Linux Kernel Programming
Memory Management Pt.2

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Everyday questions

- I found my smartphone/laptop is low on free memory
- This app greatly increases the free memory from my phone!! Five stars!!
- I hate Google Chrome because it hogs memory
- Linux installer suggests a swap partition which is twice of the RAM size
  - By the way, I have 32GB RAM and 128GB SSD... what?
- I don't understand the performance evaluation results
  - 300 MB/sec from hard disk drive????
- I could `malloc()` 2 GB from 1 GB Raspberry Pi...?

Myth

- High memory utilization makes me feel bad ☹
  - Swapping will destroy the system performance
  - Will increase the memory allocation time
  - Will trigger *some* background operations

- Are they all true?
- Will be happy if 20% is used and the rest is free?
- What do you want to do with the *"free memory"*?

Outline

1. Metrics for memory utilization
2. Page cache
3. Page reclamation

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2. Page cache
3. Page reclamation

System memory utilization

Metrics for memory utilization

- The portion of memory that is currently used in the system
- Memory in use + free memory = total memory
- Allocated memory / total memory or
  (total memory - free memory) / total memory
- E.g., using 3 GB out of 4 GB: 3 GB / 4 GB = 75%

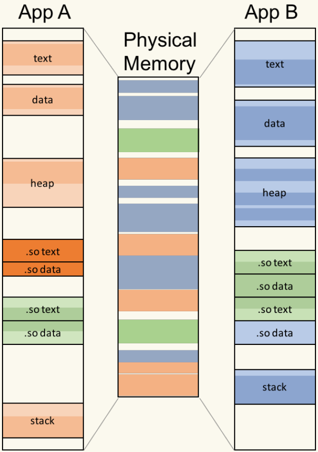
Per-process memory utilization

Metrics for memory utilization

- Processes request the kernel for virtual memory areas (VMAs)
- A read causes the corresponding page to be mapped to the zero page.
- A write causes the copy-on-write to the zero page
  - Allocate the actual page
  - Update the mapping to the new page
- VMAs can be shared between processes
- The sharing can be private

Per-process memory utilization

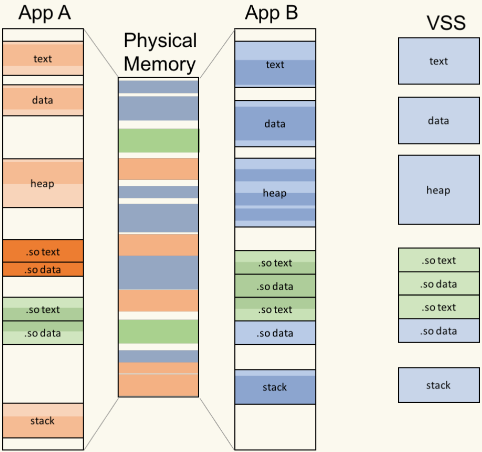
Metrics for memory utilization



Virtual set size (VSS)

Metrics for memory utilization

- The size of virtually allocated memory



Virtual set size (VSS)

Metrics for memory utilization

- The size of virtually allocated memory
- Usually, way to large than the actual memory footprint
- Can obtain by summing the size of each VMA
  - $\sum_{\text{Each VMA}} |\text{VMA}|$

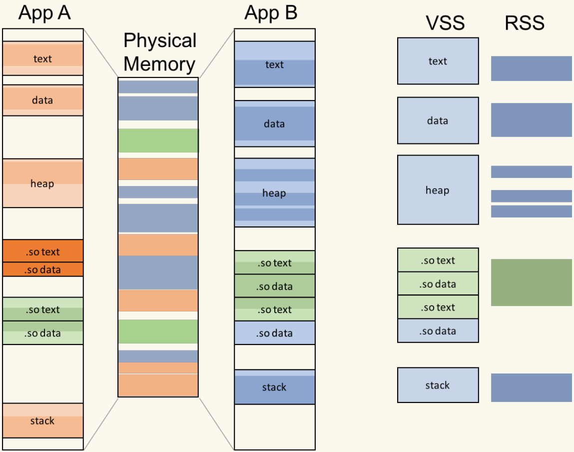
```
/* in include/linux/mm_types.h */

struct mm_struct {
  /* ... */
  unsigned long total_vm; /* Total pages mapped */
  /* ... */
};
```

Resident set size (RSS)

