CS 5264/4224; ECE 5414/4414
(Advanced) Linux Kernel Programming
Lecture 19

Page Cache

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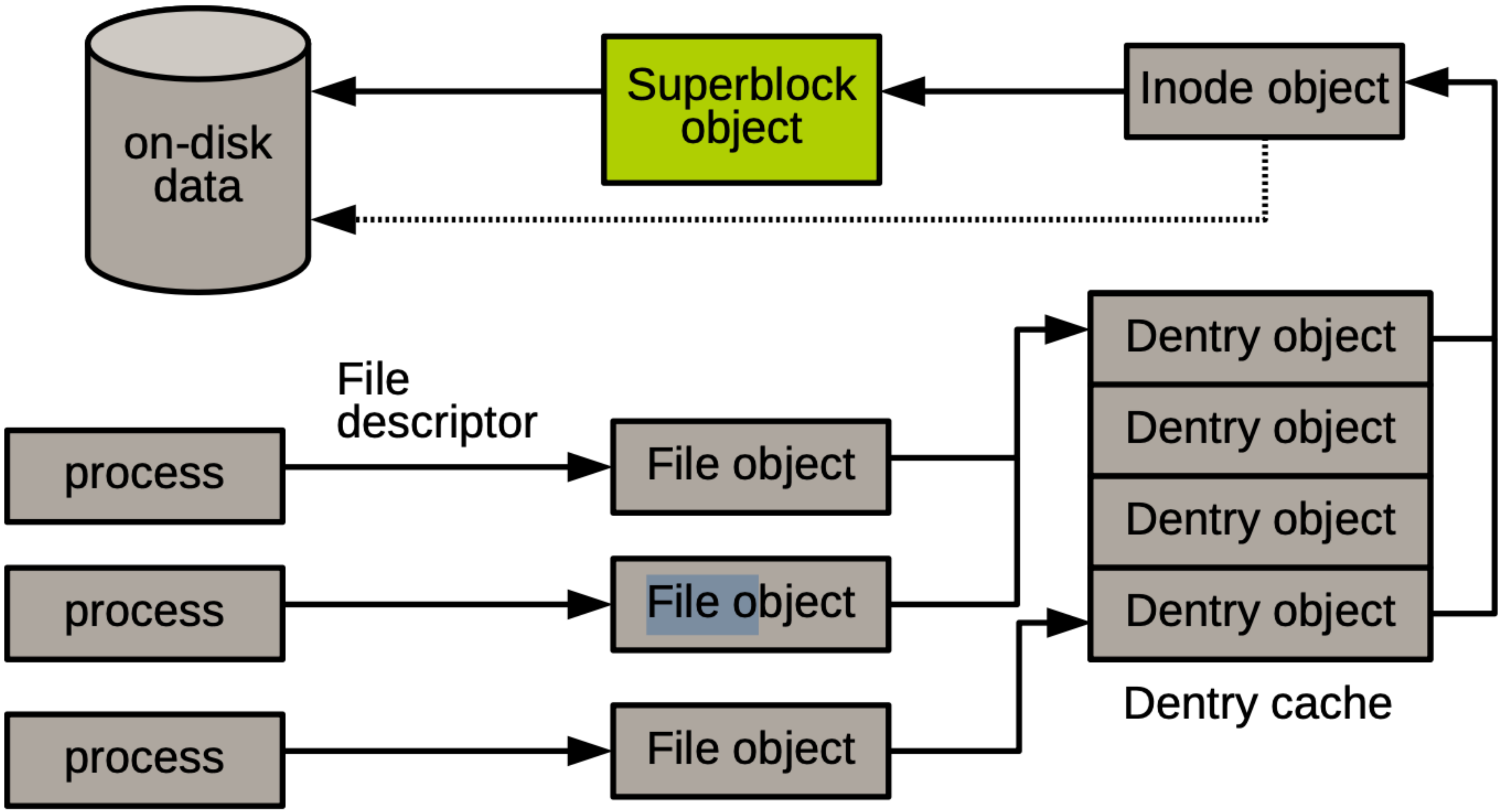
https://people.cs.vt.edu/huaicheng/lkp-sp25/

Acknowledgement: Credits to Dr. Changwoo Min for the original LKP lecture slides.

Superblock


on-disk
data
Superblock
object
Inode object
File
descriptor
process
process
process
File object
File object
File object
Dentry object
Dentry object
Dentry object
Dentry object
Dentry cache

Latency Numbers

```
L1 cache reference ......................... 0.5 ns
Branch mispredict ............................ 5 ns
L2 cache reference ........................... 7 ns
Mutex lock/unlock ........................... 25 ns
Main memory reference ...................... 100 ns
Compress 1K bytes with Zippy ............. 3,000 ns  =   3 µs
Send 2K bytes over 1 Gbps network ....... 20,000 ns  =  20 µs
SSD random read ........................ 150,000 ns  = 150 µs
Read 1 MB sequentially from memory ..... 250,000 ns  = 250 µs
Round trip within same datacenter ...... 500,000 ns  = 0.5 ms
Read 1 MB sequentially from SSD* ..... 1,000,000 ns  =   1 ms
Disk seek ........................... 10,000,000 ns  =  10 ms
Read 1 MB sequentially from disk .... 20,000,000 ns  =  20 ms
Send packet CA->Netherlands->CA .... 150,000,000 ns  = 150 ms
```

Source: https://gist.github.com/hellerbarde/2843375

Latency Numbers

If we multiply these durations by a billion:

Minute:

L1 cache reference	0.5 s	One heart beat (0.5 s)
Branch mispredict	5 s	Yawn
L2 cache reference	7 s	Long yawn
Mutex lock/unlock	25 s	Making a coffee

Hour:

Main memory reference	100 s	Brushing your teeth
Compress 1K bytes with Zippy	50 min	One episode of a TV show (including ad breaks)

Day:

Send 2K bytes over 1 Gbps network	5.5 hr	From lunch to end of work day

Week

SSD random read	1.7 days	A normal weekend
Read 1 MB sequentially from memory	2.9 days	A long weekend
Round trip within same datacenter	5.8 days	A medium vacation
Read 1 MB sequentially from SSD	11.6 days	Waiting for almost 2 weeks for a delivery

