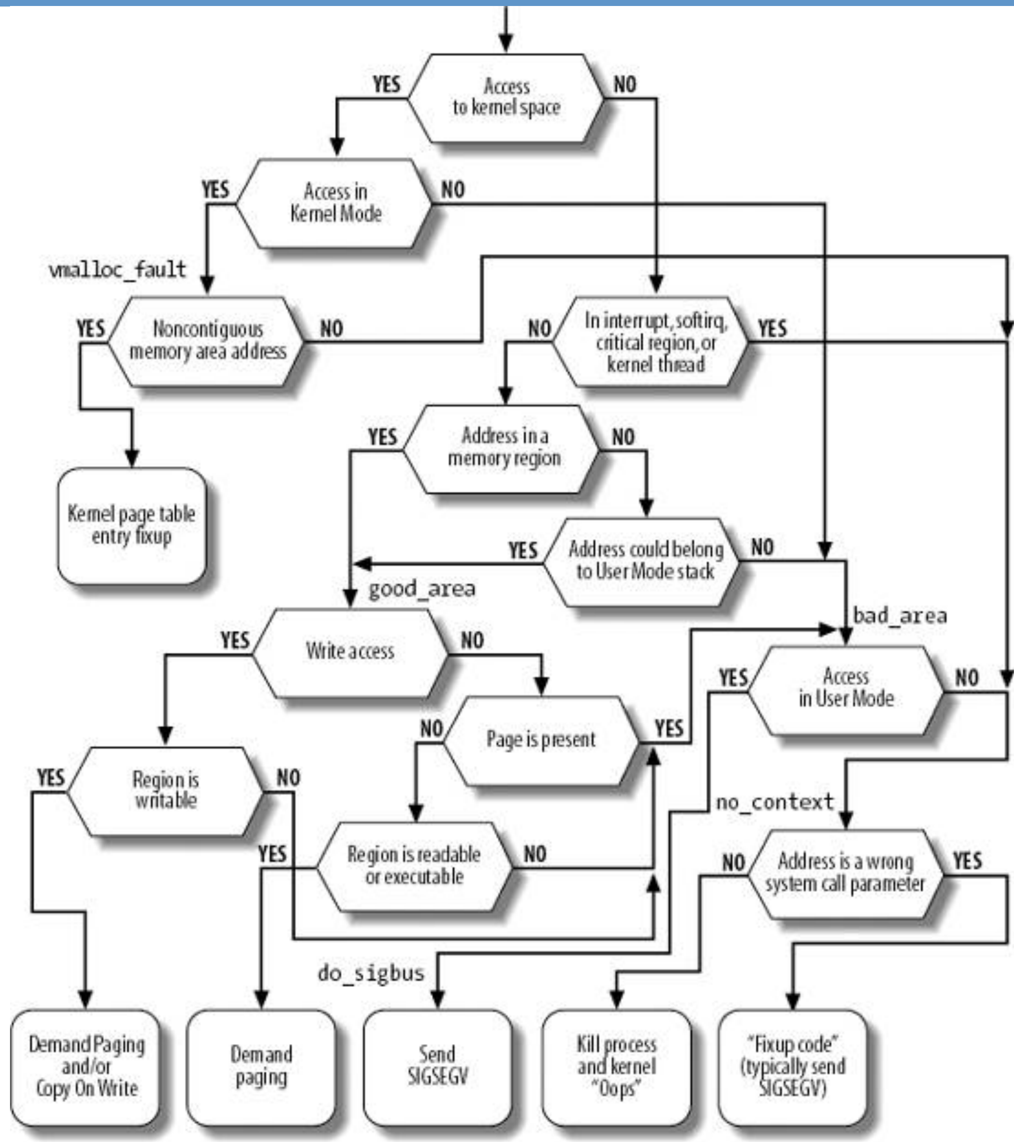
Fault Handling

- Entry point: handle_pte_fault (mm/memory.c)
- Identify which VMA faulting address falls in
- Identify if VMA has registered a fault handler
- Default fault handlers
  - do_anonymous_page: no page and no file
  - do_linear_fault: vm_ops registered?
  - do_swap_page: page backed by swap
  - do_nonlinear_fault: page backed by file
  - do_wp_page: write protected page (CoW)

The Page Fault Handler



Complex logic: easier to read code than read a book!