Metrics for memory utilization

- The memory footprint that the process actually occupies



Resident set size (RSS)

Metrics for memory utilization

- The memory footprint that the process actually occupies
- Can get by counting the valid page table entries
  - Page size × # of mapped pages

```
/* In include/linux/mm.h */

static inline unsigned long get_mm_rss(struct mm_struct *mm);
```

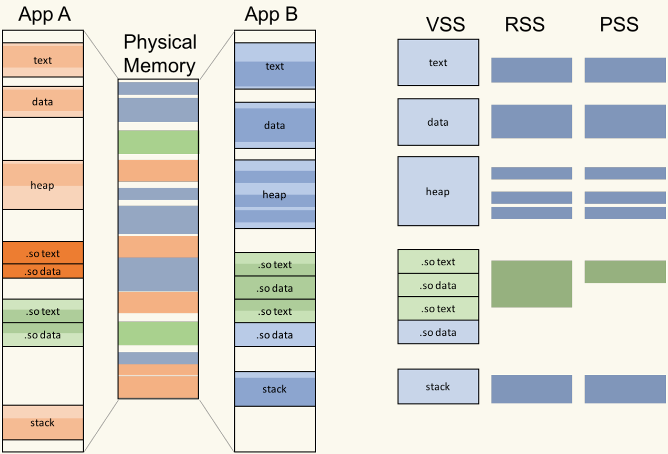
Proportional set size (PSS) / Unique set size (USS)

Metrics for memory utilization

- VSS and RSS do not consider the memory sharing between processes
- Note: VMA is the unit of memory sharing
- Proportional set size (PSS)
  - Account for the number of sharing processes
  - Indicate the memory contribution of the process
  - Page size $\times \sum_{\text{Each VMA}}$ # of mapped pages / # of share
  - E.g., VMA contains 10 pages and shared by 4 processes
    = 4 KB $\times$ 10 / 4 = 10 KB
- Unique set size (USS)
  - The memory footprint that is not shared with any other processes
  - The amount of memory that can be reclaimed by killing the process

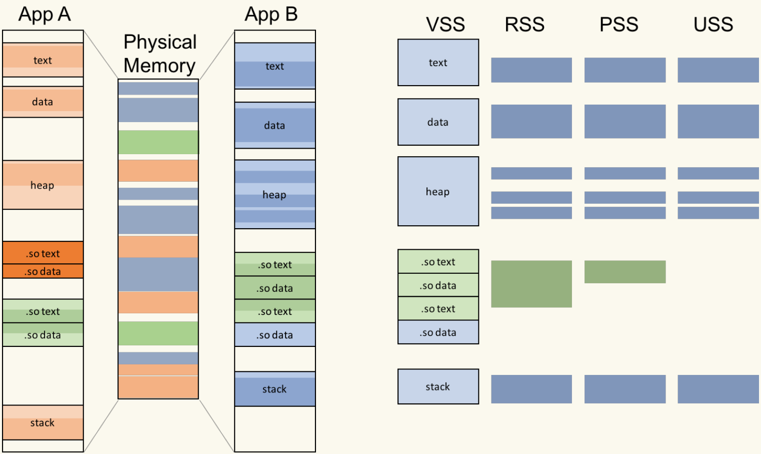
Proportional set size (PSS) / Unique set size (USS)

Metrics for memory utilization



Proportional set size (PSS) / Unique set size (USS)

Metrics for memory utilization



Accessing the metrics

Metrics for memory utilization

- `top`

```
3. sanghoon@cerberus: ~
sanghoon@cerberus: ~
top - 12:04:53 up 58 days, 23:10,  2 users,  load average: 0.00, 0.02, 0.00
Tasks: 292 total,   1 running, 291 sleeping,   0 stopped,   0 zombie
%Cpu(s):  0.0 us,  0.0 sy,  0.0 ni, 99.9 id,  0.1 wa,  0.0 hi,  0.0 si,  0.0 st
KiB Mem : 12300996 total,  3241476 free,   153492 used,  8906028 buff/cache
KiB Swap: 15616892 total, 15567456 free,    49436 used. 11428304 avail Mem

  PID USER      PR  NI    VIRT    RES    SHR S  %CPU %MEM     TIME+ COMMAND
 3854 sanghoon  20   0   42064   3896   3008 R   0.7  0.0   0:00.60 top
 3796 sanghoon  20   0   45380   4828   3884 S   0.0  0.0   0:00.04 systemd
 3799 sanghoon  20   0   63412   1972      0 S   0.0  0.0   0:00.00 (sd-pam)
 3841 sanghoon  20   0   99504   3108   2148 S   0.0  0.0   0:00.01 sshd
 3842 sanghoon  20   0   22832   5336   3208 S   0.0  0.0   0:00.11 bash
```