Year

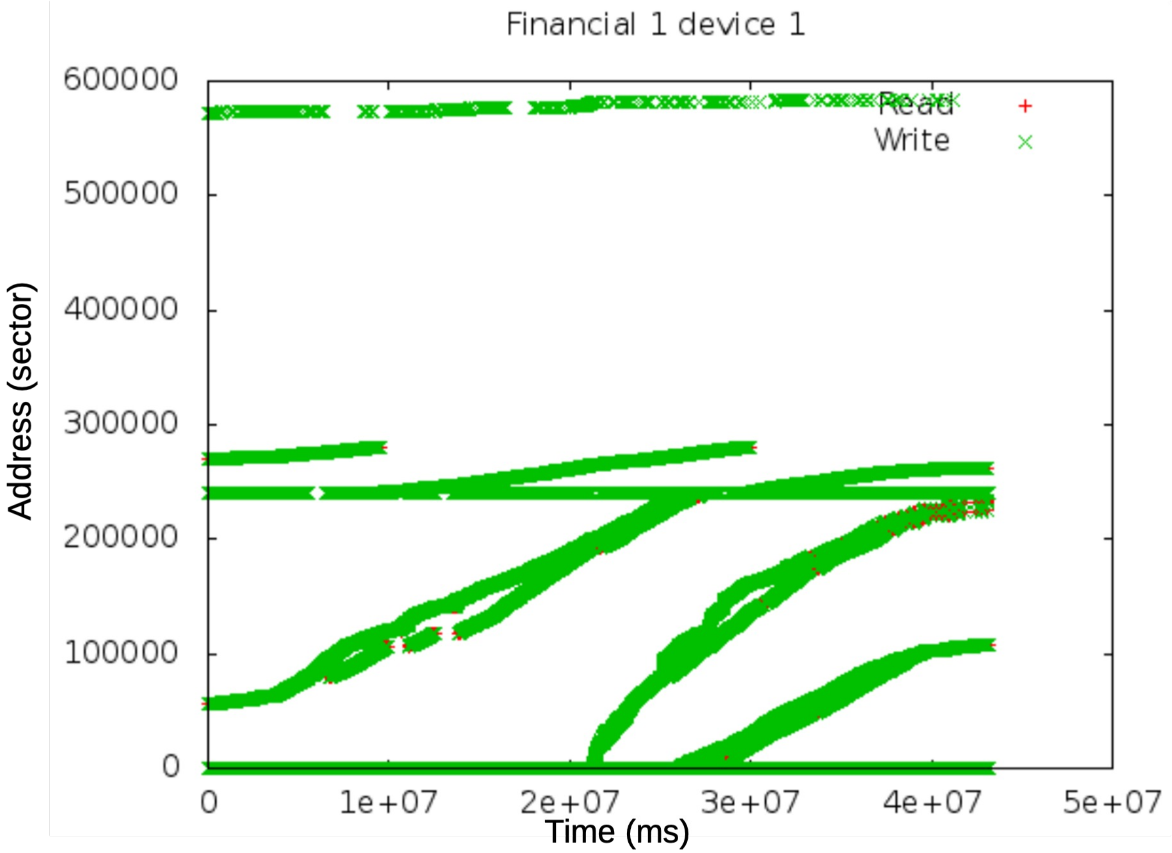
Disk seek	16.5 weeks	A semester in university
Read 1 MB sequentially from disk	7.8 months	Almost producing a new human being
The above 2 together	1 year	

Decade

Send packet CA->Netherlands->CA	4.8 years	Average time it takes to complete a bachelor's degree

Why Caching

- Disk access is several orders of magnitude slower than memory access
- Data accessed once will likely be accessed again in the near future
  - Temporal locality
  - Spatial locality

