Tour de Linux memory management

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Documentation & Upstream development

- **Documentation/vm**
  - Quite ad-hoc – systematic design documentation is missing
- **lwn.net**
  - Many very good articles
- **Understanding The Linux Virtual Manager – by Mel Gorman**
  - Very good and systematic coverage but too old – from 2.4 era (with What’s new in 2.6 sections)
  - Still very useful to understand core design principals
  - [https://www.kernel.org/doc/gorman/](https://www.kernel.org/doc/gorman/)
- **Upstream development**
  - Mailing list linux-mm@kvack.org
  - Patches routed usually via Andrew Morton <akpm@linux-foundation.org> and hist mm tree
  - Code lives mostly in mm/ and many include files
Purpose and the scope of MM

- **Manage system RAM**
  - Architecture independent view on the memory
  - Support for UMA/NUMA architectures
  - Memory hotplug support – used by NVDIMMs
- **Support for memory over-commit**
  - Virtual memory
  - On demand memory reclaim
  - CopyOnWrite
- **Support also for MMUless architectures**
Purpose and the scope of MM APIs for kernel

- Bootmem/memblock allocator – early initialization
- Page allocator – page order ($2^n$ physically contiguous pages)
- SLAB allocator – sub page granularity, internal fragmentation management
  - SLOB – very rudimentary for small devices
  - SLAB – based on Solaris design – optimized for CPU cache efficiency, NUMA aware
  - SLUB – new generation design – aimed for better scalability
- Vmalloc – virtually contiguous memory allocator – via page tables
- Mempool allocator
  - Guarantee for a forward progress – mostly for IO paths
- Page cache management for filesystems
- Memory tracking for userspace – process management
- Page table management
  - get_user_pages – virtual → struct page translation
- On-demand memory paging
Purpose and the scope of MM APIs for userspace

- **Sysecalls to manage memory**
  - mmap, munmap, mprotect, brk, mlock – POSIX
  - madvise – hints from userspace e.g. MADV_DONTNEED, MADV_FREE etc...
  - userfaultfd – page fault handling from userspace
  - SystemV shared memory – IPC, shmget, shmat, shmdt
  - memfd_create – anonymous memory referenced by a file descriptor – for IPC
- **Memory backed filesystems**
  - Ramdisk – fixed sized memory backed block device
  - Ramfs – simple memory backed filesystem
  - Tmpfs – more advanced memory backed filesystem, support for swapout, ACL, extended attributes
- **Memory cgroups controller – more fine grained partitioning of the system memory**
  - Mostly for user space consumption limiting, kernel allocations are opt-in
  - Support for hard limit, soft/low limit, swap configuration, userspace OOM killer
- **Access to huge pages (2MB, 1GB)**
  - Hugetlbfs – filesystem backed by preallocated huge pages
  - THP – transparent huge pages
- **NUMA allocation policies**
  - Mbind, set_mempolicy, get_mempolicy
Physical Memory representation

- Managed in page size granularity – arch specific, mostly 4kB
- Each page is represented by `struct page`
- Heavily packed – 64B on 64b systems (~1.5% with 4kB pages)
  - Lots of unions to distinguish different usage
  - Special tricks to save space – set bottom bits in addresses etc...
- Statically allocated during boot/memory hotplug - `memmap`
- Reference counted
  - `get_page()`, `put_page()`, `get_page_unless_zero()`, `put_page_test_zero()`
  - memory is returned to the page allocator when 0
- `PFN_valid()`, `PFN_to_page()`, `page_toPFN()` – physical page frame number to `struct page` translation
- `page_owner` – tracks stack of the allocation request – very useful for debugging
Physical Memory representation

- Memory ranges exported by BIOS/EFI firmware
  - E820 for x86 systems
    
    ```
    [ 0.000000] e820: BIOS-provided physical RAM map:
    [ 0.000000] BIOS-e820: [mem 0x0000000000000000-0x000000000009dbff] usable
    [ 0.000000] BIOS-e820: [mem 0x000000000009dc00-0x000000000009ffff] reserved
    [ 0.000000] BIOS-e820: [mem 0x00000000000f0000-0x00000000000fffff] reserved
    [ 0.000000] BIOS-e820: [mem 0x0000000000100000-0x00000000bf61ffff] usable
    [ 0.000000] BIOS-e820: [mem 0x00000000bf620000-0x00000000bf63bfff] ACPI data
    [ 0.000000] BIOS-e820: [mem 0x00000000bf63c000-0x00000000bf63cfff] usable
    [ 0.000000] BIOS-e820: [mem 0x00000000bf63d000-0x00000000cfffffff] reserved
    [ 0.000000] BIOS-e820: [mem 0x00000000fec00000-0x00000000fee0ffff] reserved
    [ 0.000000] BIOS-e820: [mem 0x00000000ff800000-0x00000000ffffffff] reserved
    [ 0.000000] BIOS-e820: [mem 0x0000000100000000-0x0000000403ffe0ff] usable
    ```

