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SWE3015: Operating System Project

PAGE FAULT HANDLER

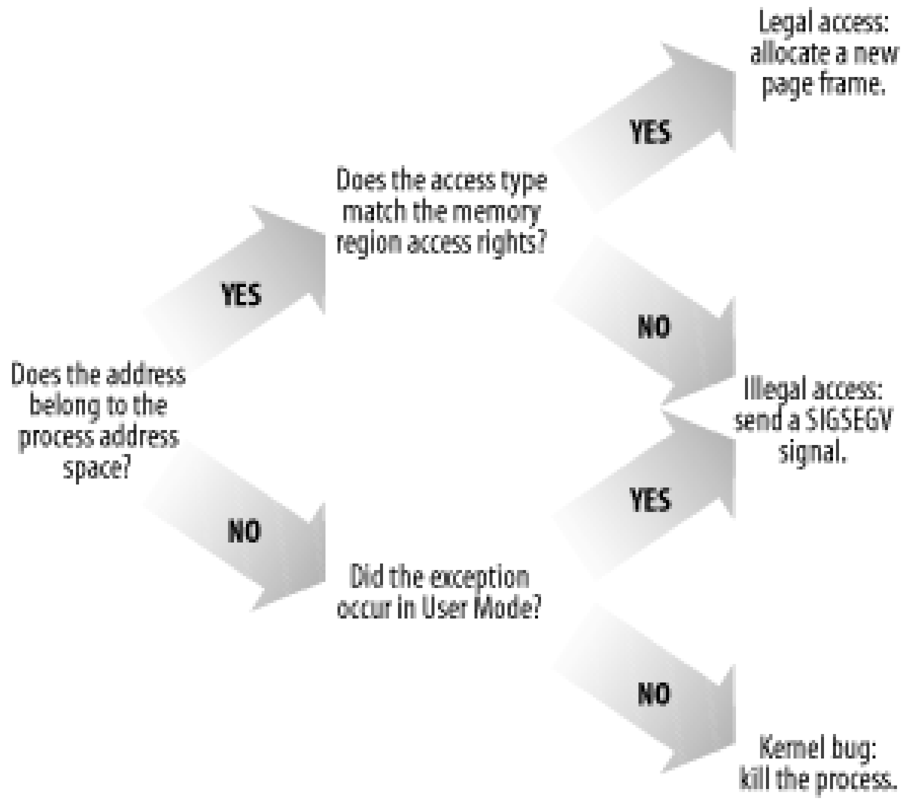
Page Fault

- a trap to the software raised by the hardware
  - when a program accesses a page that is mapped in the virtual address space,
  - but not loaded in physical memory

- Typical reasons are…
  - Demand paging
  - Copy on Write
  - User software bug (SIGSEGV)
  - Or even kernel bug (kernel "Oops")

Page Fault Handling

- <arch/x86/mm/fault.c> do_page_fault()