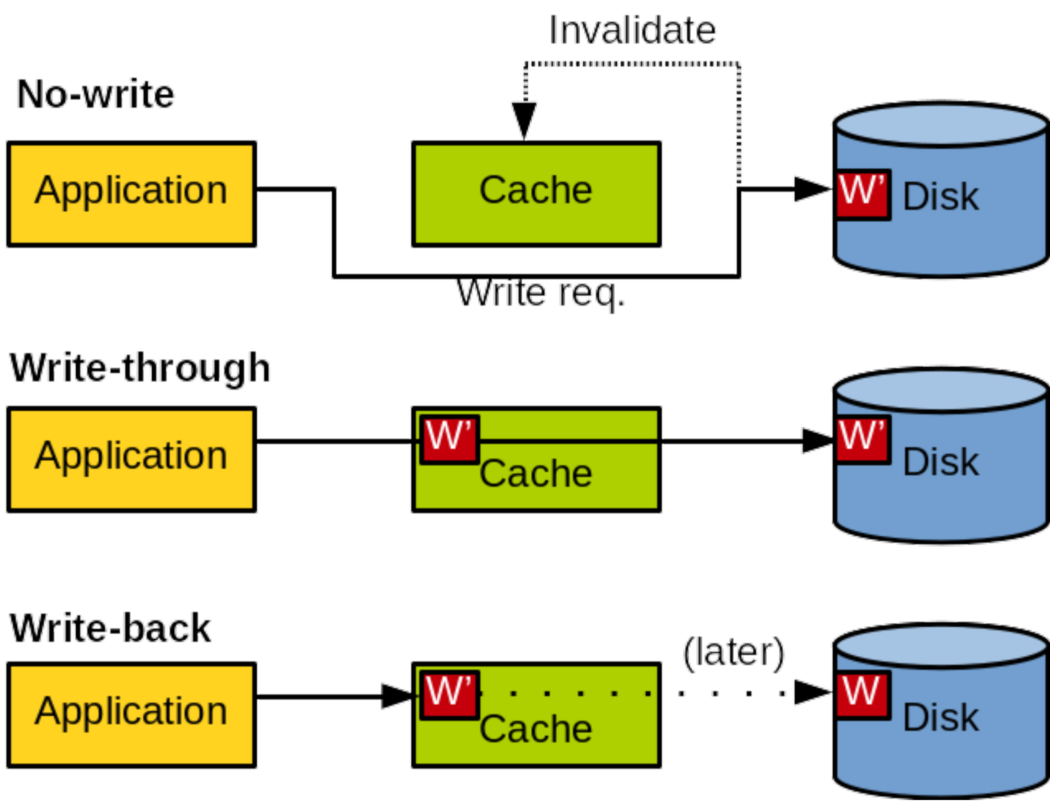


Page Cache

- Physical pages in DRAM holding disk content (blocks)
  - Disk is called a backing store
  - Works for regular files, memory mapped files, and block device files
- Dynamic size
  - Grows to consume free memory not used by kernel and processes
  - Shrinks to relieve memory pressure
- Buffered I/O operations (w/o O_DIRECT), the page cache of a file is first checked
- Cache hit: if data is in the page cache, return directly
- Cache miss: otherwise, VFS asks the FS (e.g., ext4) to read data from disk
  - Read/write operations populate the page cache

Write Cache Policies

- No-write: does not cache write operations
- Write-through: write operations immediately go through to disk
  - Keeping the cache coherent
  - No need to invalidate cached data → simple
- Write-back: write operations update page cache but disk is not immediately updated → Linux page cache policy
  - Pages written are marked dirty using a tab in radix tree
  - Periodically write dirty pages to disk → writeback
  - Page cache absorbs temporal locality to reduce disk access

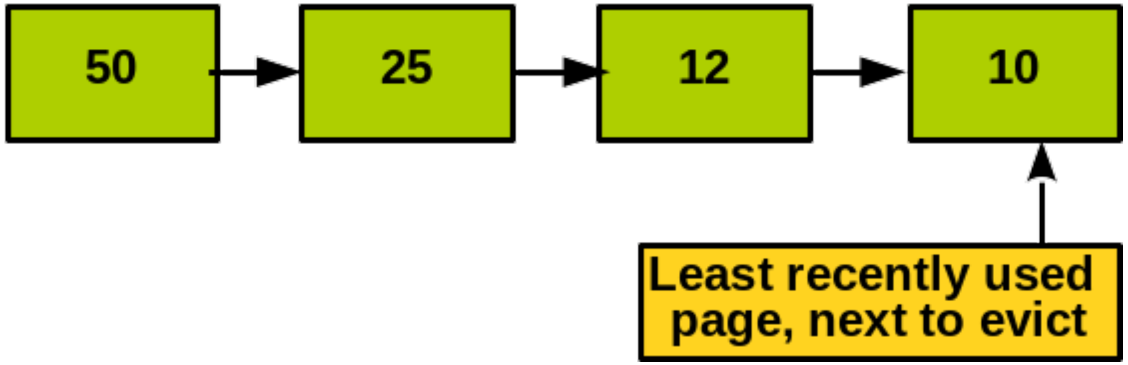


Cache Eviction

- When should data be removed from the cache?
  - Need more free memory (memory pressure)
- What data should be removed from the cache?
  - Ideally, evict cache pages that will not be accessed in the future
  - Eviction policy: deciding what to evict