- Memory model defines how we represent physical memory ranges
  - Flatmem – the simplest one, single range of physical memory, doesn’t support NUMA
  - Discontigmem – more advanced, supports holes, NUMA, doesn’t support memory hotplug
  - Sparsemem – the most widely used, supports NUMA, memory hotplug, keeps track of memory range in memory sections
    - Vmemmap sparsemem – virtually contiguous memory map via page tables, very efficient `pfnto_page` (simple pointer arithmetic)
Page flags

- `enum pageflags` – describes the state of the page
- `PG_$NAME` are accessed via `Page$NAME()`, `SetPage$NAME()`, `TestSetPage$NAME()`, `ClearPage$NAME()`, `TestClearPage$NAME()`
  - Defined by macros
    - `PAGEFLAG(Referenced, referenced, PF_HEAD)`
    - `TESTCLEARFLAG(Referenced, referenced, PF_HEAD)`
    - `__SETPAGEFLAG(Referenced, referenced, PF_HEAD)`
  - Atomic updates
  - Non atomic variants `__SetPage$NAME`, `__ClearPage$NAME`
- **Page lock is implemented as bit lock**
- Upper part of flags is used to encode numa node/section_nr, zone id
Physical Memory representation

- NUMA node represented by `struct pglist_data`
- UMA machines have one static numa node, NUMA has an array of nodes
- SRAT tables on x86 systems – describe nodes, distances
- Kswapd kernel thread for the background memory reclaim
- LRU lists for the memory reclaim
- Free pages are maintained on the per-zone bases
- Counters - `/proc/zone_info`
ACPI: SRAT: Node 0 PXM 0 [mem 0x00000000-0xbfffffff]
ACPI: SRAT: Node 0 PXM 0 [mem 0x100000000-0x103fffffff]
ACPI: SRAT: Node 1 PXM 1 [mem 0x1040000000-0x203fffffff]
ACPI: SRAT: Node 2 PXM 2 [mem 0x2040000000-0x303fffffff]
ACPI: SRAT: Node 3 PXM 3 [mem 0x3040000000-0x403fffffff]
NUMA: Node 0 [mem 0x00000000-0xbfffffff] + [mem 0x100000000-0x103fffffff] -> [mem 0x00000000-0x103fffffff]
NODE_DATA(0) allocated [mem 0x103ffde000-0x103fffffff]
NODE_DATA(1) allocated [mem 0x203ffde000-0x203fffffff]
NODE_DATA(2) allocated [mem 0x303ffde000-0x303fffffff]
NODE_DATA(3) allocated [mem 0x403ffdd000-0x403fffefff]

$ numactl -H
available: 4 nodes (0-3)
node 0 cpus: 0 4 8 12 16 20 24 28 32 36 40 44 48 52 56 60
node 0 size: 64295 MB
node 0 free: 53958 MB
node 1 cpus: 1 5 9 13 17 21 25 29 33 37 41 45 49 53 57 61
node 1 size: 64509 MB
node 1 free: 48875 MB
node 2 cpus: 2 6 10 14 18 22 26 30 34 38 42 46 50 54 58 62
node 2 size: 64509 MB
node 2 free: 50959 MB
node 3 cpus: 3 7 11 15 19 23 27 31 35 39 43 47 51 55 59 63
node 3 size: 64507 MB
node 3 free: 33646 MB
node distances:
node    0  1  2  3
  0: 10 20 20 20
  1: 20 10 20 20
  2: 20 20 10 20
  3: 20 20 20 10
Physical Memory representation

- Memory zones for the page allocator – struct zone
  - Defines a class of memory
    - ZONE_DMA – low 16MB for legacy HW (ISA buses)
    - ZONE_DMA32 – low 4GB for 32b restricted devices
    - ZONE_NORMAL – memory usable by the kernel directly
    - ZONE_HIGHMEM – memory for userspace on 32b systems – has to be mapped to be used from the kernel
    - ZONE_MOVABLE – allocations which can be migrated – mostly user memory, page cache
    - ZONE_DEVICE – special zone to describe device memory – non-volatile memory DAX, non-coherent device memory HMM
  - Free pages maintained in zone::free_area
  - Watermarks to limit access to free pages zone::watermark[]
Virtual Memory representation

