Page cache and Page fault

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Summary of last lectures

- Tools: building, exploring, and debugging Linux kernel
- Core kernel infrastructure
- Process management & scheduling
- Interrupt & interrupt handler
- Kernel synchronization
- Memory management
- Virtual file system

Today: page cache and page fault

- Introduction to cache
- Page cache in Linux
- Cache eviction
- Interaction with memory management
- Flusher daemon

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: [Latency numbers every programmer should know]

Humanized version (x 1,000,000,000)

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
Main memory reference	100 s	Brushing your teeth
Compress 1K bytes with Zippy	50 min	One episode of a TV show (including ad breaks)
Send 2K bytes over 1 Gbps network	5.5 hr	From lunch to end of work day
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
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	
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, with a high likelihood, find itself accessed again in the near future → **temporal locality**

Page cache (or buffer cache)

- Physical pages in RAM 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 unused by kernel and processes
  - Shrinks to relieve memory pressure

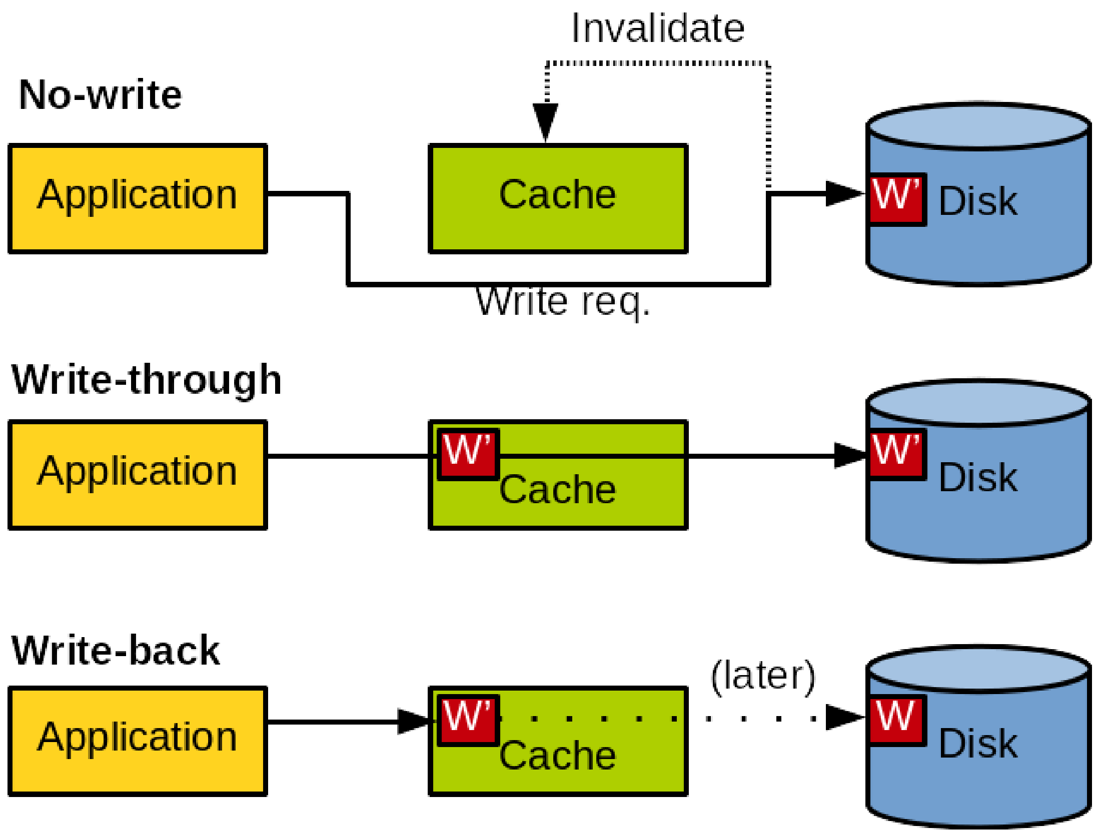
Page cache (or buffer cache)

- Buffered IO operations (without `O_DIRECT`), the page cache of a file is first checked
- **Cache hit**: if data is in the page cache, copy from/to user memory
- **Cache miss**: otherwise, VFS asks the concrete file system (e.g., ext4) to read data from disk
    - Read/write operations populate the page cache

Write caching 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 tag in radix tree
  - Periodically, write dirty pages to disk → *writeback*
  - Page cache absorbs temporal locality to reduce disk access