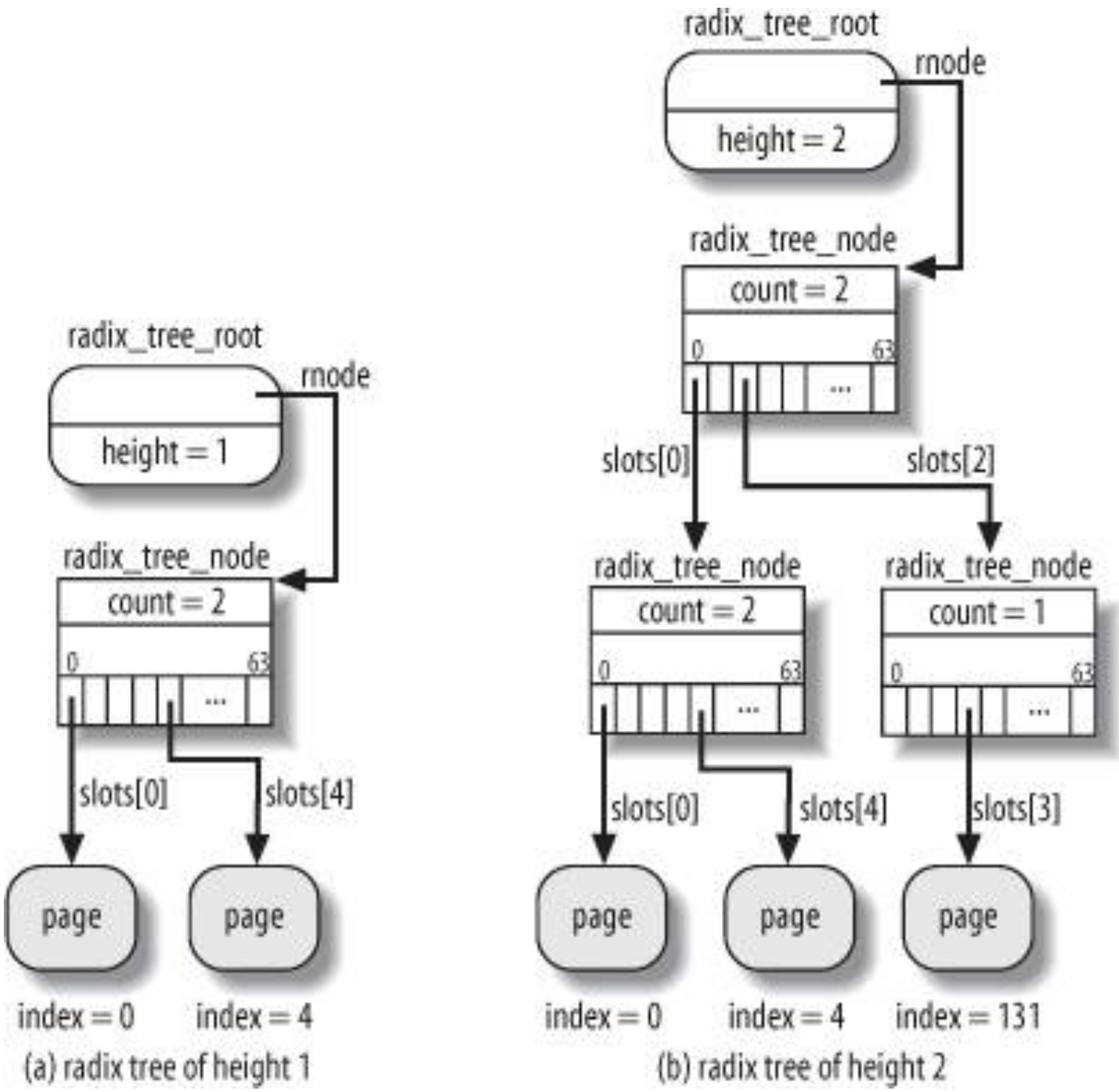
Copy on Write

- PTE entry is marked as un-writeable
- But VMA is marked as writeable
- Page fault handler notices difference
  - Must mean CoW
  - Make a duplicate of physical page
  - Update PTEs, flush TLB entry
  - do_wp_page

Which page to map when no PTE?

- If PTE doesn't exist for an anonymous mapping, its easy
  - Map standard zero page
  - Allocate new page (depending on read/write)
- What if mapping is a memory map? Or shared memory?
  - Need some additional data structures to map logical object to set of pages
  - Independent of memory map of individual task
- The address_space structure
  - One per file, device, shared memory segment, etc.
  - Mapping between logical offset in object to page in memory
  - Pages in memory are called "page cache"
  - Files can be large: need efficient data structure
- You don't have to use address_space for hw4. Use a simple array to maintain your offset->page mapping.