- 48b (128TB) view of contiguous memory which is translated to the physical memory by page tables
- Support for future 52b (4PB) physical address space in 5-level pte (57b of virtual)
  - Explicit opt in to use in userspace by addr hint to mmap
- Kernel vs. User space view
  - Virtual address space is split to kernel and userspace
    - Kernel part is static and doesn’t change with context switches
    - 32b - Lowmem (1GB for direct usage) vs. Highmem (3GB)
      - Only low mem can be accessed directly, highmem has to be mapped temporarily
      - Only 896MB usable – 128MB reserved for vmalloc and kmap
        - 00000000 – BFFFFFFF user space
        - C000000 – F7xxxxxx kernel (direct mapping)
        - F7xxxx – FF7FE0000 vmalloc
        - FF80000 – FFC00000 kmap
    - 64b – negative address space kernel, positive userspace
      - 0000000000000000 – 00007FFFFFFFF – user space
      - FFFF880000000000 – FFFFC7FFFFFFFF – direct mapping
      - FFFFC90000000000 – FFFFE8FFFFFFFF – vmalloc
  - Kernel space is configured to use direct 1:1 mapping
    - Translation is a simple arithmetic operation (__va(), __pa())
Virtual Memory representation

- **Page table walkers use unified 5 page table levels**
  - `pgd_t`, `p4d`, `pud_t`, `pmd_t` and `pte_t`
  - `pgd_alloc`, `pgd_none`, `pgd_index`, `pgd_offset` etc...
  - Architectures with a different pte topology emulate 5 levels (e.g. `include/asm-generic/5level-fixup.h`)

- **Simple page table walk**
  
  ```c
  pgd = pgd_offset(mm, addr) /* mm of the process or init_mm */
  P4d = p4d_offset(pgd, addr)
  pud = pud_offset(p4d, addr)
  pmd = pmd_offset(pud, addr)
  pte = pte_offset_map_lock(mm, pmd, addr, &ptl)
  ```

- **Once we have pte – `vm_normal_page()`**
  - `pte_pfn()` + `pfn_to_page` with some special casing for special mappings
Address space descriptor

• Each process has its address space descriptor struct `mm_struct`
• Keeps track of all the mapped memory
  • `mm_struct::mmap` – linked list of all mapped areas (VMA)
  • `mm_struct::mm_rb` – RedBlack tree for quick VMA lookups - `find_vma`
• Reference counted
  • `mm_count` – `mmgrab()`, `mmdrop()`
    • Number of `mm_struct` users – last reference will free the data structure
  • `mm_users` – `mmget()`, `mmget_not_zero()`, `mmput()`
    • Number of users of the address space – last user will unmmap the whole address space
• Links to the top page table entry – `mm_struct::pgd`
• Counters – number of page table entries, locked memory, `high_rss` etc...
• `mmap_sem` – RW lock to serialize address space operations
  • And more abusers unfortunately
Address space descriptor

- Mapped memory range struct `vm_area_struct`
- Created for mmap, brk, special mappings (VDSO)
- `vm_flags`
  - Access protection – `VM_READ`, `VM_WRITE`, `VM_EXEC`
  - Mlock status – `VM_LOCKED`
  - Special mapping – `VM_IO`, `VM_PFNMAP`, `VM_MIXEDMAP`
- Link to the mapped object – `vm_file` or `anon_vma`
- Memory policy for the area
- Set of “virtual functions” - `vm_ops`
  - How to handle page fault – `fault()`
  - Notify the backing store that a read only page will become writable – `page_mkwrite()` – FS can refuse due to ENOSPACE and process will get SIGBUS
  - Other hooks for special device mappings
On demand paging