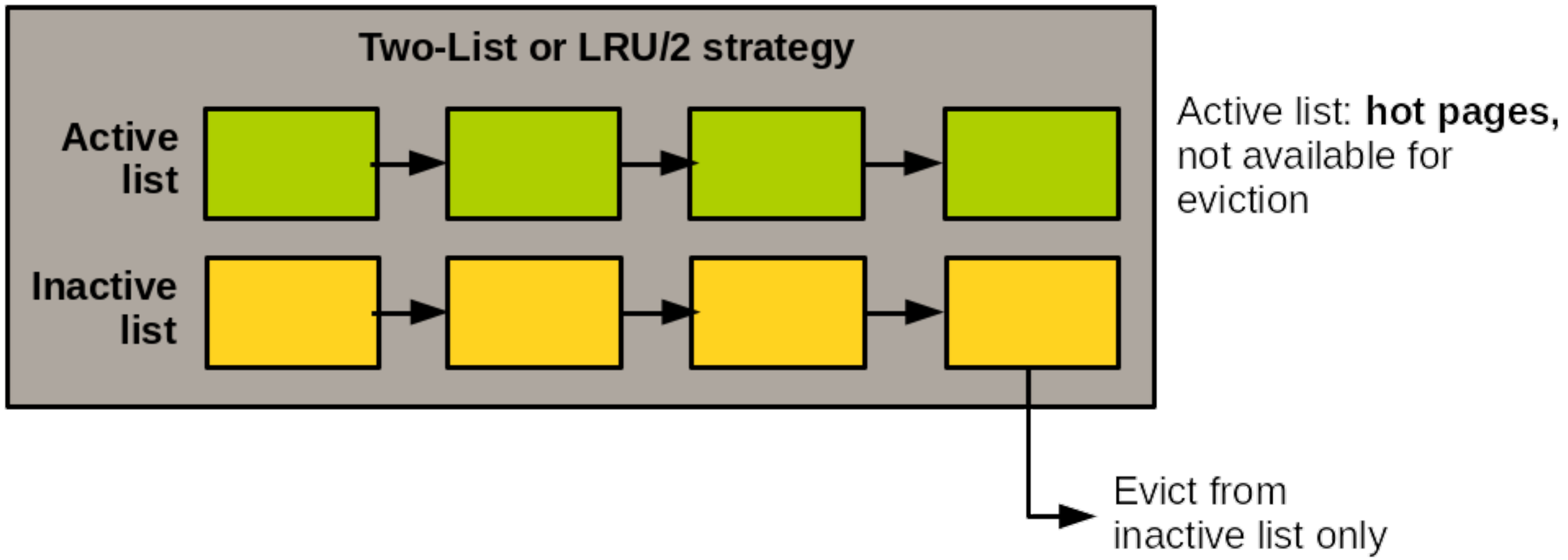
Eviction Policy: LRU

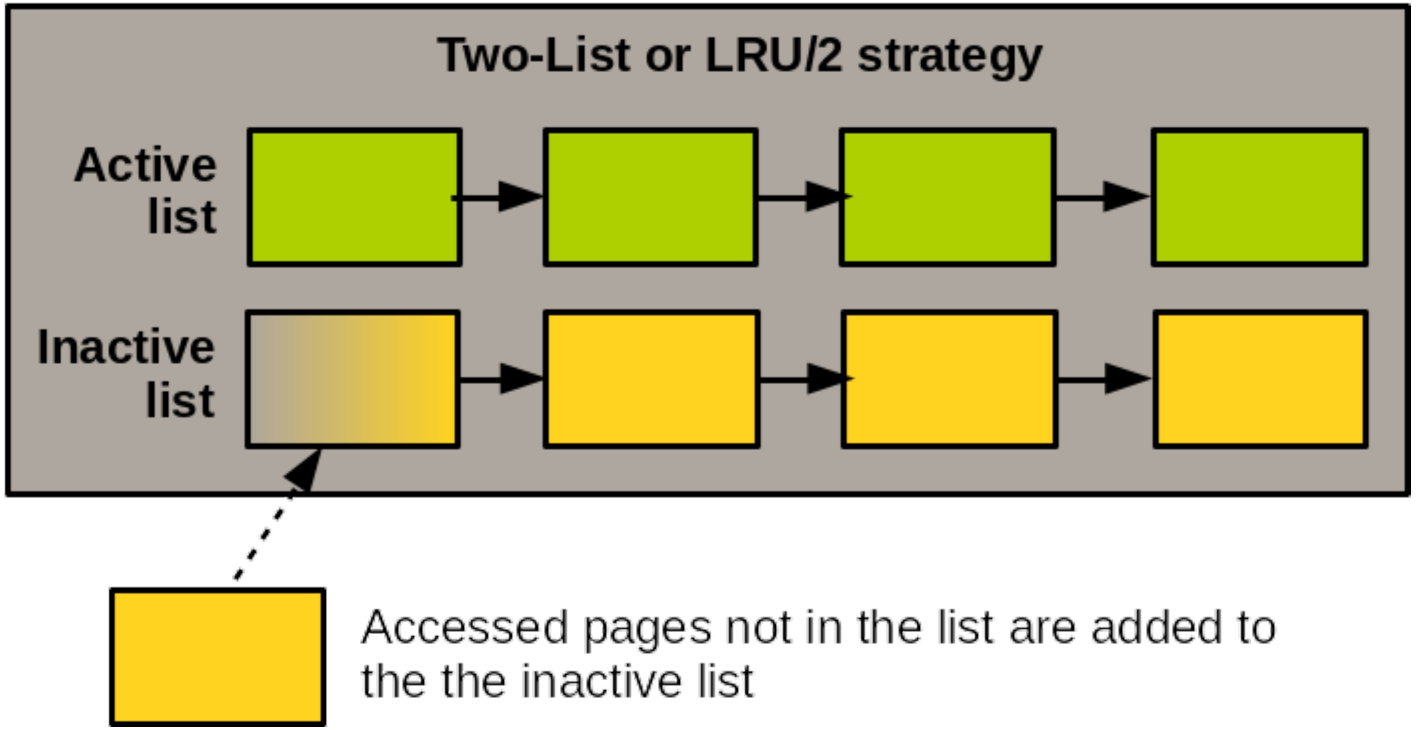
- Least recently used (LRU) policy
  - Keep track of when each page is accessed
  - Evict the pages with the oldest timestamp
- Failure cases of LRU policy
  - Many files are accessed once and then never again
  - LRU puts them at the top of the list → suboptimal
- How to track page reference?