Page Fault Handling

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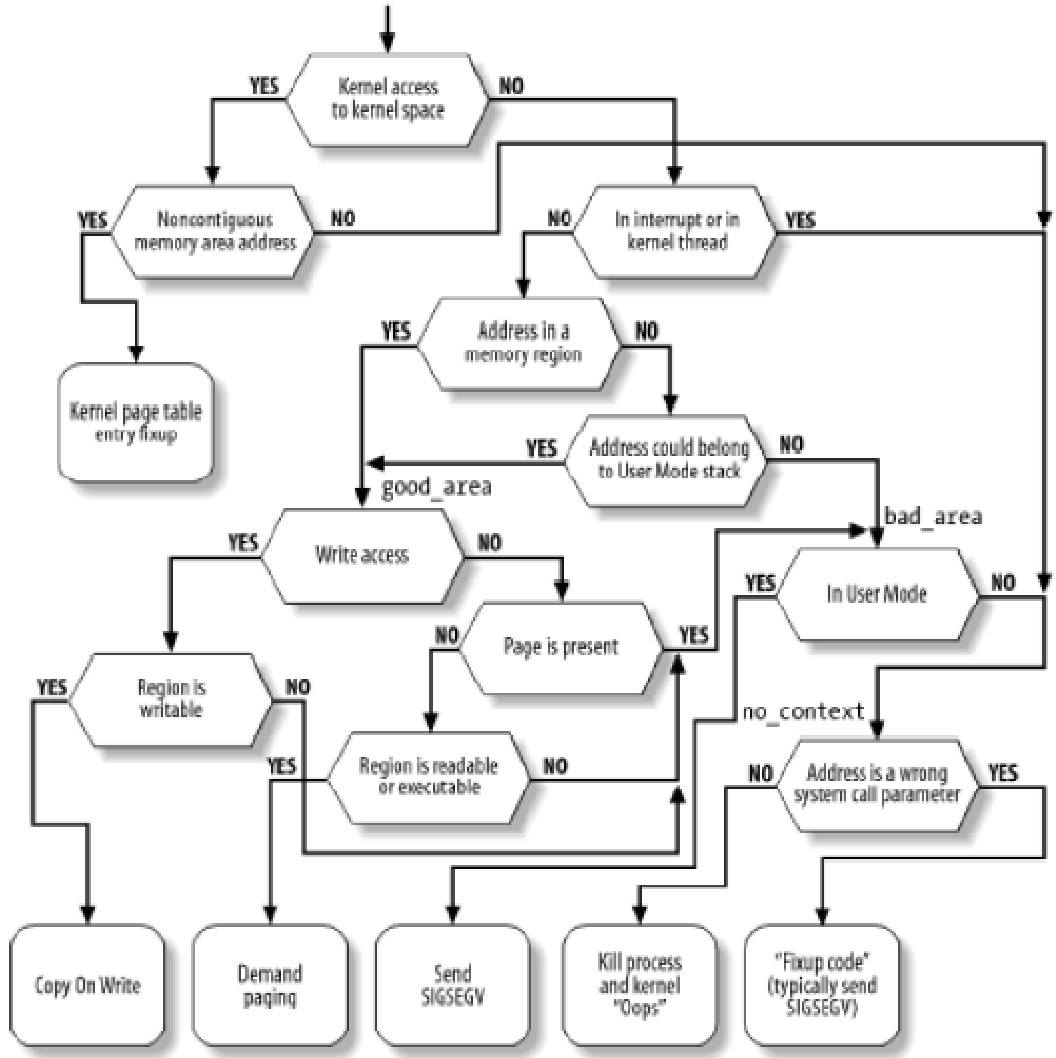

Page Fault Handling

- __do_page_fault(struct pt_regs *regs, unsigned long error_code)
  - regs: the values of the microprocessor registers when the exception occurred
  - A 3-bit error_code
    - Refer http://anselmo.homeunix.net/ebooks/linuxkernel2/060.htm

1. reading the linear address that caused the page fault

```
static void __kprobes
__do_page_fault(struct pt_regs *regs, unsigned long error_code)
{
        struct vm_area_struct *vma;
        struct task_struct *tsk;
        unsigned long address;
        struct mm_struct *mm;
        int fault;
        int write = error_code & PF_WRITE;
        unsigned int flags = FAULT_FLAG_ALLOW_RETRY | FAULT_FLAG_KILLABLE |
                                        (write ? FAULT_FLAG_WRITE : 0);

        tsk = current;
        mm = tsk->mm;

        /* Get the faulting address: */
        address = read_cr2();
```

Page Fault Handling

- __do_page_fault(cont'd)

2. Check the address is kernel space

```
if (unlikely(fault_in_kernel_space(address))) {
        if (!(error_code & (PF_RSVD | PF_USER | PF_PROT))) {
                if (vmalloc_fault(address) >= 0)
                        return;

                if (kmemcheck_fault(regs, address, error_code))
                        return;
        }
```

   - Accessing a noncontiguous memory area in kernel mode

3. Check whether the exception occurred in interrupt or process

```
if (unlikely(in_atomic() || !mm)) {
        bad_area_nosemaphore(regs, error_code, address);
        return;
}
```

   - If interrupt, goto *no_context*
     - Making SIGSEGV or kernel "Oops"

Page Fault Handling

- __do_page_fault(cont'd)

4. Find the vma(current) which includes the faulty address

```
vma = find_vma(mm, address);
if (unlikely(!vma)) {
        bad_area(regs, error_code, address);
        return;
}
if (likely(vma->vm_start <= address))
        goto good_area;
if (unlikely(!(vma->vm_flags & VM_GROWSDOWN))) {
        bad_area(regs, error_code, address);
        return;
}
```