Write caching policies

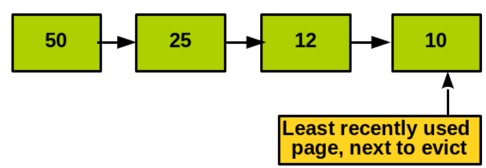


Cache eviction

- **When data should be removed from the cache?**
  - Need more free memory (memory pressure)
- **Which 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 LRU list → not optimal

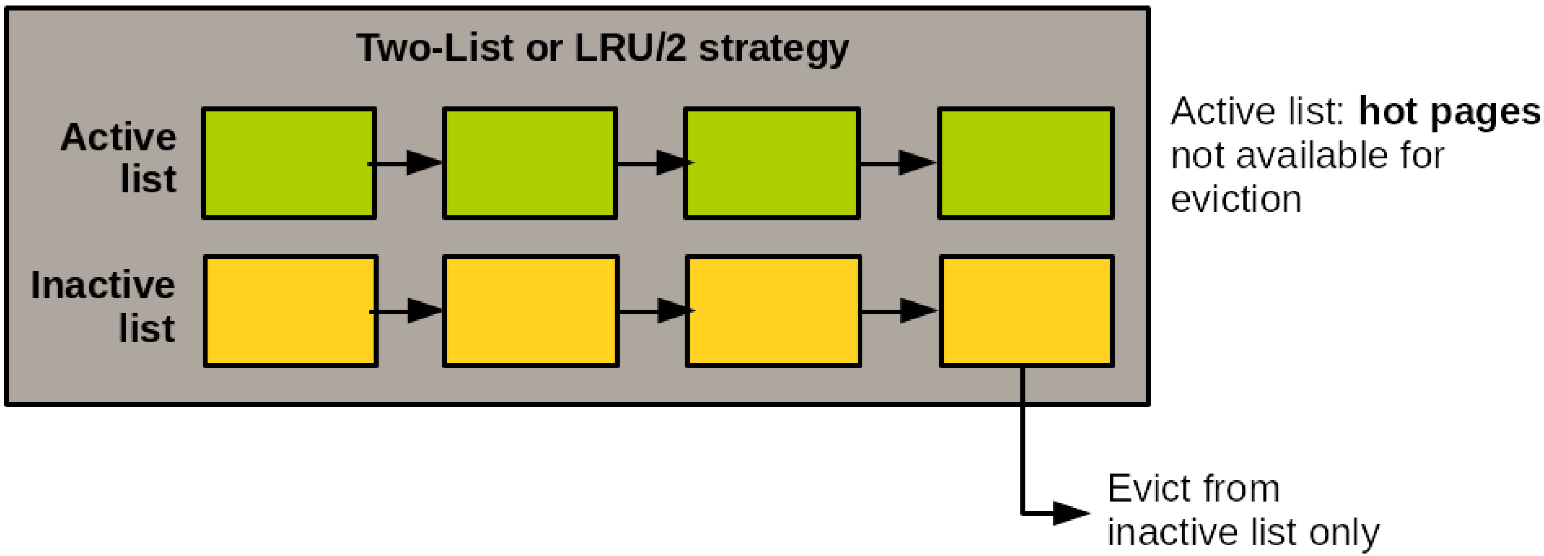
The two-list strategy

- **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

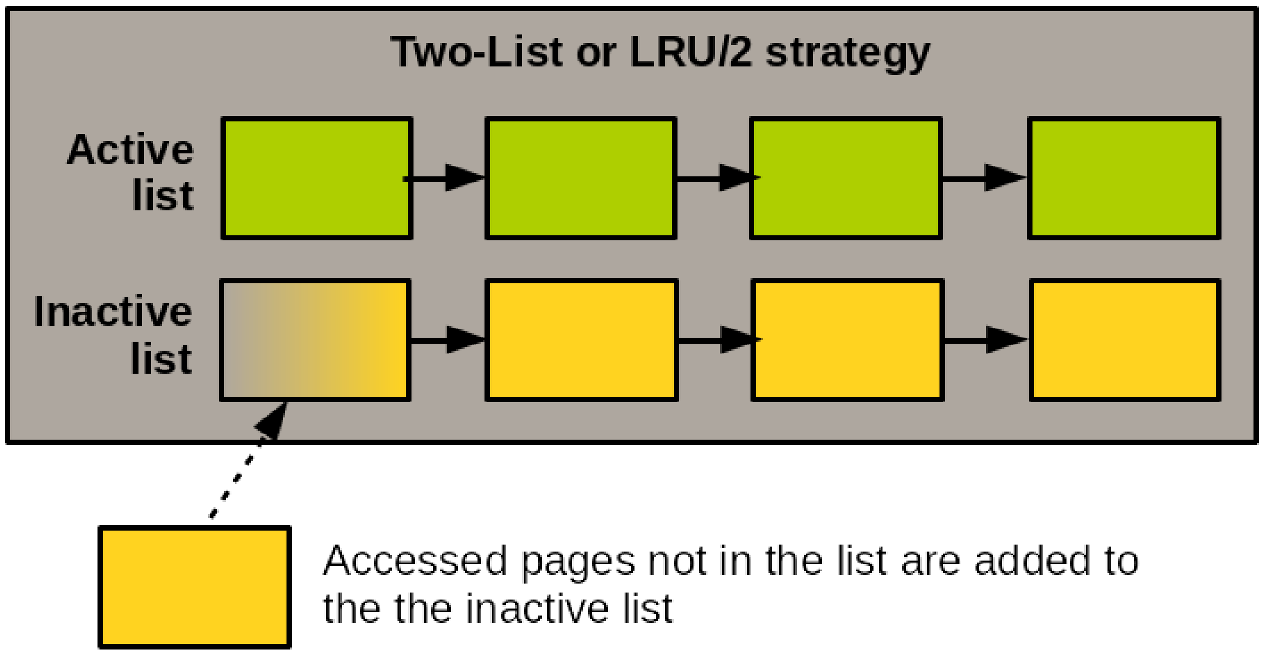
The two-list strategy

- 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 inactive list, its access permission in the page table is disabled to track its access.*