- HW (onx86) will trigger #PF exception when the pte is not mapped or the current protection doesn’t allow requested operation (e.g. Write on ReadOnly pte).
- do_page_fault – main entry – arch specific
  - A lot of special casing – e.g. faults from kernel, fixups, errata workarounds etc
  - Take mmap_sem in read mode
  - find_vma – no VMA → SEGV
  - Expand stack VMAs – VM_GROWS_{UP,DOWN}
  - handle_mm_fault – arch independent page fault handling
    - Wrong access SEGV
  - __handle_mm_fault → pte_walk, handle large pages (PUD, PMD) or handle_pte_fault for base pages
    - do_anonymous_page – allocates a new page, setups page table, reverse mapping, adds page the LRU list
    - do_fault – relies on vm_ops→fault() - many filesystems rely on filemap_fault
    - do_swap_page – swapped out page – swap it in
    - do_numa_page – used by numa balancing
    - do_wp_page – break CoW page – allocate new anonymous page for private mappings
  - Parallel page faults are handled by rechecking pte against the saved one under the page table lock (pte_same())
page → VMA mappings

- How to get from struct page to all mappings? (mm/rmap.c)
  - rmap_walk – rmap_walk_control defines callback to call for each mapping
- page::mapping, page::index
  - Anonymous pages – page::mapping has the lowest bit set
    - anon_vma = page->mapping & ~PAGE_MAPPING_FLAGS
    - Address space of all anonymous pages – hierarchical tree of interval trees
      INTERVAL_TREE_DEFINE(struct anon_vma_chain, rb, unsigned long, rb_subtree_last,
                             avc_start_pgoff, avc_last_pgoff,
                             static inline, __anon_vma_interval_tree)
      - More on https://lwn.net/Articles/383162/
- pgoff = page->index
- anon_vma_interval_tree_foreach – iterates over all VMAs which contain pgoff
- File backed pages
  - Mapping points to struct address_space – one per each inode/block device
  - mapping->i_mmap contains interval tree of all VMAs
  - vma_interval_tree_foreach iterates over all VMAs which contain pgoff
Address space – gluing it together
Page cache management

- **address_space::page_tree** - radix_tree of pages belonging to the inode – move to xarray in the recent past
- **filemap_fault**
  - **find_get_page**
    - Returns an existing page from the radix tree or allocates a new one
      __page_cache_alloc() and inserted to the radix tree
      __add_to_page_cache_locked() and LRU list
    - Page is locked and !PageUptodate() if newly allocated
  - **do_async_mmap_readahead()** – triggers asynchronous read from the backing storage (including readahead).
  - **do_sync_mmap_readahead()** – synchronous read
  - **read_pages** – mapping→a_ops→readpages() – to do the actual read from the (fs usually use mpage_readpages())
  - Once we have the content – SetPageUptodate() + PageUnlock()
Page allocator

- `__alloc_pages_nodemask(gfp_t gfp_mask, unsigned int order, struct zonelist *zonelist, nodemask_t *nodemask)` to get a struct page
- `__get_free_pages()` to get a directly usable pointer – use with care!
- `gfp_mask` – bitmask for the allocation mode
  - Request specific zones – `__GFP_DMA, __GFP_DMA32, __GFP_HIGHMEM, __GFP_MOVABLE`
  - `GFP_NOWAIT, GFP_ATOMIC` – non sleeping allocations, no direct reclaim
  - `GFP_KERNEL` – standard kernel allocations
  - `GFP_USER, GFP_USER_MOVABLE` – allocations for userspace
  - `GFP_NOFAIL` – non-failing allocations
  - `GFP_NOFS, GFP_NOIO` – do not recurse to fs perform any IO from the reclaim
- **Order** – size of the allocation $2^\text{order}$ contiguous pages
  - `PAGE_ALLOC_COSTLY_ORDER (3)` – small allocations are special – trigger OOM killer rather than fail
- **Zonelists** – list of zones to allocate from
  - Start with zones of a local or requested node - `node_zonelist()`
  - `build_zonelists()` - `numa_zonelist_order` kernel boot parameter – node order, zone order
- **Nodemask to filter only allowed nodes defined by memory policy**
  - Note that there is also cpuset API to overrule memory policies
  - Funny things will happen if those two disagree
Page allocator

- **Slow path quite complex**
  - Wake up kswapd/kcompactd
  - Triggers direct memory reclaim/compaction when needed
  - Triggers the OOM killer when no progress was made during the reclaim

- **Core of the page allocator – get_page_from_freelist()**
  - Checks watermarks to not allow memory depletion
  - Per-cpu allocation for order-0 – no locking, batch refill, freeing - rmqueue_pcplist()
  - __rmqueue() for other orders