- !vma means no memory region ending after address.
  - Goto *bad_area*
    - » Make SIGSEGV if user mode, or goto no_context

Page Fault Handling

- __do_page_fault(cont'd)

5. Check if it is an access error (e.g. write on write-protected)

```
good_area:
        if (unlikely(access_error(error_code, vma))) {
                bad_area_access_error(regs, error_code, address);
                return;
        }
```

- If the access error, goto *bad_area*
- The error types are regulated in bad_area_access_error

6. Call mm_fault_handler
   - Call pte_fault_handler
     - If the accessed page is not presented, demand paging
     - If presented and writing on read only, CoW
   - Refer the code. It is too complicated to explain in class.

Page Fault Handling

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Page Recamation

SWE3015

Jeaho Hwang

Memory Overcommit

- Most OSes allow memory overcommit
  - Allocate more virtual memory than physical memory
- How does this work?
  - Physical pages allocated on demand only
  - Allocated pages are not reclaimed until it is actually needed
    - Even if it will never accessed.
  - If free space is low…
    - OS frees some pages non-critical pages (e.g., cache)
    - Worst case, page some stuff out to disk

Memory Overcommit

- To swap a page out…
  - Save contents of page to disk
  - What to do with page table entries pointing to it?
    - Clear the PTE_P bit
- If we get a page fault for a swapped page…
  - Allocate a new physical page
    - Read contents of page from disk
  - Re-map the new page (with old contents)

Reclaiming Pages

- Until we run out of memory…
  - Kernel caches and processes go wild allocating memory
- When we run out of memory…
  - Kernel needs to reclaim physical pages for other uses
  - Doesn't necessarily mean we have zero free memory
    - Maybe just below a "comfortable" level
- Where to get free pages?
  - Goal: Minimal performance disruption
    - Should work on phone, supercomputer, and everything in between

Types of Pages

- Unreclaimable:
  - Free pages (obviously)
  - Pinned/wired pages
  - Locked pages

- Swappable: anonymous pages
- Dirty Cache: data waiting to be written to disk
- Clean Cache: contents of disk reads

General Principles

- Free harmless pages first
  - Consider dropping clean disk cache (can read it again)
  - Steal pages from user programs
    - Especially those that haven't been used recently
    - Must save them to disk in case they are needed again
  - Consider dropping dirty disk cache
    - But have to write it out to disk first
    - Doable, but not preferable
- When reclaiming page, remove all references at once
  - Removing one reference is a waste of time
  - Consider removing entire object (needs extra linked list)

Finding Candidates to Reclaim

- Try reclaiming pages not used in a while
  - All pages are on one of 2 LRU lists: active or inactive
  - Access causes page to move to the active list
  - If page not accessed for a while, moves to the inactive list
- How to know when an inactive page is accessed?
  - Remove PTE_P bit
    - Page fault is cheap compared to paging out bad candidate
- How to know when page isn't accessed for a while?
  - Would page fault too often on false candidates
  - Use PTE_Accessed bit (e.g., clock algorithm)

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SWE3015: Operating System Project