The Page Cache Radix Tree



Physical pages: struct page

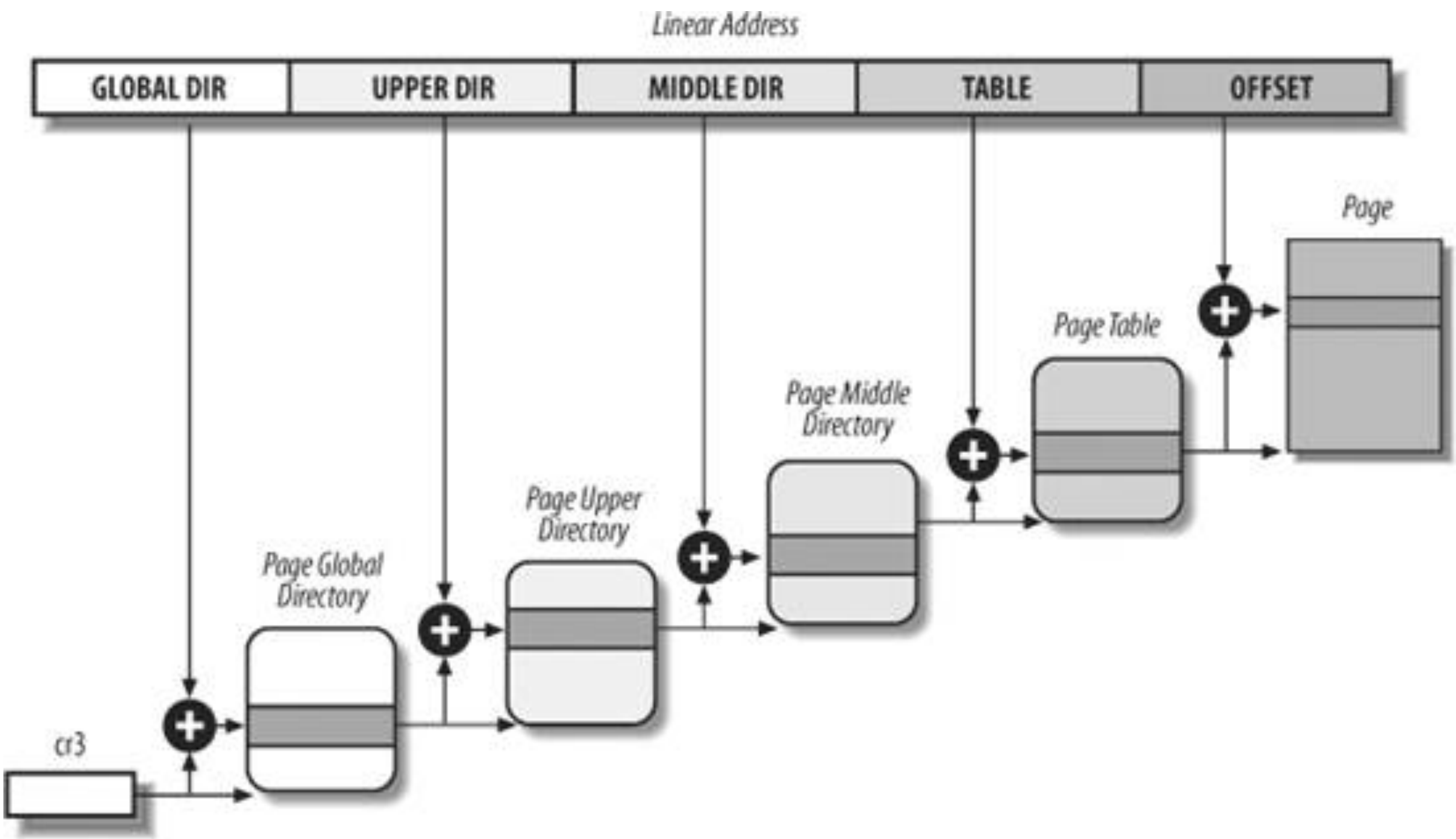
- Each physical page has a page descriptor associated with it
- Contains reference count for the page
- Contains a pointer to the reverse map (struct address space or struct anon_vma)
- Contains pointers to lru lists (to evict the page)
- Descriptor to address: void * page_address(struct page *page)

```
struct page {
    unsigned long flags;
    atomic_t _count;
    atomic_t _mapcount;
    struct address_space *mapping;
    pgoff_t index;
    struct list_head lru;
};
```

Allocating a Physical Page

- Physical memory is divided into "zones"
  - ZONE_DMA: low order memory (<16MB) certain older devices can only access so much
  - ZONE_NORMAL: normal kernel memory mapping into the kernel's address space
  - ZONE_HIGHMEM: high memory not mapped by kernel. Identified through (struct page *). Must create temporary mapping to access
- To allocate, use kmalloc or related set of functions. Specify zone and options in mask
  - kmalloc, __get_free_pages, __get_free_page, get_zeroed_page: return virtual address (must be mapped)
  - alloc_pages, alloc_page: return struct page *