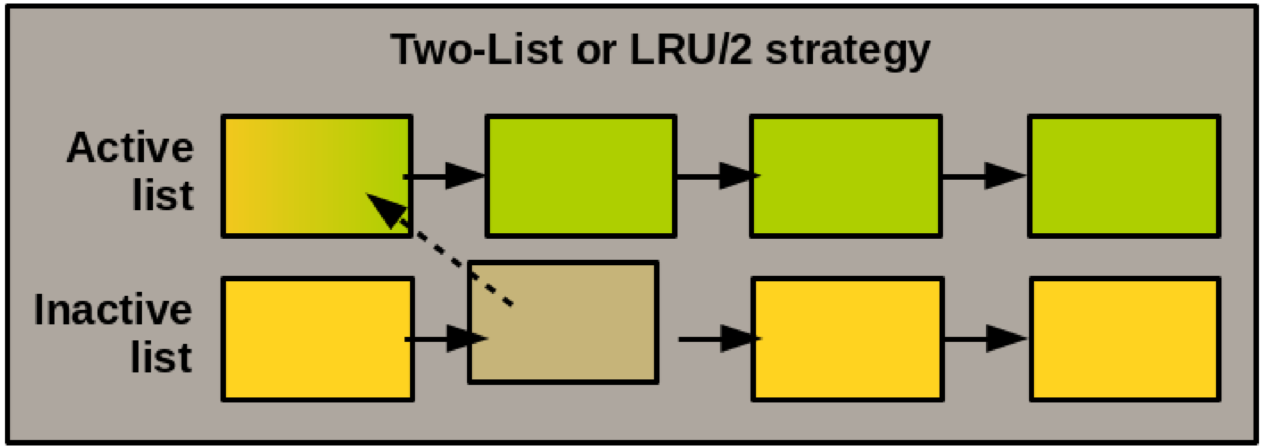
The two-list strategy



The two-list strategy

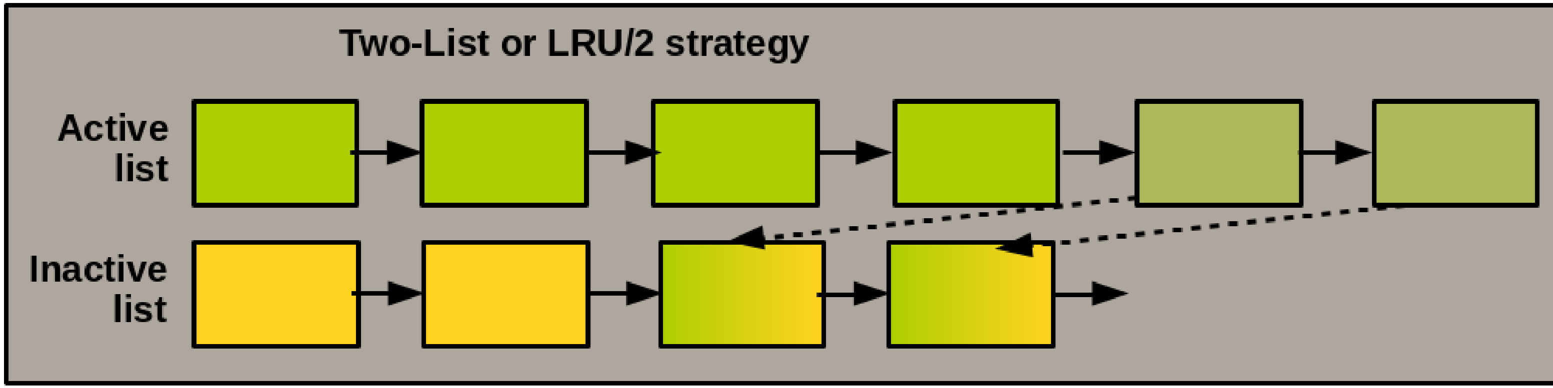


The two-list strategy



Inactive page accessed
are added to the active list

The two-list strategy



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

The Linux page cache (or buffer 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 */
};

/* Insert an item into the radix tree at position @index. */
int radix_tree_insert(struct radix_tree_root *root,
            unsigned long index, void *item);

/* linux/mm/shmem.c */
static int shmem_add_to_page_cache(struct page *page,
    struct address_space *mapping, pgoff_t index, void *expected)
{
    error = radix_tree_insert(&mapping->page_tree, index, page);
}
```

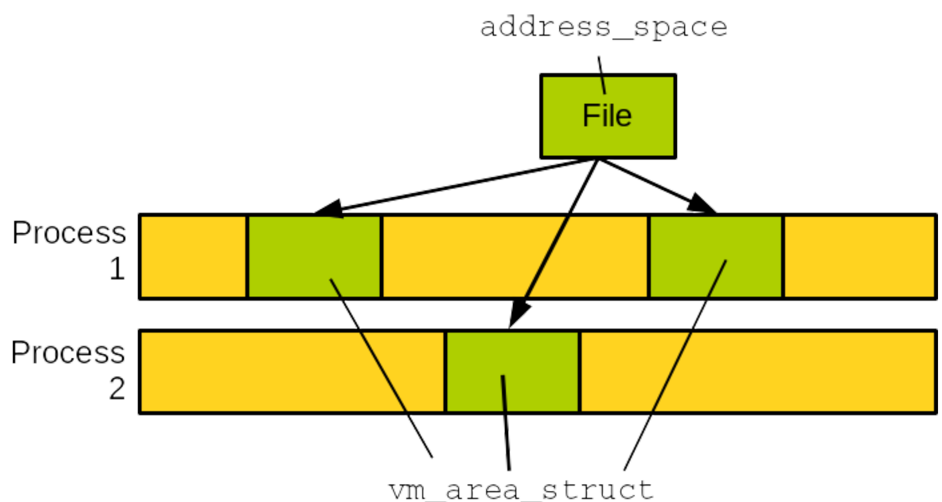
The Linux page cache (or buffer cache)

```
$> sudo cat /proc/1/maps
7fe87b1f1000-7fe87b21d000 r-xp 00000000 fd:00 1975147  /usr/lib64/libseccomp.so
7fe87b21d000-7fe87b41c000 ---p 0002c000 fd:00 1975147  /usr/lib64/libseccomp.so
7fe87b41c000-7fe87b431000 r--p 0002b000 fd:00 1975147  /usr/lib64/libseccomp.so
7fe87b431000-7fe87b432000 rw-p 00040000 fd:00 1975147  /usr/lib64/libseccomp.so
7fe87b432000-7fe87b439000 r-xp 00000000 fd:00 1975989  /usr/lib64/librt-2.26.so
7fe87b439000-7fe87b638000 ---p 00007000 fd:00 1975989  /usr/lib64/librt-2.26.so
7fe87b638000-7fe87b639000 r--p 00006000 fd:00 1975989  /usr/lib64/librt-2.26.so
7fe87b639000-7fe87b63a000 rw-p 00007000 fd:00 1975989  /usr/lib64/librt-2.26.so
```

- Q: the number of `vm_area_struct`
- Q: the number of `inode`
- Q: the number of `address_space`

`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`

- `i_mmap`: all shared and private mappings concerning this address space
- `nrpages`: total number of pages in the address space
- `host`: points to the inode of the corresponding file
- `a_ops`: address space operations

address_space_operations