Accessing the metrics

Metrics for memory utilization

- /proc/[pid]/smap

```
00400000-004f2000 r-xp 00000000 08:01 21233800          /bin/bash
Size:                    968 kB
Rss:                     888 kB
Pss:                     177 kB   /* 888 / 177 = 5 */
Shared_Clean:            888 kB   /* Rss == Shared */
Shared_Dirty:              0 kB

...

006f1000-006f2000 r--p 000f1000 08:01 21233800          /bin/bash
Size:                      4 kB
Rss:                       4 kB
Pss:                       4 kB

...

7f92acb43000-7f92acd42000 ---p 0000b000 08:01 14682101    /lib/x86_64-linux
     -gnu/libnss_files-2.19.so
Size:                   2044 kB
Rss:                       0 kB
Pss:                       0 kB
```

Outline

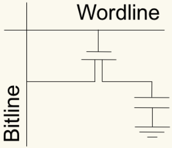
1 Metrics for memory utilization

2 Page cache

3 Page reclamation

Is high memory utilization bad?
Page cache

- In fact, you are wasting your memory if you don't utilize it
- Keep dissipating 5–30% of system energy [1, 2, 3]
  - The cells in DRAM are effectively capacitors
  - The value is determined by the amount of electron charges (i.e., voltage) in the cell
  - Should be refreshed periodically ($\sim$64ms)



- Free pages and used pages are all the same from the memory modules' perspective
- Miss the opportunity to utilize the *fastest* storage in the system that you/OS can fully control its contents
  - Explicitly utilize as RAM disks
  - Else?

Page cache

Page cache

- Utilize free pages to cache the data from slow storage devices
- Implemented at the virtual file system (VFS) layer
  - Will be discussed in the following lecture
- Maintain file-backed pages
  - Pages are indexed by ({device, file}, offset)

- When `read()/fread()` from a file,
  - Look up the page cache
  - If exist, copy the data from the page cache page. Fast!!
  - If not,
    - Allocate page(s)
    - Put the page into the page cache and lock properly
    - Generate I/O request(s) to corresponding block device/file system
    - Copy the read content to the user-space buffer

Page cache

Page cache

- When `write()/fwrite()` to a file,
  - Look up the page cache
  - If exist, apply the write to the page and flag it dirty. Fast!!
  - If not,
    - Allocate page(s)
    - Generate I/O request(s) to corresponding block/file system
    - Apply the write to those pages, make them dirty
  - Dirty pages will be *magically* written back to the storage
  - The write-back makes the page clean

Page cache

Page cache

- Page cache significantly improves the system performance
  - Can read without accessing the slow storage devices
  - Can buffer writes
  - Merge overwrites before writing to the storage
  - Can shape the write pattern to the storage device
- In enterprise and HPC environments, performance-critical servers are equipped with a huge amount of memory for the page cache

How large is the page cache?

Page cache

```
sanghoon@echo_debian:~$ free -m
              total       used       free     shared    buffers     cached
 Mem:         32133      26789       5344         24       1592      23720
 -/+ buffers/cache:       1475      30658
 Swap:            0          0          0
```

- Memory utilizatoin = 26,789 / 32,133 = 83%
- Page cache = 23,720 MB (88% / 74%)
- Available = 5,344 + (1,592 + 23,720) $\pm\epsilon$ = 30,656 MB

```
sanghoon@cerberus_ubuntu:~$ free -m
              total       used       free     shared  buff/cache   available
Mem:          12012        156       3158         88        8697       11154
Swap:         15250         48       1520
sanghoon@echo:~$
```

- Memory utilizatoin = (156 + 8,697) / 12,012 = 74%
- Page cache = +-8,697 MB (98% / 72%)
- Available = 3,158 + 8,697 $\pm$ ϵ = 11,154 MB