Page Table Structure



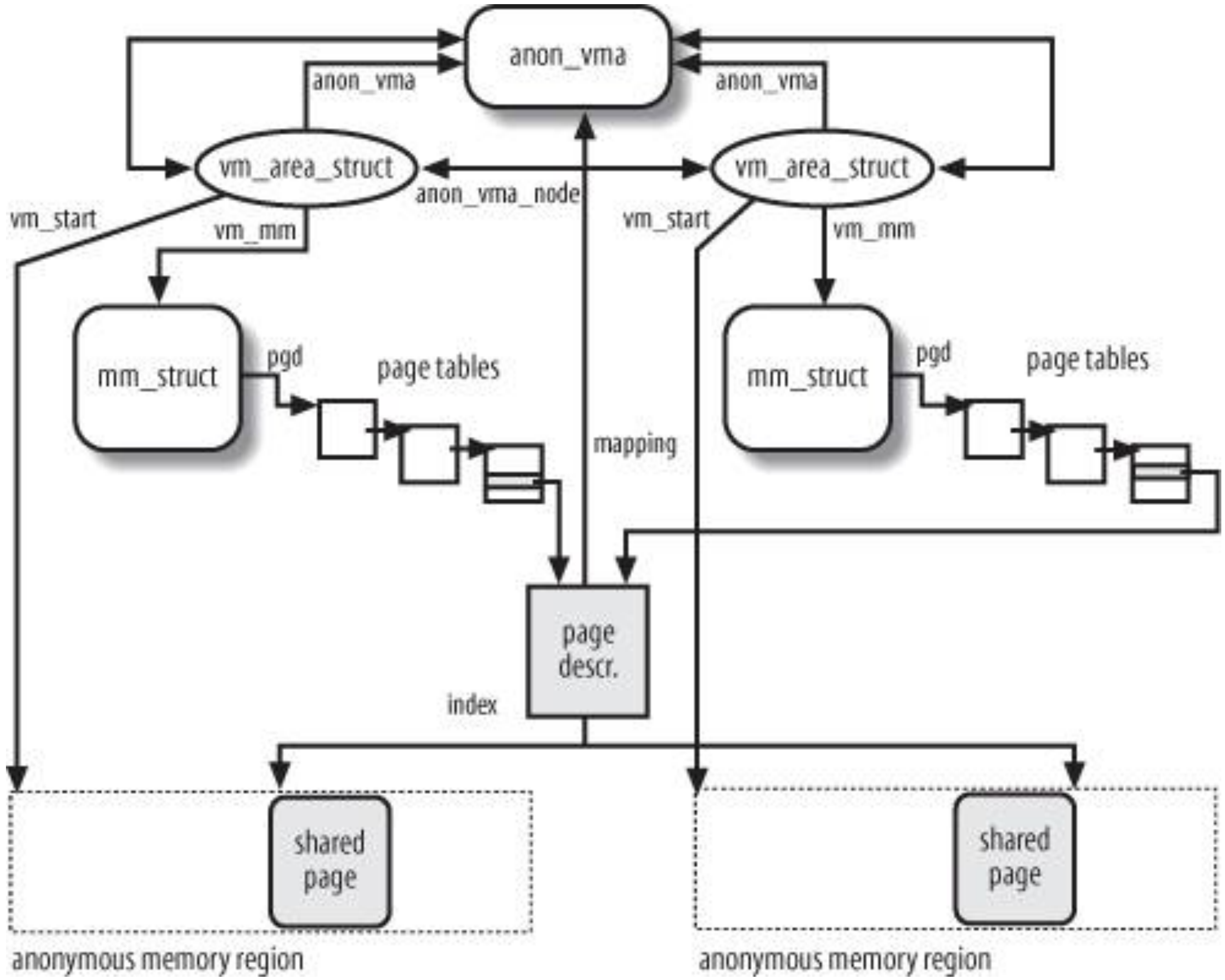
Working with Page Tables

- Access page table through mm_struct->pg_d
- Must to a recursive walk, pgd, pud, pmd, pte
  - Kernel includes code to assist walking
  - mm/pagewalk.c: walk_page_range
  - Can specific your own function to execute for each entry
- Working with PTE entries
  - Lots of macros provided (asm/pgtable.h, page.h)
  - Set/get entries, set/get various bits
  - E.g., pte_mkyoung(pte_t): clear accessed bit, pte_wrprotect(pte_t): clear write bit
  - Must also flush TLB whenever entries are changed
    - include/asm-generic/tkb.h: tlb_remove_tlb_entry(tlb)

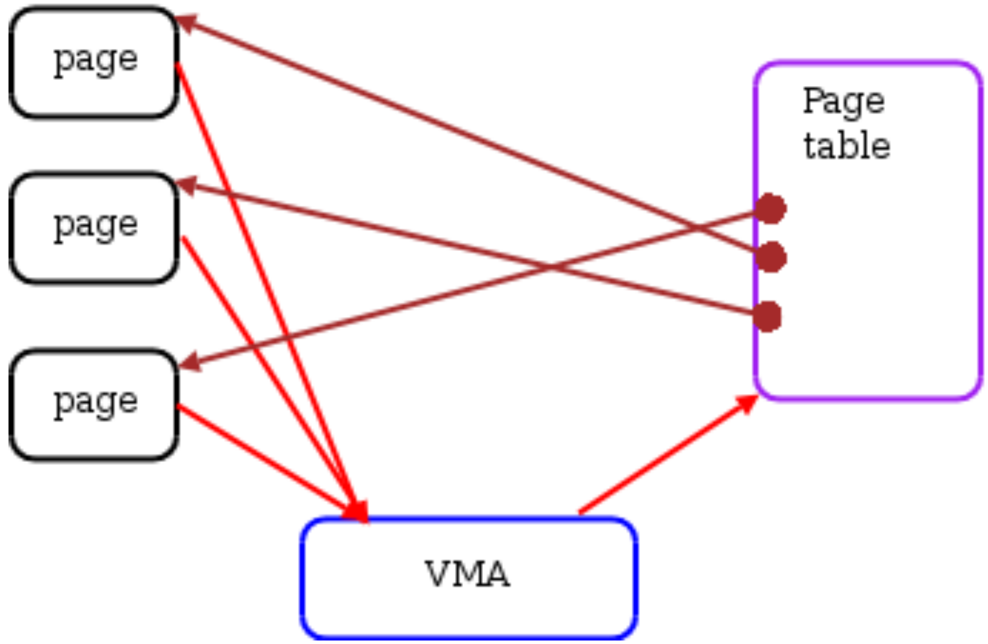
Reverse Mappings

- Problem: how to swap out a shared mapping?
  - Many PTEs may point to it
  - But, we know only identity of physical page
    - Could maintain reverse PTE
    - i.e., for every page, list of PTEs that point to it
    - Could get large. Very inefficient.
- Solution: reverse maps
  - Anonymous reverse maps: anon_vma
  - Idea: maintain one reverse mapping per vma (logical object) rather than one reverse mapping per page
  - Based on observation most pages in VMA or other logical object (e.g., file) have the same set of mappers
  - rmap contains VMAs that may map a page
  - Kernel needs to search for actual PTE at runtime