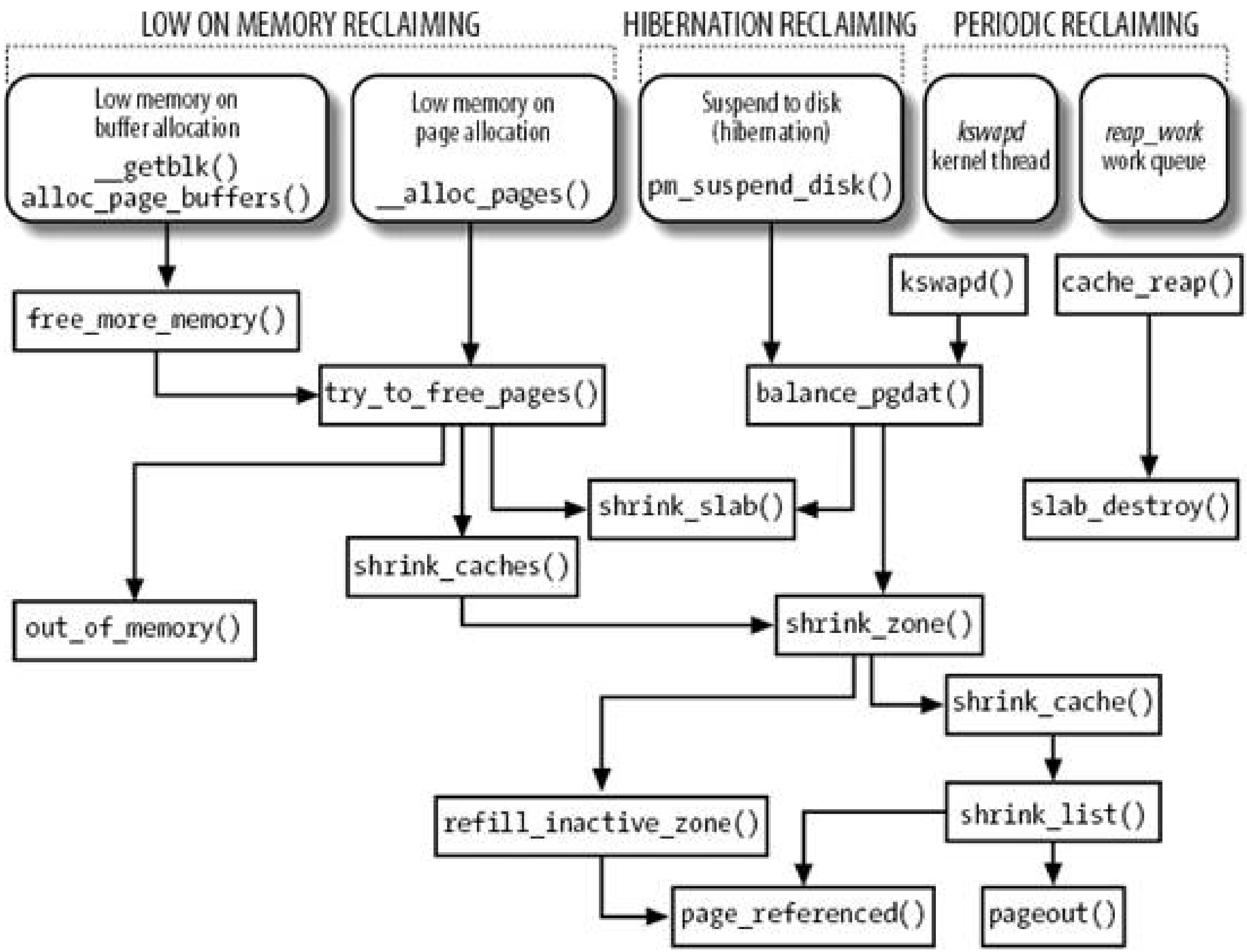
LINUX KERNEL IMPLEMENTATIONS FOR MEMORY RECLAMATION

/proc/meminfo

- http://www.reddit.com/r/linux/comments/1hk5ow/free_buffer_swap_dirty_procmeminfo_explained/

```
hahaman5@ubuntu: ~/linux-3.8.0
hahaman5@ubuntu:~/linux-3.8.0$ cat /proc/meminfo
MemTotal:        2051312 kB
MemFree:         1408160 kB
Buffers:           66084 kB
Cached:           468628 kB
SwapCached:            0 kB
Active:           266376 kB
Inactive:         293056 kB
Active(anon):      24884 kB
Inactive(anon):      164 kB
Active(file):     241492 kB
Inactive(file):   292892 kB
Unevictable:           0 kB
Mlocked:               0 kB
SwapTotal:        520188 kB
SwapFree:         520188 kB
Dirty:                 4 kB
Writeback:             0 kB
AnonPages:         24928 kB
Mapped:            10420 kB
Shmem:               328 kB
Slab:              60356 kB
SReclaimable:      50168 kB
SUnreclaim:        10188 kB
KernelStack:        1312 kB
PageTables:         2960 kB
NFS_Unstable:          0 kB
Bounce:                0 kB
WritebackTmp:          0 kB
```

When Reclamation Starts?



When Reclamation Starts?