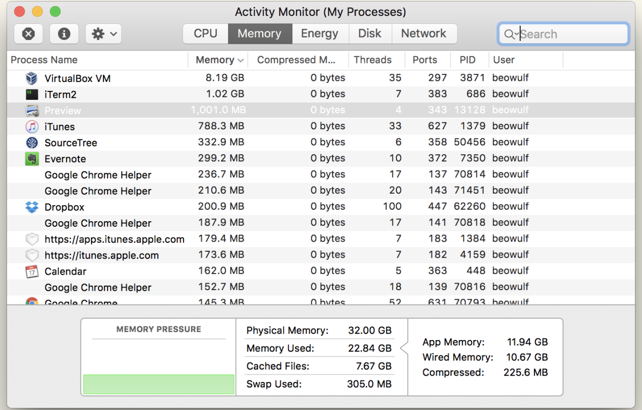
How large is the page cache?

Page cache

```
# cat /proc/meminfo
MemTotal:       32904980 kB
MemFree:         4971852 kB
MemAvailable:   32399416 kB
Buffers:         1634068 kB
Cached:         24768688 kB <--
  ...
```

How large is the page cache?

Page cache



Activity Monitor (My Processes)

CPU | Memory | Energy | Disk | Network

Process Name	Memory	Compressed M...	Threads	Ports	PID	User
VirtualBox VM	8.19 GB	0 bytes	35	297	3871	beowulf
iTerm2	1.02 GB	0 bytes	7	383	686	beowulf
Preview	1,001.0 MB	0 bytes	4	343	13128	beowulf
iTunes	788.3 MB	0 bytes	33	627	1379	beowulf
SourceTree	332.9 MB	0 bytes	6	358	50456	beowulf
Evernote	299.2 MB	0 bytes	10	372	7350	beowulf
Google Chrome Helper	236.7 MB	0 bytes	17	137	70814	beowulf
Google Chrome Helper	210.6 MB	0 bytes	20	143	71451	beowulf
Dropbox	200.9 MB	0 bytes	100	447	62260	beowulf
Google Chrome Helper	187.9 MB	0 bytes	17	141	70818	beowulf
https://apps.itunes.apple.com	179.4 MB	0 bytes	7	183	1384	beowulf
https://itunes.apple.com	173.6 MB	0 bytes	7	182	4159	beowulf
Calendar	162.0 MB	0 bytes	5	363	448	beowulf
Google Chrome Helper	152.7 MB	0 bytes	18	139	70816	beowulf
Google Chrome	145.3 MB	0 bytes	52	631	70793	beowulf

MEMORY PRESSURE

Physical Memory:	32.00 GB
Memory Used:	22.84 GB
Cached Files:	7.67 GB
Swap Used:	305.0 MB

App Memory:	11.94 GB
Wired Memory:	10.67 GB
Compressed:	225.6 MB

QnA

Page cache

Q: I don't understand the performance evaluation results

- 300 MB/sec from hard disk drive????

A: Check whether the data is accessed from the page cache

- Unfair between the 1st run and subsequent runs
- Drop or warm up the page cache
- You can explicitly drop page caches
- Bypass the page cache by `open()` with `O_DIRECT`

```
/* To free pagecache: */
$ echo 1 > /proc/sys/vm/drop_caches

/* To free reclaimable slab objects (includes dentries and inodes): */
$ echo 2 > /proc/sys/vm/drop_caches

/* To free slab objects and pagecache: */
$ echo 3 > /proc/sys/vm/drop_caches
```

QnA

Page cache

Q: I found my smartphone/laptop is low on free memory

A: Don't panic

- Your operating system is doing its best to maximize the system performance
- By the way, check the swap status for sure

Q: This app increases the free memory from my phone!! Five stars!!

A: ...

Outline

1. Metrics for memory utilization
2. Page cache
3. Page reclamation

Memory is limited

Page reclamation

- Eventually, memory will be filled up with page cache pages and process-allocated pages
- The kernel cannot keep allocating pages
- Should reclaim allocated memory somehow

- When the kernel should start the reclamation?
- Who will reclaim the memory?
- Which memory should be reclaimed?
- How reclaim?

When to start the memory reclamation?