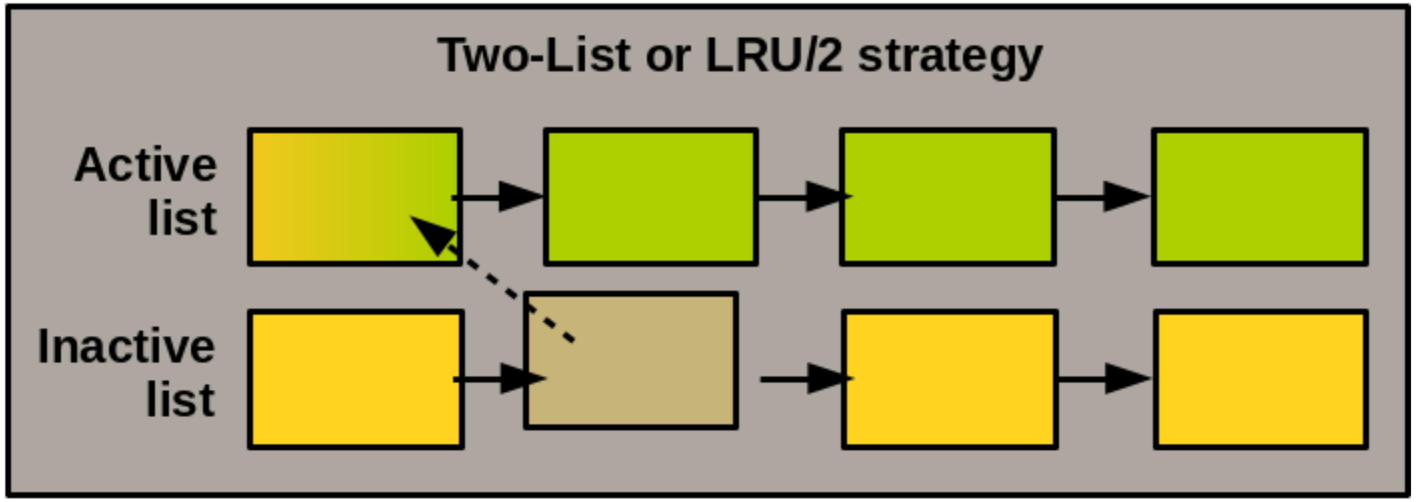


Two-list Strategy

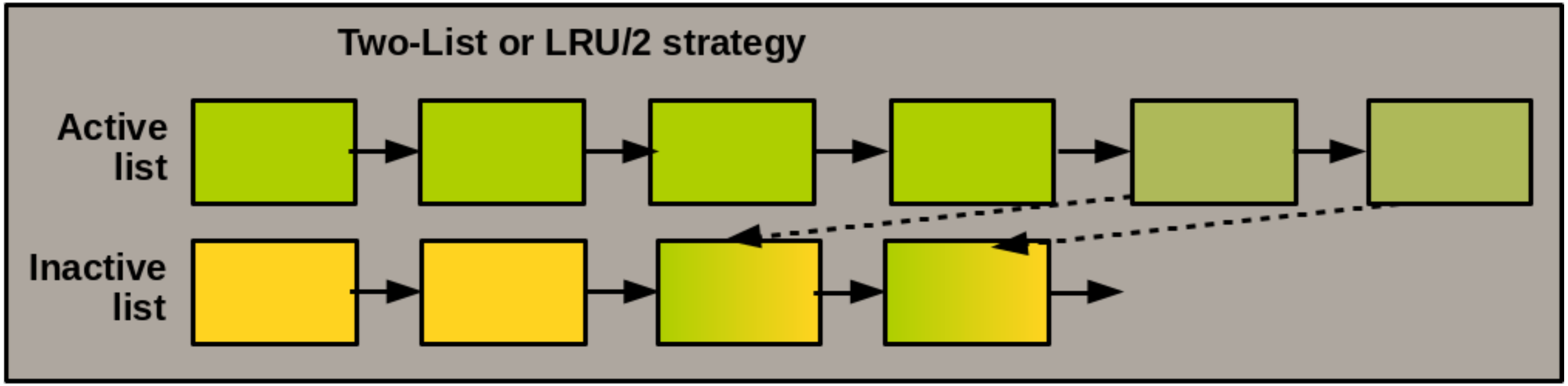
- Active list
  - Pages in the active list is considered hot
  - Not available for eviction
- Inactive list
  - Pages in the inactive list is considered cold
  - Available for eviction
- Newly accessed pages are added to inactive list
- If a page in an inactive list is accessed again, it is promoted to an active list
  - When a page is moved to an inactive list, its access permission in a page table is removed
- If an active list becomes much larger than an inactive list, items from the active list's head are moved back to the inactive list
- When a page is added to the inactive list, its access permission in the page table is disabled to track its access.


Two-List or LRU/2 strategy
Active list
Inactive list
Active list: hot pages, not available for eviction
Evict from inactive list only


Two-List or LRU/2 strategy
Active list
Inactive list
Accessed pages not in the list are added to the the inactive list



Inactive page accessed
are added to the active list



Lists are balanced and active pages are evicted in the inactive list

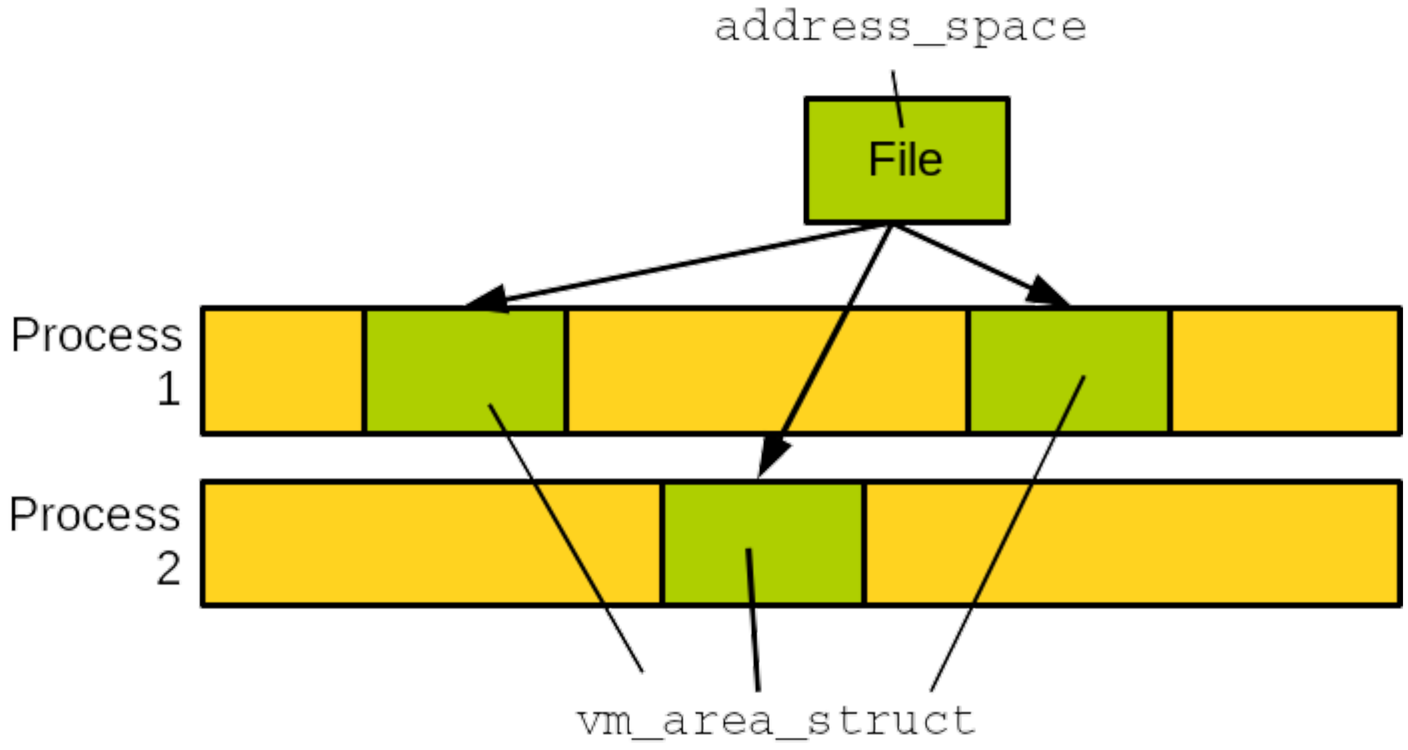
Linux Page Cache

```
/* linux/include/linux/fs.h */
struct inode {
    const struct inode_operations   *i_op;
    struct super_block              *i_sb;
    struct address_space            *i_mapping;
    unsigned long                   i_ino;
};

struct address_space {
    struct inode                    *host;      /* owner: inode, block_device */
    struct radix_tree_root          page_tree;  /* radix tree of all pages */
    spinlock_t                      tree_lock;  /* and lock protecting it */
};
```