Anonymous rmaps: anon_vma

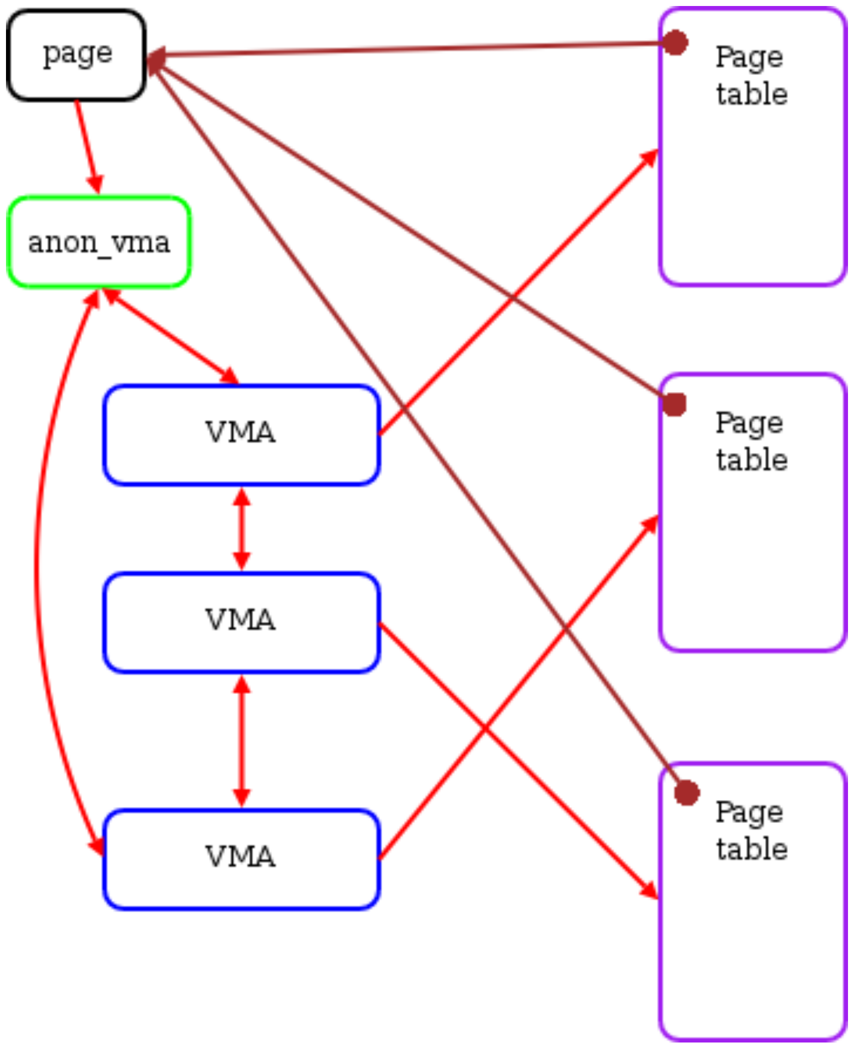


anon_vma in Action



Reference: Virtual Memory II: the return of objrmap. http://lwn.net/Articles/75198/