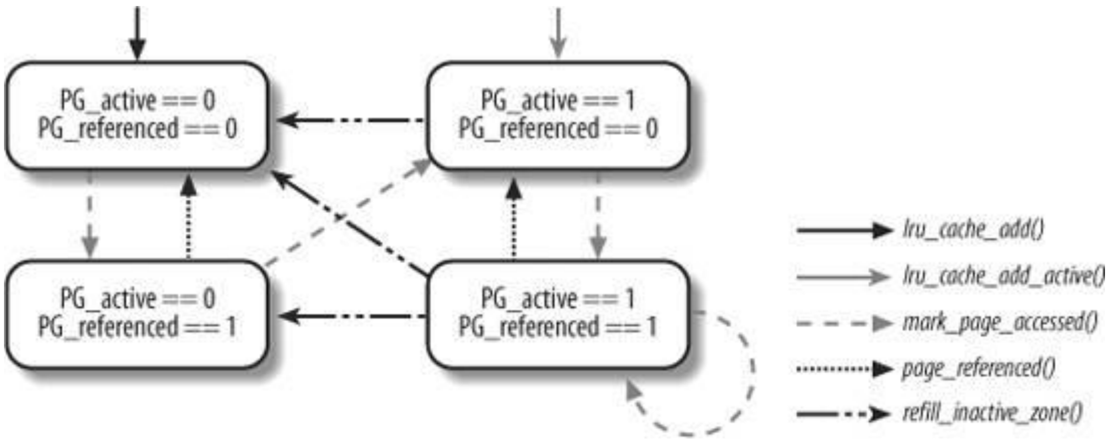
- Low on memory reclaiming
  - Failed to allocate a new buffer page
  - Failed to allocate the temporary buffer heads
  - __alloc_pages() failed to allocate contiguous pages
- Hibernation reclaiming
  - Must free memory for entering in the suspend-to-disk state
    - No more discussion for this class
- Periodic reclaiming
  - The kswapd kernel threads check *pages_high* watermark

The LRU Lists

- Active/inactive list
  - All user mode pages or page caches are belonged one of them.
    - Current implementation divides each list for anon. and file.
  - Unreferenced pages in active list are moved to inactive list.
  - Referenced pages in inactive list are move to active list.
  - Unreferenced pages in inactive list are opt to be reclaimed.

The LRU Lists

- Active/inactive list



Low On Memory Reclaiming

- free_more_memory()
  - wakeup_pdflush(): write back some dirty pages
  - Calls try_to_free_pages()
- try_to_free_pages()
  - Does loop from priority 12 to 0
    - Update discriptors
    - Call shrink_zones()
    - Call shrink_slab()
    - If got the goal (reclaiming 32 pages) exit the loop

Low On Memory Reclaiming

- shrink_zones()
  - Calls shrink_zone for each zone
- shrink_zone()
  - Extracts LRU list and calls shrink_lruvec()
- shrink_lruvec()
  - Determines how aggressively the lists should be scanned.
  - Fore each LRU list, calls shrink_list
  - Add nr of reclaimed pages from shrink_list
  - Repeat until obtaining the scan count

Low On Memory Reclaiming

- shrink_list()
  - If the list is an active list, calls shrink_active_list
    - Only if the inactive list has insufficient pages
    - Return 0 because nothing reclaimed
  - If the list is an inactive list, calls shrink_inactive_list
- shrink_active_list()
  - Scans inactive and evictable pages in the active list
    - And moves them to the inactive list
- shrink_inactive_list()
  - Isolates maximum 32 evictable pages to local list
  - Calls shrink_page_list and pass the local list as an argument
  - Reassigns failed-to-reclaim pages to the (in)active lists
  - Return the number of actually reclaimed pages

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Low On Memory Reclaiming

- shrink_page_list()
  - Determines whether it is currently to be activated, kept, or reclaimable
    - Reclaim only reclaimable pages