address_space

- An entity present in the page cache
  - An address_space = a file = accessing a page cache of a file
  - An address_space = one or more vm_area_struct



address_space

```
/* linux/include/linux/fs.h */
struct address_space {
    struct inode                *host;              /* owning inode */
    struct radix_tree_root      page_tree;          /* radix tree of all pages */
    spinlock_t                  tree_lock;          /* page tree lock */
    unsigned int                i_mmap_writable;    /* VM_SHARED (writable)
                                                     * mapping count */
    struct rb_root              i_mmap;             /* list of all mappings */
    unsigned long               nrpages;            /* total number of pages */
    pgoff_t                     writeback_index;    /* writeback start offset */
    struct address_space_operations a_ops;          /* operations table */
    unsigned long               flags;              /* error flags */
    gfp_t                       gfp_mask;           /* gfp mask for allocation */
    struct backing_dev_info     backing_dev_info;   /* read-ahead info */
    spinlock_t                  private_lock;       /* private lock */
    struct list_head            private_list;       /* private list */
    struct address_space        assoc_mapping;      /* associated buffers */
    /* ... */
}
```

address_space_operations

```c
/* linux/include/linux/fs.h */
struct address_space_operations {
    int (*writepage)(struct page *page, struct writeback_control *wbc);
    int (*readpage)(struct file *, struct page *);
    int (*writepages)(struct address_space *, struct writeback_control *);
    int (*set_page_dirty)(struct page *page);
    int (*readpages)(struct file *filp, struct address_space *mapping,
            struct list_head *pages, unsigned nr_pages);
    int (*write_begin)(struct file *, struct address_space *mapping,
                loff_t pos, unsigned len, unsigned flags,
                struct page **pagep, void **fsdata);
    int (*write_end)(struct file *, struct address_space *mapping,
                loff_t pos, unsigned len, unsigned copied,
                struct page *page, void *fsdata);
    /* ... */
};
```

Page Read Operation

- read() function from file_operations
  - generic_file_buffered_read()
- Search the data in the page cache
  - page = find_get_page(mapping, index)
- Adding the page to the page cache
  - page = __page_cache_alloc(gfp_mask)
- Then, read data from disk
  - mapping->a_ops->readpage(filp, page)

Page Write Operation

- When a page is modified in the page cache, mark it as dirty
  - SetPageDirty(page)
- Default write path: in mm/filemap.c

```
/* search the page cache for the desired page. If the page is not present,
an entry is allocated and added: */
page = __grab_cache_page(mapping, index, &cached_page, &lru_pvec);
/* Set up the write request: */
status = a_ops->write_begin(file, mapping, pos, bytes, flags, &page, &fsdata);
/* Copy data from user-space into a kernel buffer: */
copied = iov_iter_copy_from_user_atomic(page, i, offset, bytes);
/* write data to disk: */
status = a_ops->write_end(file, mapping, pos, bytes, copied, page, fsdata);
```

Interaction with Memory Management

- file, file_operations
  - How to access the file contents
- address_space, address_space_operations
  - How to access the page cache of a file?
- vm_area_struct, vm_operations_struct
  - How to handle page fault of a virtual memory region?
- Page table in x86

A File

```
/* linux/include/linux/fs.h */
struct file {
    struct path             f_path;             /* contains the dentry */
    struct file_operations *f_op;               /* operations */
    spinlock_t              f_lock;             /* lock */
    atomic_t                f_count;            /* usage count */
    unsigned int            f_flags;            /* open flags */
    mode_t                  f_mode;             /* file access mode */
    logg_t                  f_pos;              /* file offset */
    struct fown_struct      f_owner;            /* owner data for signals */
    const struct cred      *f_cred;             /* file credentials */
    struct file_ra_state    f_ra;               /* read-ahead state */
    u64                     f_version;          /* version number */
    void                   *private_data;       /* private data */
    struct list_head        f_ep_link;          /* list of epoll links */
    spinlock_t              f_ep_lock;          /* epoll lock */
    struct address_space   *f_mapping;          /* page cache mapping */
    /* ... */
};
```

file_operations

```
/* linux/include/linux/fs.h */
struct file_operations {
    struct module *owner;
    loff_t (*llseek) (struct file *, loff_t, int);
    ssize_t (*read) (struct file *, char __user *, size_t, loff_t *);
    ssize_t (*write) (struct file *, const char __user *, size_t, loff_t *);
    ssize_t (*read_iter) (struct kiocb *, struct iov_iter *);
    ssize_t (*write_iter) (struct kiocb *, struct iov_iter *);
    int (*iterate) (struct file *, struct dir_context *);
    int (*iterate_shared) (struct file *, struct dir_context *);
    unsigned int (*poll) (struct file *, struct poll_table_struct *);
    /* ... */
};
```