anon_vma in Action



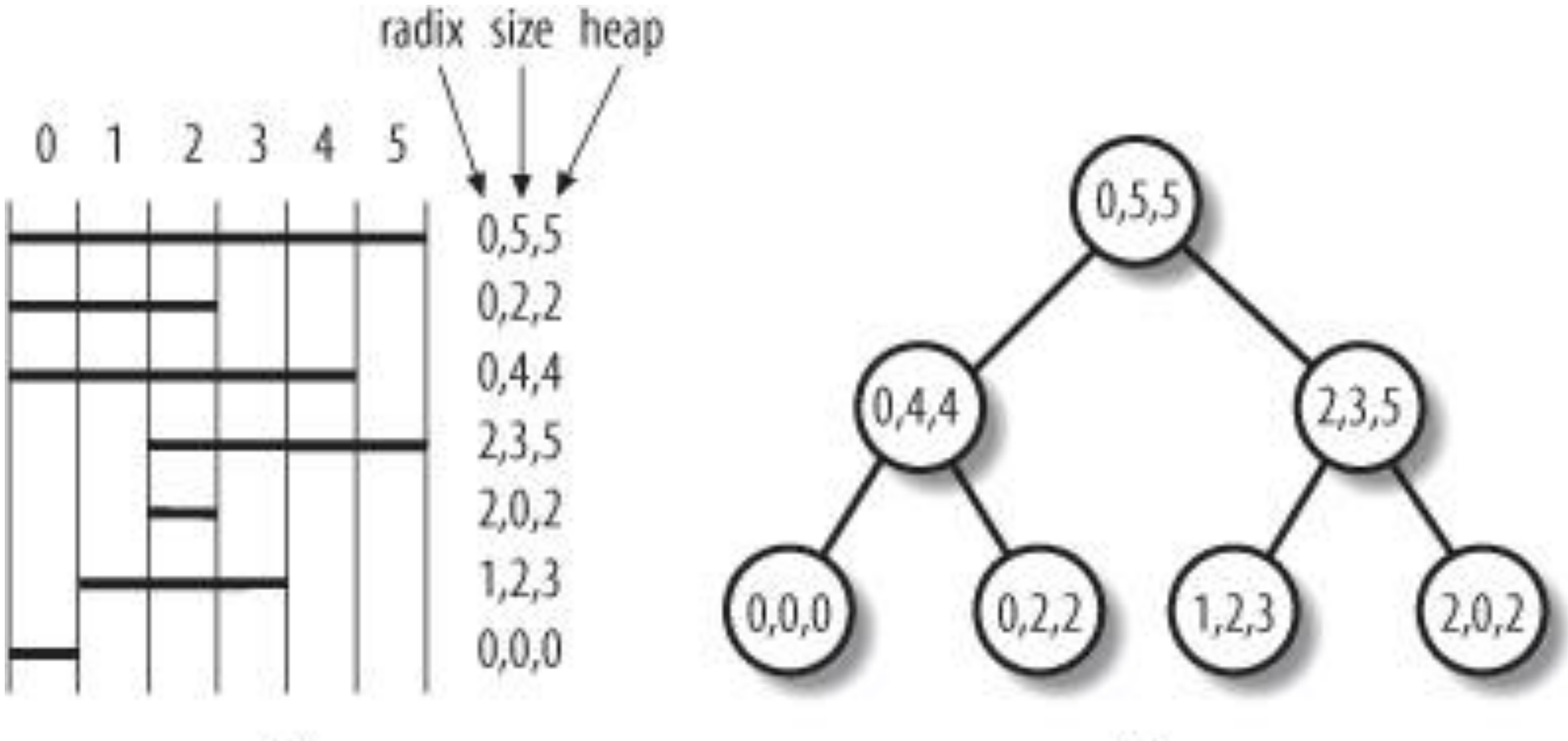
Reference: Virtual Memory II: the return of objrmap. http://lwn.net/Articles/75198/

Reverse Mapping for Memory Maps

- Problem: anon_vma is good for limited sharing
  - Memory maps can be shared by large numbers of processes
  - E.g., libc shared by everyone
  - I.e., need to do linear search for every eviction
  - Also, different processes may map different ranges of a memory map into their address space
- Need efficient data structure
  - Basic operation: given an offset in an object (such as a file), or a range of offsets, return vmas that map that range
  - Enter priority search trees
  - Allows efficient interval queries
- Note: you don't need this for hw4. Use anon_vma

i_mmap Priority Tree

Part of struct address_space in fs.h



(a) (b)

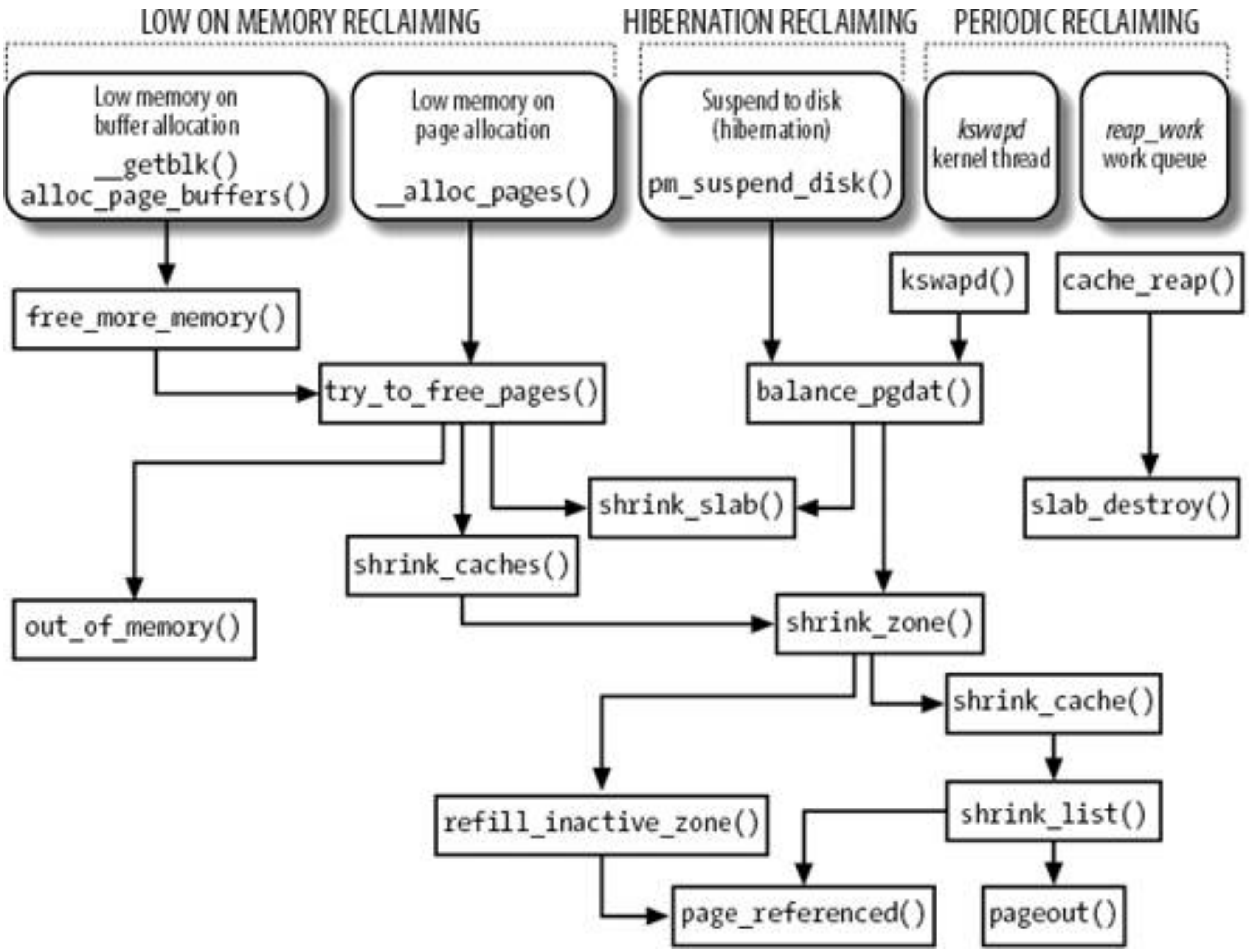
Page Frame Reclaiming (Swapping)