```
/* 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 the `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 contents of a file
- `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 processor

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`

```
/* 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 */
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    unsigned long               nrpages;            /* total number of pages */
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    struct address_space_operations a_ops;          /* operations table */
    unsigned long               flags;              /* error flags */
    gfp_t                       gfp_mask;           /* gfp mask for allocation */
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`address_space`

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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);
    /* ... */
};
```

- *Q: what is the difference between `file->read()` and `asop->readpage()`? See `linux/fs/ext4/file.c`*

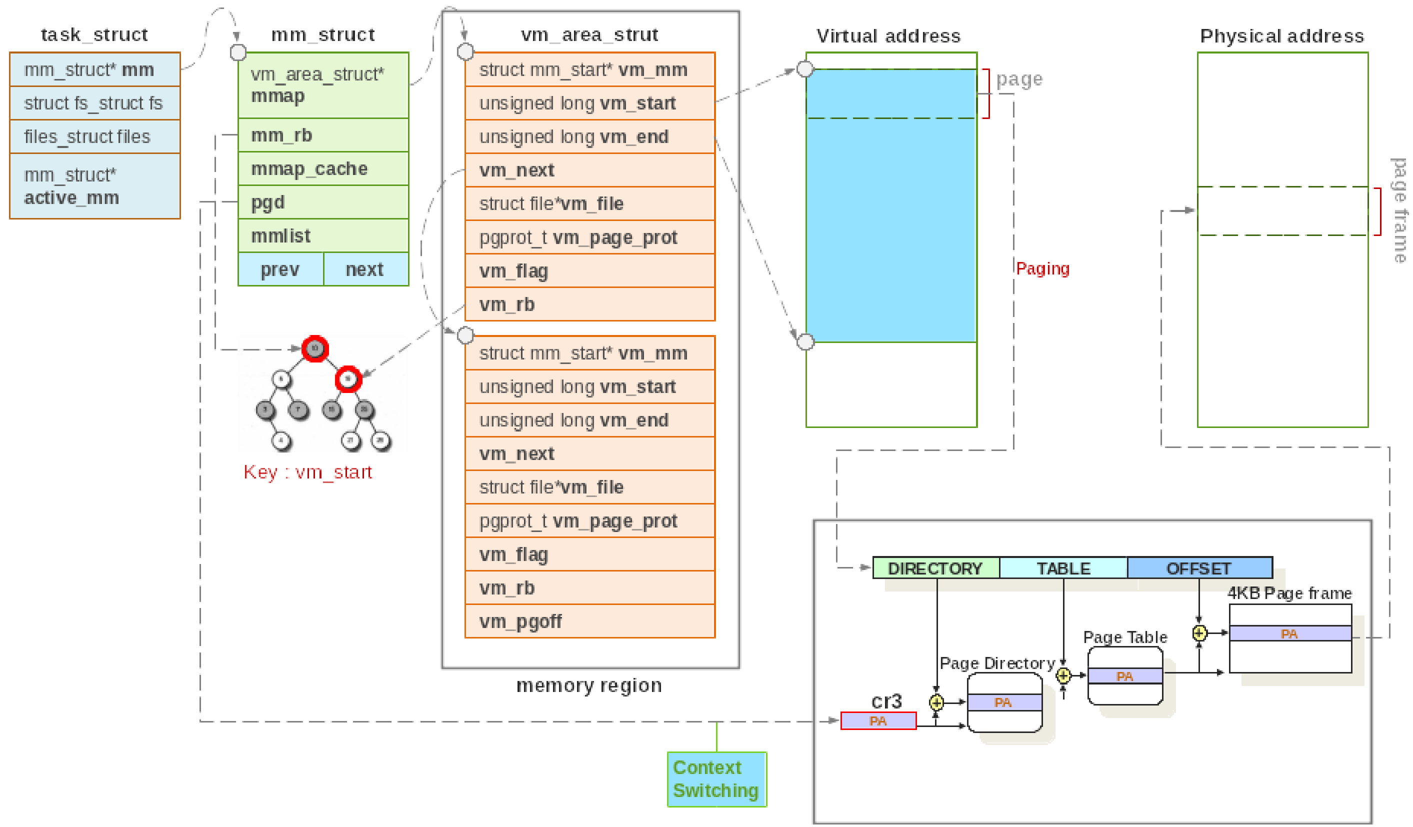
vm_area_struct

```
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 */
    /* ... */
}
```