address_space

```
/* linux/include/linux/fs.h */
struct address_space {
    struct inode                    *host;             /* owning inode */
    struct radix_tree_root          page_tree;         /* radix tree of all pages */
    spinlock_t                      tree_lock;         /* page tree lock */
    unsigned int                    i_mmap_writable;   /* VM_SHARED (writable)
                                                        * mapping count */
    struct rb_root                  i_mmap;            /* list of all mappings */
    unsigned long                   nrpages;           /* total number of pages */
    pgoff_t                         writeback_index;   /* writeback start offset */
    struct address_space_operations a_ops;             /* operations table */
    unsigned long                   flags;             /* error flags */
    gfp_t                           gfp_mask;          /* gfp mask for allocation */
    struct backing_dev_info         backing_dev_info;  /* read-ahead info */
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address_space

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    int (*set_page_dirty)(struct page *page);
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            struct list_head *pages, unsigned nr_pages);
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                loff_t pos, unsigned len, unsigned flags,
                struct page **pagep, void **fsdata);
    int (*write_end)(struct file *, struct address_space *mapping,
                loff_t pos, unsigned len, unsigned copied,
                struct page *page, void *fsdata);
    /* ... */
};
```
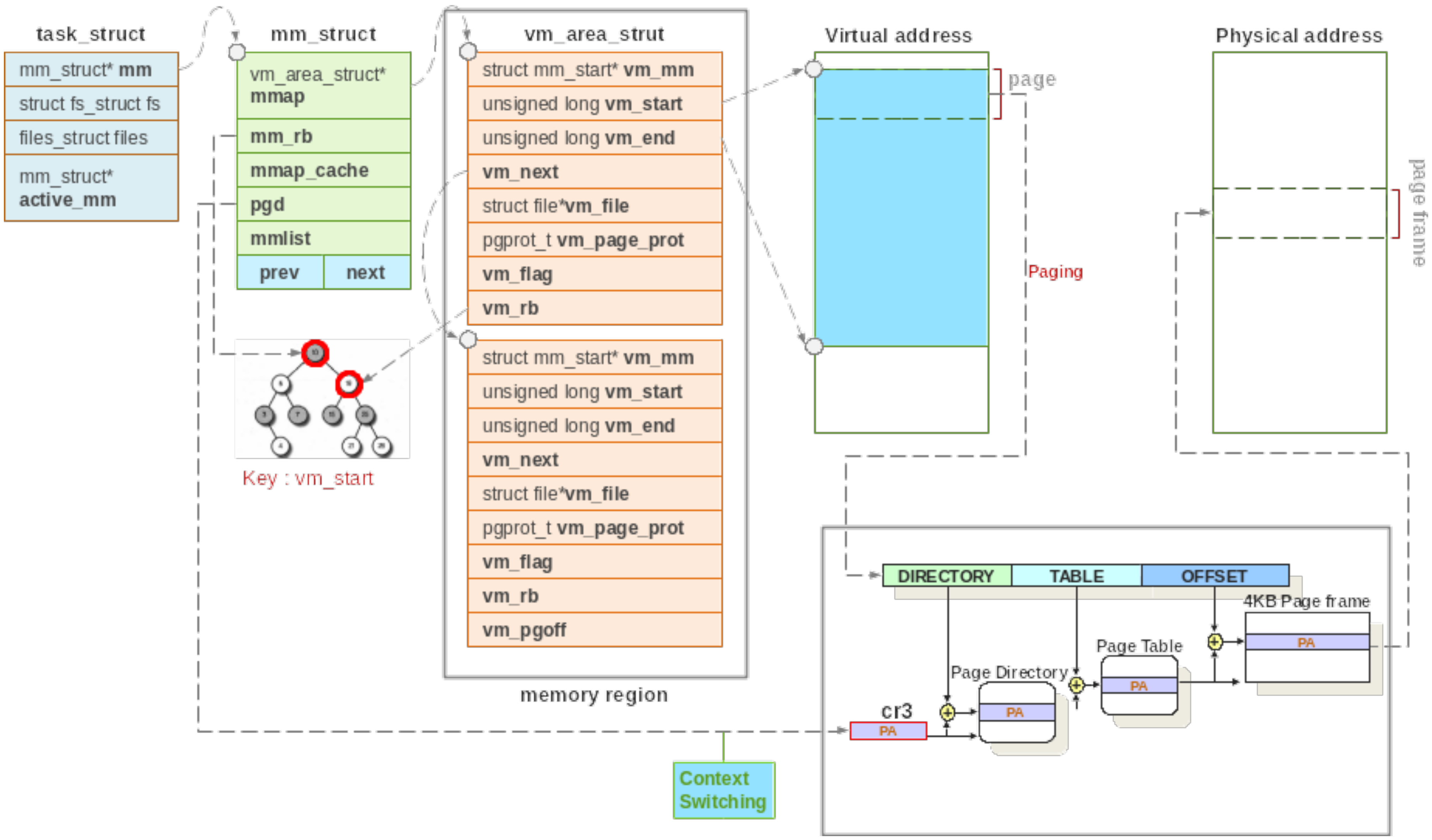