- Generic subsystem for memory and files (vmscan.c)
  – Handles anonymous pages (swapping)
  – Memory mapped files (synchronizing)
- Handles anonymous/file pages differently
  – Unreclaimable: pages locked in memory (PG_locked)
  – Swappable: anonymous user mode pages
  – Syncable: memory mapped pages, synchronize with original file they were loaded from
  – Discardable: unused pages in memory caches, non-dirty pages in page cache
- PFRA Design
  – Identify pages to evict using simplified LRU
  – Unmap all mappers of shared using reverse map (try_to_unmap function)

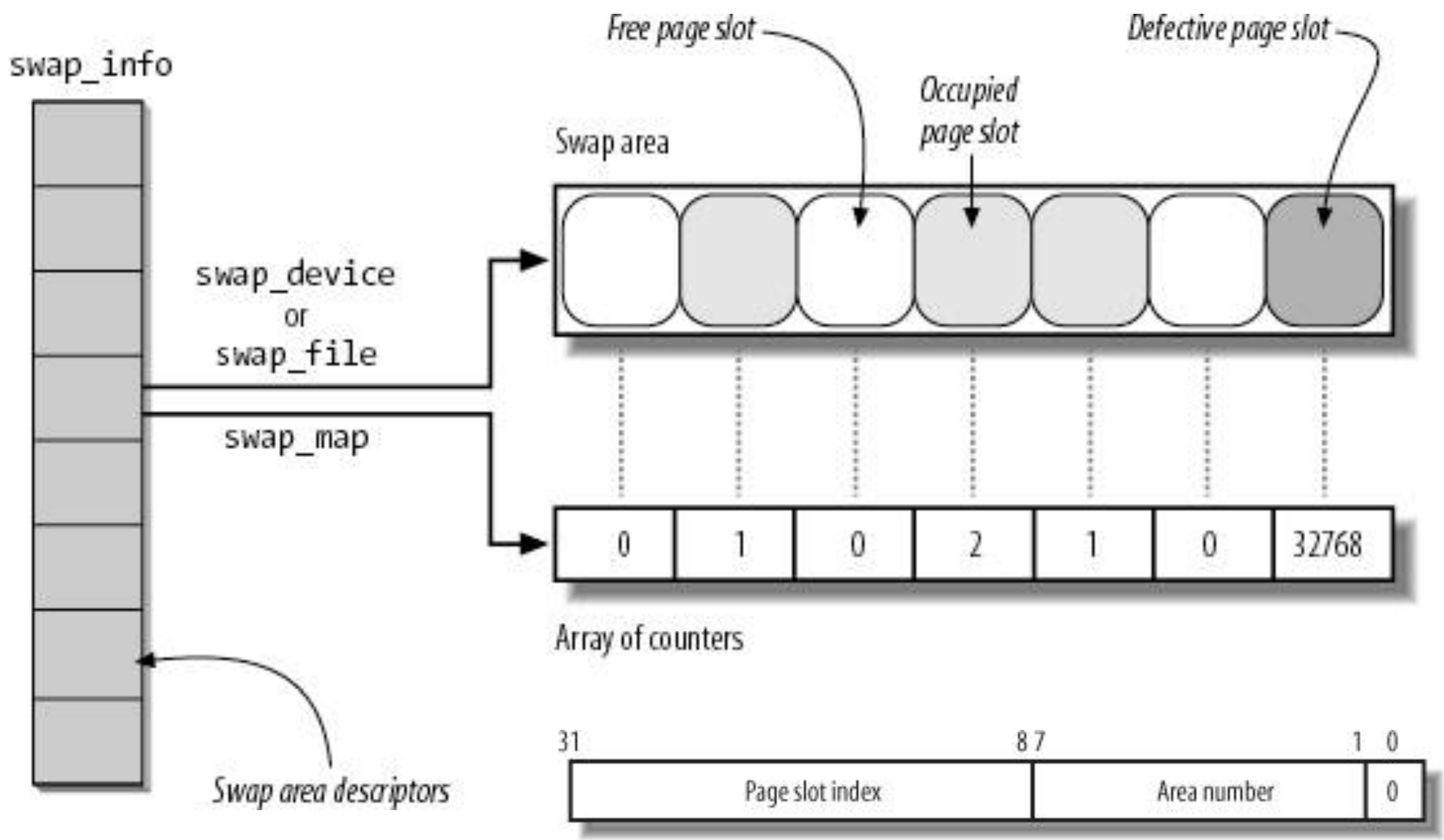
When is PFRA Invoked?