Page reclamation

- When fail to allocate a page from `alloc_pages()`
  - Mostly due to zone imbalancing (e.g., alloc_page(GFP_DMA))
  - `ZONE_DMA, ZONE_DMA32, ZONE_NORMAL, ZONE_HIGHMEM`
- Based on the amount of free memory

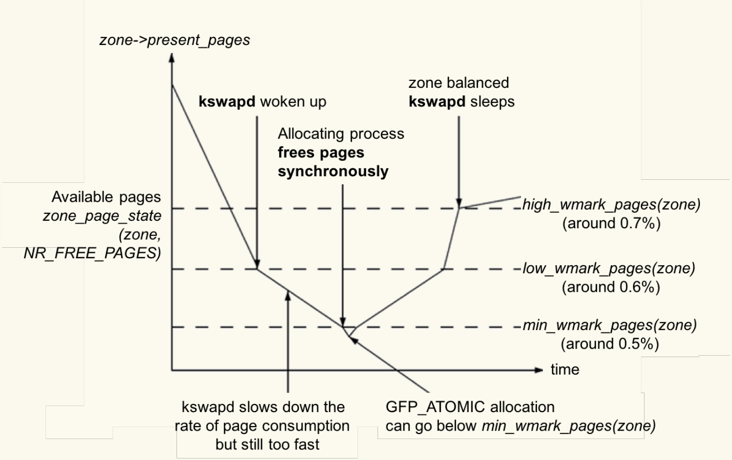
Who will reclaim?

Page reclamation

- Direct reclamation
  - When `alloc_pages()` fails
  - Synchronously reclaim pages for critical page allocation
- Background reclamation
  - Triggered when `alloc_pages()` fails
  - A kernel thread a.k.a `kswapd` reclaims the page frames
  - Keep the free memory above thresholds

Background reclamation

Page reclamation



What to reclaim?

Page reclamation

- Should evict file pages
  - Memory is for anonymous pages originally
  - Reclaiming clean file pages is fast
    - Drop the page from the page cache
  - Require slow I/Os to swap-out and -in anonymous pages
  - Many files are only accessed once
    - E.g., multimedia files
- Should keep file pages
  - Many clean pages are performance critical (e.g., code)
  - The write-back might block the reclamation
  - Cold anonymous pages are really cold
  - Storage devices are (were) extremely slow

What to reclaim?

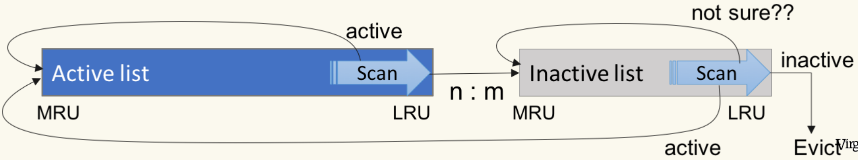
Page reclamation

- Keep *important* pages
  - Keep important pages whatever they are for
  - Can apply the traditional cache management policies
    - LRU, LFU, LRFU, CLOCK, ARC, CAR, MQ, ...
  - Anonymous pages and file-back pages have different characteristics
    - Many files are only accessed once
    - Code pages are performance critical
    - Cold anonymous pages are really cold
- OK. let manage them separately

2Q

Page reclamation

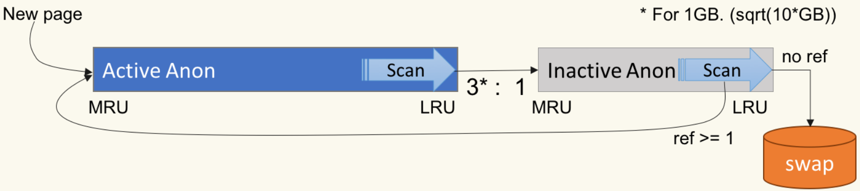
- None of OS/cache uses the LRU/LFU in practice
  - Updating the position upon every access requires a significant overhead
- Linux employs a modified 2Q policy
  - Known good to separate inactive pages from active ones
  - Maintain an LRU list for inactive pages and an LRU list for active pages
  - Scan a part of the lists
  - Migrate pages between the lists according to some policies



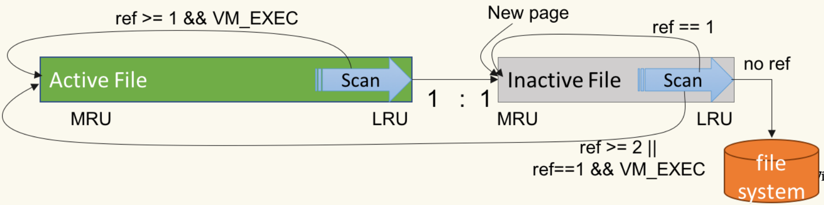
Managing the page lists

Page reclamation

- Anonymous pages



- File pages



Swappiness

Page reclamation

- Tendency to reclaim anonymous pages with swap-out
- Integer between 0 to 200 (60 by default)
  - 60 means anon:file = 60:140
  - 100 means anon:file = 100:100
- Effectively 0 when no swap device exists
- Can control via `/proc/sys/vm/swappiness`