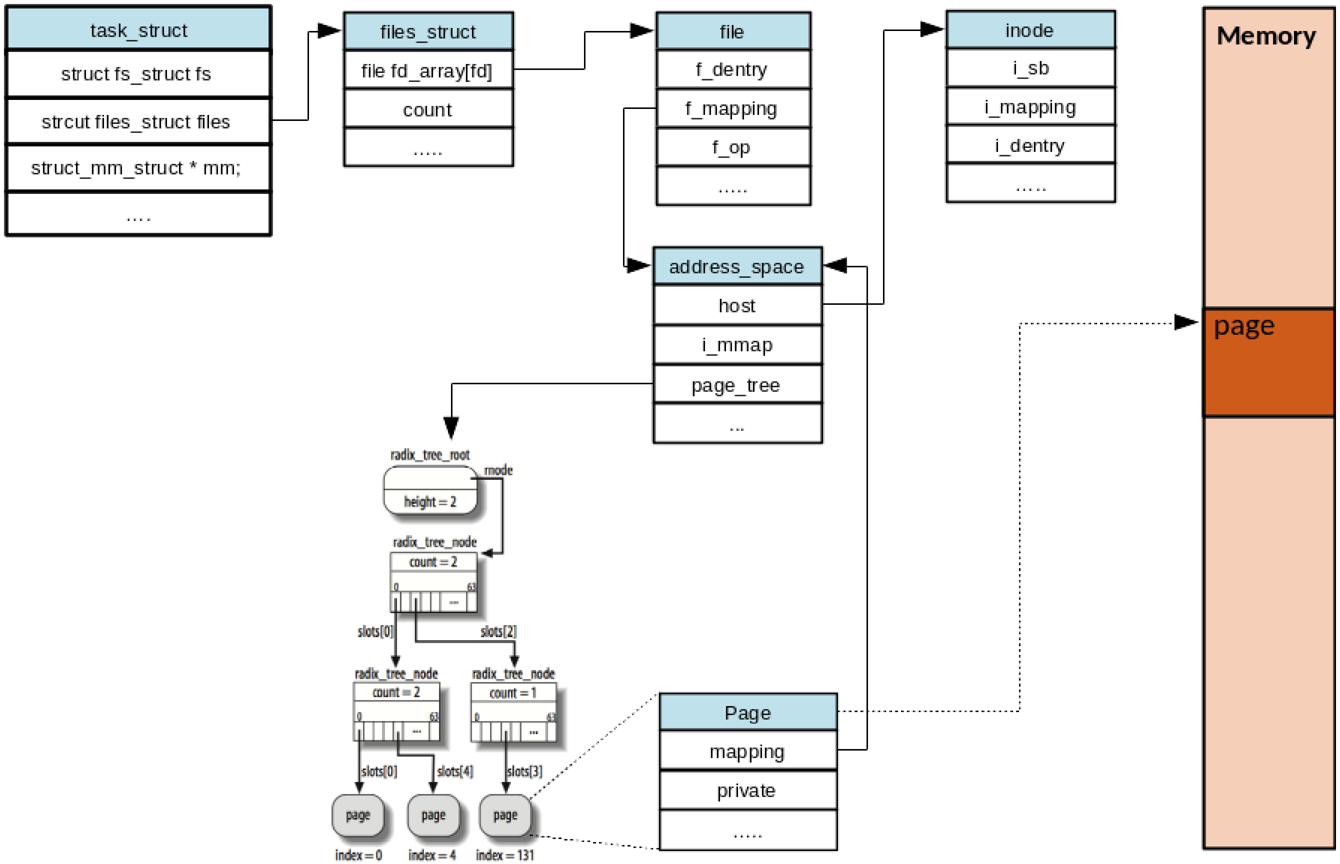
vm_area_struct

```
/* 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: `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 entry

Flusher daemon

- Write operation are deferred, data is marked *dirty*
  - RAM 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

Flusher daemon

- When the free memory goes below a given threshold, the kernel `wakeup_flusher_threads()`
  - Wakes up one or several flusher threads performing writeback though `bdi_writeback_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
  - `/proc/sys/vm/dirty_background_ratio`

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/sysctl/vm.txt

Further readings

- Latency numbers every programmer should know
- LWN: Better active/inactive list balancing
- LWN: Flushing out pdflush
- LWN: User-space page fault handling
- W4118 @ Columbia University