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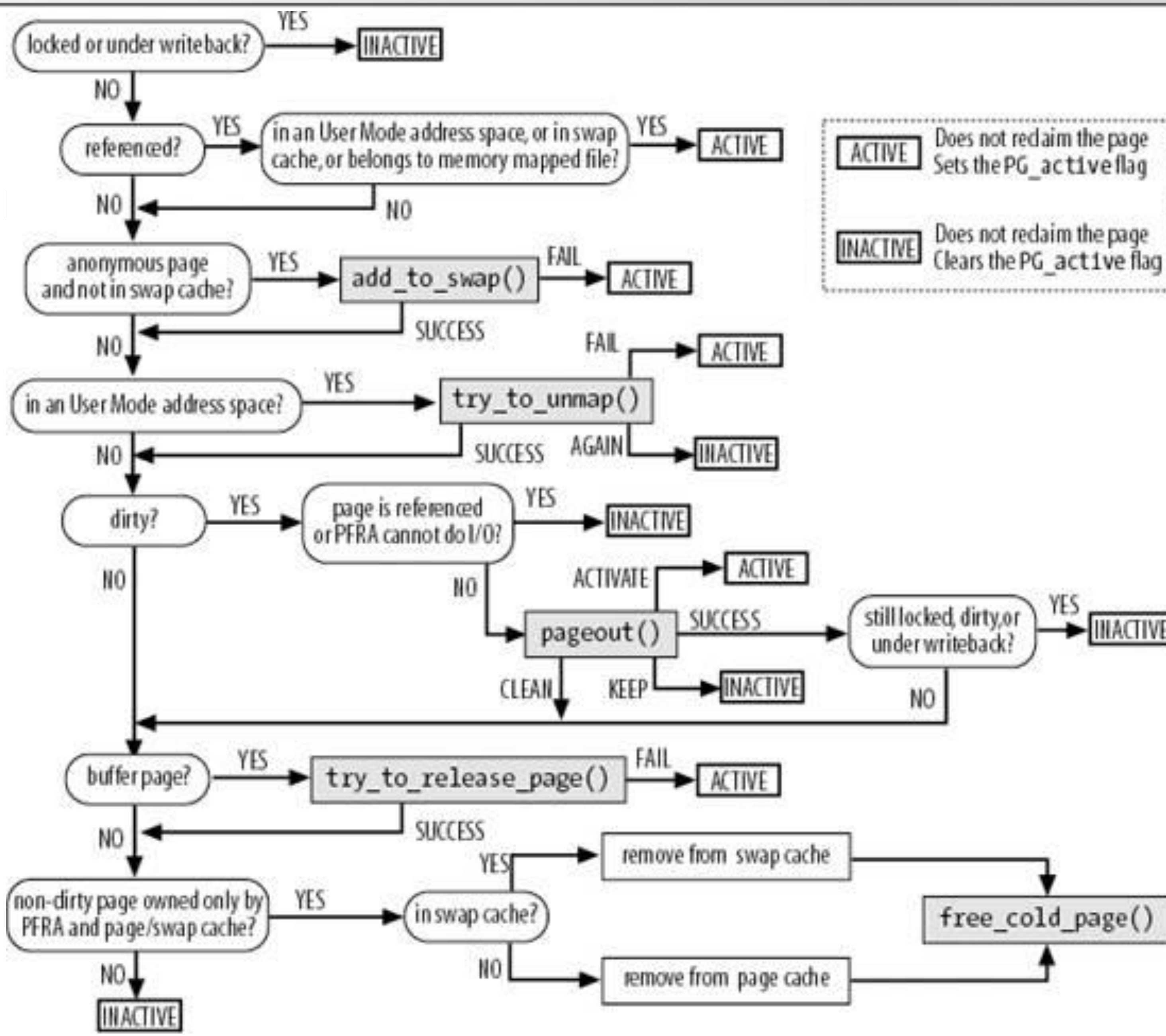
ing

• sh

– or



Periodic Reclaiming

- kswapd kernel thread
  - Wakes up periodically and checks free memory for each zone
    - To guarantee enough free pages.
    - To leverage cpu power during idle
  - Starts reclamation if less free pages are in some zones
    - Same mechanism to previous explanation
  - __alloc_pages() could wake it up
    - When the free page rate is over its threshold (WMARK_LOW)