Have a look at the source code

Page reclamation

- `mm/vmstat.c` and `mm/vmscan.c`
- Isolate pages from the lists
  - `shrink_inactive_list()`
  - `shrink_active_list()`
- Process the isolated page
  - `shrink_page_list()`

Check the size of page lists

Page reclamation

```
# cat /proc/meminfo
MemTotal:        32904980 kB
MemFree:          4971852 kB
MemAvailable:    32399416 kB
  ...
Active:          14175700 kB
Inactive:        12260264 kB
Active(anon):       34020 kB
Inactive(anon):     24728 kB
Active(file):    14141680 kB
Inactive(file): 12235536 kB
  ...
```

- Comment: We cannot tell whether the pages in the active/inactive page list are actually active/inactive or not
  - The activeness can be determined by examining the page
  - The pages evicted from the inactive list are inactive.

How to reclaim?

Page reclamation

- File pages
  - Clean: Drop from the page cache
    - The data is in the filesystem
  - Dirty: May drop after writing them back, or keep it
- Anonymous pages
  - Perform the swap-out

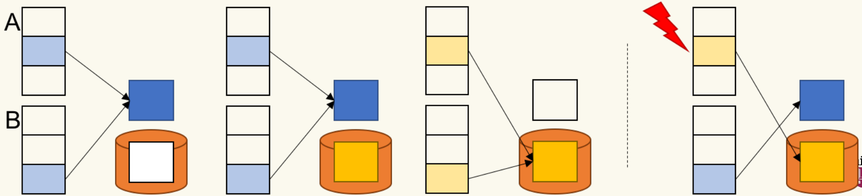
Swap-out v0.1

Page reclamation

- Note: A page can be shared between processes

- Allocate a swap entry from the swap device
- Write the page to the swap entry
- For each PTE points to the page (Q: How?)
  - Mark the PTE as invalid and update to the swap entry

- What if a process accesses the swapped-out page during the swap-out?

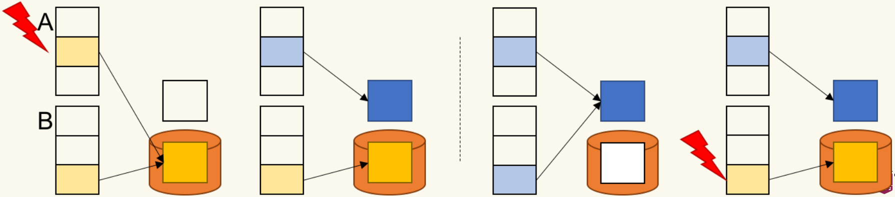


Swap-in v0.1

Page reclamation

- When a process accesses the swapped out PTE
- Allocate a page
- Read in the page from the swap device
- Update the PTE accordingly

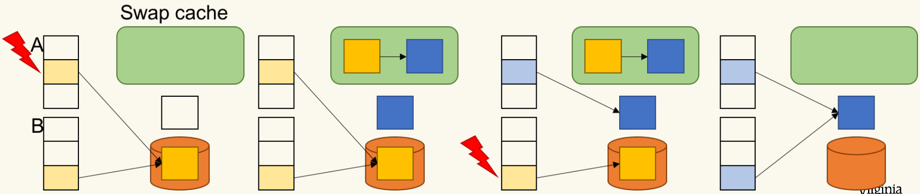
- Should the kernel fix the PTE from other processes and release swap entry?
- Which one is the current one?



Swap cache

Page reclamation

- Prevent the race conditions during the swap-in and out
- Keep (swap entry ID, page) mappings for transient pages
- Consult to the swap cache first to swap-in
- If a corresponding mapping exists, update the PTE to the page in the memory instead of loading the swap entry



Conclusion

- Do not under-utilize your memory
- Trust the techniques that are reviewed, evaluated, and proved

- Yes, memory management is dirty and complicated
- However, it is connected to everything
- Non-volatile memory and flash memory provide new opportunities

Bibliography I

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