- Invoked on three different occasions:
  - Kernel detects low on memory condition
    - E.g., during alloc_pages
  - Periodic reclaiming
    - kernel thread kswapd
  - Hibernation reclaiming
    - for suspend-to-disk

Page Frame Reclaiming Algorithm



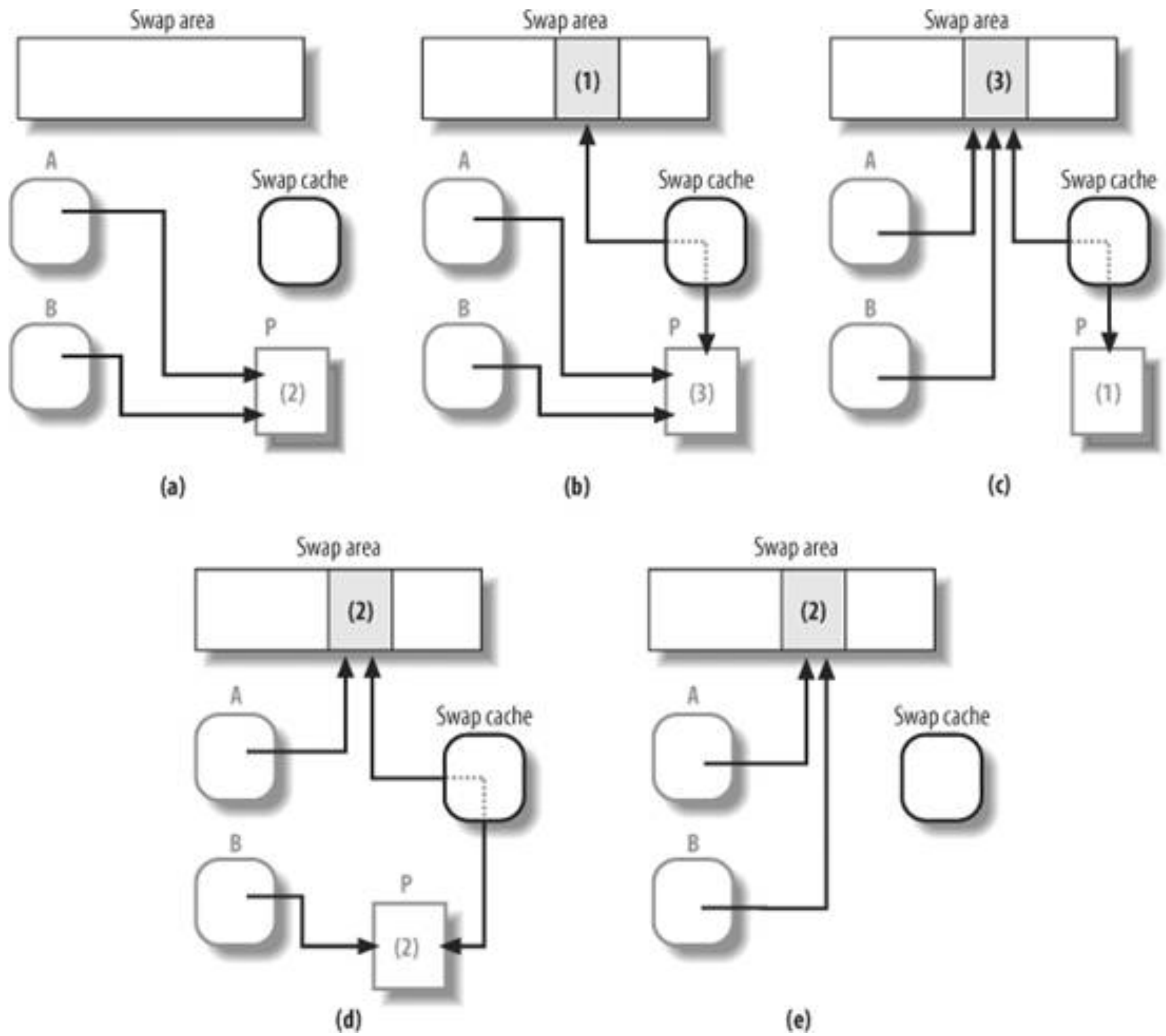
The Swap Area Descriptor



The Swap Cache

- Goal: prevent race conditions due to concurrent page-in and page-out
- Solution: page-in and page-out serialized through a single entity: swap cache
- Page to be swapped out simply moved to cache
- Process must check if swap cache has a page when it wants to swap in
  - If the page is there in the cache already: minor page fault
  - If page requires disk activity: major page fault

The Swap Cache



Page Allocation

- Buddy Allocator
- SLAB allocator: data structure specific
- SLOB: simple list of blocks
- SLUB: efficient SLAB

We'll see next