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OOM Killer

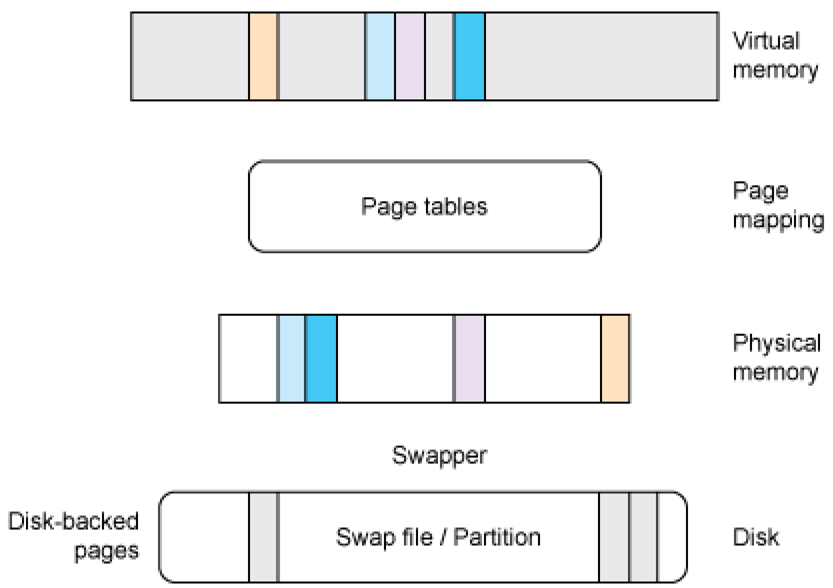
- If reclamation is failed?
  - __alloc_pages calls out_of_memory() (OOM).
  - determines a victim process which
    - Owns a large number of page frames
    - Might lose a small amount of work
    - Is a low static priority process
    - Is not a root process
    - Does not directly access hardware devices
    - Is not neither swapper nor init
  - Sends SIGKILL to the victim

Summary

- Memory pages are reclaimed if
  - No sufficient pages to allocate
  - The number of free pages is under the threshold
- Simple (in)active LRU list is maintained
  - A page has been referenced since the last check is active.
  - Pages to be evicted are collected in inactive lists.
  - If a page to be evicted becomes active or is being written back, it is reassigned to its list.
  - During eviction, some pages can be swappable, and written to the swap device.
- Almost all flow is done in mm/vmscan.c

Swapping

- introduced to offer a backup on disk for unmapped pages
  - Three kinds of pages that must be handled by the swapping
    - But we know/talk only one: anonymous pages



Swap Area

- Stores the swapped-out pages
  - Either as a disk partition or as a file
  - Multiple swap area can be defined (MAX_SWAPFILES)

- Each swap area consists of a sequence of page slots
  - 4KB blocks: PAGE_SIZE
  - Slot 0 has info structure including magic number
    - "SWAPSPACE2"

Creating a swap area

```
hahaman5@ubuntu: ~
hahaman5@ubuntu:~$ dd bs=4096 count=10 if=/dev/zero of=swap
10+0 records in
10+0 records out
40960 bytes (41 kB) copied, 0.000397511 s, 103 MB/s
hahaman5@ubuntu:~$ sudo mkswap swap -L os_project
Setting up swapspace version 1, size = 36 KiB
LABEL=os_project, UUID=ab2b6bef-11cc-4af5-a1cc-c11dde2827c5
hahaman5@ubuntu:~$ sudo swapon swap
hahaman5@ubuntu:~$ cat /proc/swaps
Filename                                Type            Size    Used    Priority
/dev/dm-1                               partition       520188  56      -1
/home/hahaman5/swap                     file            36      0       -2
hahaman5@ubuntu:~$ sudo swapoff swap
hahaman5@ubuntu:~$ cat /proc/swaps
Filename                                Type            Size    Used    Priority
/dev/dm-1                               partition       520188  56      -1
hahaman5@ubuntu:~$
```

Swapping Out Pages

- Inserting the page frame in the swap cache
  - In shrink_page_list(), if a victim page is anonymous and not swap cache, add_to_swap() is called to allocate a new slot in a swap area

- Writing the page into the swap area
  - Invoked in pageout() called in shrink_page_list()
  - pageout() invokes *writepage* method of the page's *address_space* strcture.
    - The implementation is swap_writepage().
      - See the code if you are interested.

Swapping Out Pages

- Removing the page frame from the swap cache
  - shrink_list( ) verifies that no process has tried to access the page frame.
    - Then invokes delete_from_swap_cache() to reclaim the physical page frame.

Swapping in Pages

- The page fault handler triggers a swap-in operation if
  - The page for the fault is a valid one.
  - The page is not present in memory.
  - The pte for the page is not null but the Dirty bit is clear.
  - Then handle_ptd_fault() invokes do_swap_page()
    - Also refer the code if you are interested.