vm_area_struct

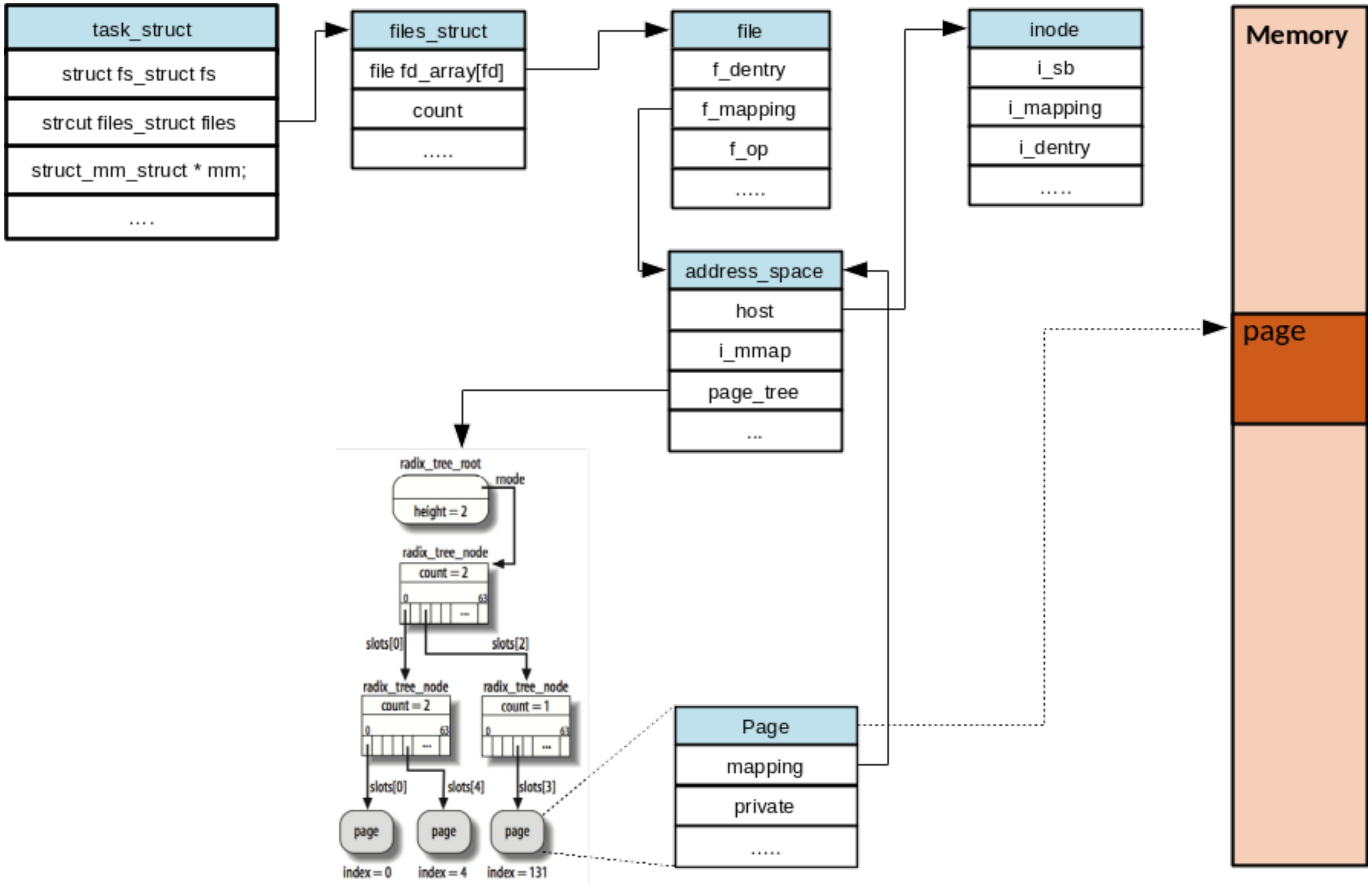
```
struct vm_area_struct {
    struct                        mm_struct *vm_mm; /* associated address space */
    unsigned long                 vm_start;         /* VMA start, inclusive */
    unsigned long                 vm_end;           /* VMA end, exclusive */
    struct vm_area_struct         *vm_next;         /* list of VMAs */
    struct vm_area_struct         *vm_prev;         /* list of VMAs */
    pgprot_t                      vm_page_prot;     /* access permissions */
    unsigned long                 vm_flags;         /* flags */
    struct rb_node                vm_rb;            /* VMA node in the tree */
    struct list_head              anon_vma_chain;   /* list of anonymous mappings */
    struct anon_vma               *anon_vma;        /* anonmous vma object */
    struct vm_operation_struct *vm_ops;             /* operations */
    unsigned long                 vm_pgoff;         /* offset within file */
    struct file                   *vm_file;         /* mapped file (can be NULL) */
    void                          *vm_private_data; /* private data */
    /* ... */
}
```

```c
/* linux/include/linux/mm.h */
struct vm_operations_struct {
    /* called when the area is added to an address space */
    void (*open)(struct vm_area_struct * area);

    /* called when the area is removed from an address space */
    void (*close)(struct vm_area_struct * area);

    /* invoked by the page fault handler when a page that is
     * not present in physical memory is accessed*/
    int (*fault)(struct vm_area_struct *vma, struct vm_fault *vmf);

    /* invoked by the page fault handler when a previously read-only
     * page is made writable */
    int (*page_mkwrite)(struct vm_area_struct *vma, struct vm_fault *vmf);
    /* ... */
}
```

vm_area_struct – page table



Page Cache – Physical Page



Page Fault Handling

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

File-mapped Page Fault

- filemap_fault
- PTE entry does not exist (---)
- But, VMA is marked as accessible (e.g, rwx) and has an associated file (vm_file)
- Page fault handler notices differences
  - In filemap_fault
  - Look up a page cache of the file
  - If cache hit, map the page in the cache
  - Otherwise, mapping->a_ops->readpage(file, page)

Copy on Write (CoW)

- do_wp_page
- PTE entry is marked as un-writable (e.g., r--)
- But VMA is marked as writable (e.g., rw-)
- Page fault handler notices differences
  - In do_wp_page
  - Must mean CoW
  - Make a duplicate of physical page
  - Update PTEs and flush TLB

Flusher Daemon

- Write operation are deferred, data is marked as dirty
  - DRAM data is out-of-sync with the storage media
- Dirty page writeback occurs
  - Free memory is low and the page cache needs to shrink
  - Dirty data grows older than a specific threshold
  - User process calls sync() or fsync()
- Multiple flusher threads are in charge of syncing dirty pages from the page cache to disk
- When the free memory goes below a given threshold, the kernel wakeup_flusher_threads()
  - Wakes up one or several flusher threads performing writeback through bdi_riteback_all
- Thread write data to disk until
  - num_pages_to_write have been written
  - and the amount of memory drops below the threshold
- Percentage of total memory to trigger flusher daemon:

- At boot time, a timer is initialized to wake up a flusher thread calling wb_writeback()
- Writes back all data older than a given value
  - /proc/sys/vm/dirty_expire_interval
- Timer reinitialized to expire at a given time in the future: now + period
  - /proc/sys/vm/dirty_writeback_interval
- Multiple other parameters related to the writeback and the control of the page cache in general are present in /proc/sys/vm
  - More info: Documentation/admin-guide/sysctl/vm.rst

What Happens in the Kernel?

```
int main(int argc, char *argv[])
{
        char buff[8192];
        char *addr;
        int fd;
        int i;

        fd = open ("test-file.dat", O_CREAT | O_RDWR | O_TRUNC);
        for (i = 0; i < 10; ++i)
                write(fd, buff, sizeof(buff));
        addr = mmap(NULL, sizeof(buff), PROT_READ | PROT_WRITE,
                    MAP_PRIVATE, fd, 0);
        memcpy(buff, addr, sizeof(buff));
        memset(addr, 1, sizeof(buff));
        munmap(addr, sizeof(buff));
        close(fd);

        return 0;
}
```

Further Readings

- LWN: Better active/inactive list balancing
- MGLRU
- LWN: Flushing out pdflush
- LWN: User-space page fault handling