- **Based on buddy allocator**
  - Physically contiguous pages are grouped in $2^N$ chunks
  - $2^{N-1}$ blocks are merged to $2^N$ when page is freed - __free_one_page()
  - A larger block is split up when appropriate is not available - __rmqueue_smallest()
  - vs __rmqueue_fallback()

```bash
$ cat /proc/buddyinfo
Node 0, zone      DMA      1      0      1      0      1      1      1      0      1      1      1      3
Node 0, zone    DMA32      7      4      3      5      3      5      7      5      4      2    538
Node 0, zone   Normal    438    445   3397   1588    877    367    177     74     36      7    312
```
Memory reclaim

- **Background reclaim**
  - Kernel thread per NUMA node
  - Starts when free memory hit **low** watermark on all zones eligible for the allocation – `pgdat_balanced()`
  - Reclaims until **high** watermark is hit
  - The main logic implemented in `balance_pgdat()`

- **Direct reclaim**
  - All eligible zones hit the **min** watermark
  - Tries to free `SWAP_CLUSTERS_MAX` pages
  - The main logic implemented in `try_to_free_pages()`

- **Node reclaim – former zone reclaim**
  - Enforce direct reclaim on the requested node first
  - Used to be enabled on NUMA machines with large numa distances in the past
  - Has to be enabled explicitly - `/proc/sys/vm/zone_reclaim_mode`

- **OOM killer**
  - Last despair attempt to free memory by killing the task with the largest memory consumption
  - `oom_reaper` – kernel thread to unmap memory of the oom victim
  - Very tricky to get right
Memory reclaim

- Reclaimable pages are sitting on LRU lists – struct lruvec
  ```c
  enum lru_list {
      LRU_INACTIVE_ANON = LRU_BASE,
      LRU_ACTIVE_ANON = LRU_BASE + LRU_ACTIVE,
      LRU_INACTIVE_FILE = LRU_BASE + LRU_FILE,
      LRU_ACTIVE_FILE = LRU_BASE + LRU_FILE + LRU_ACTIVE,
      LRU_UNEVICTABLE,
      NR_LRU_LISTS
  };
  ```

- Used to have LRU lists per zones, now we have one per node
  - Actually per memory cgroup – more on that later

- Pages are added to the list when allocated

- Anonymous pages start on the active list

- File pages start on the inactive list
  - Pages freed recently are put to the active list - workingset_refault()

- Promotion from inactive to active list based on pte references – page_check_references()
  - Used once heuristic for file pages
  - Executable pages protection

- Active list is shrunk when it grows too large – inactive_list_is_low()
Memory reclaim

- Each reclaim pass has a priority – starting from DEF_PRIORITY (12)
  - Size of the window to scan LRU lists – lruvec_lru_size() >> priority
- get_scan_count() - keeps balance between file and anonymous LRU lists
  - Highly biased to reclaim file pages
  - /proc/sys/vm/swappiness
  - Considers recently scanned and rotated pages for each LRU
- isolate_lru_pages() - removes pages from the LRU list in a batch for further inspection
  - Reduces the lock contention
  - Skip over ineligible pages – e.g. highmem pages for GFP_KERNEL request
- shrink_page_list() - core of the reclaim
  - Referenced pages are promoted to the active list
  - Anonymous pages are added to the swap cache and scheduled for swapout - add_to_swap()
  - Dirty file pages are written out – pageout() - only in kswapd context
  - Mapped pages are unmapped – try_to_unmap_one()
    - Anonymous ptes will point to swap entries, MADV_FREE pages are dropped
    - Dirty pte states is moved to struct page – set_page_dirty()
  - __remove_mapping()
    - Dirty pages are not removed – protection for races
    - Remove from the page cache (including swap cache) – records the eviction time for file cache workingset_eviction()
Memory reclaim

- Many types of SLAB allocations are reclaimable
  - Dentry, inode cache etc...
  - Register their shrinkers
    - Not restricted to slab objects only
      ```c
      struct shrinker {
          unsigned long (*count_objects)(struct shrinker *,
                                          struct shrink_control *sc);
          unsigned long (*scan_objects)(struct shrinker *,
                                          struct shrink_control *sc);
          int seeks;       /* seeks to recreate an obj */
          long batch;     /* reclaim batch size, 0 = default */
          unsigned long flags;
          /* These are for internal use */
          struct list_head list;
          /* objs pending delete, per node */
          atomic_long_t *nr_deferred;
      };
      ```

- shrink_slab()
  - Invokes shrinkers – count_objects() to see how many are freeable, scan_objects will reclaim and age
  - Can be really inefficient because it is object rather than page based – internal fragmentation
Huge pages in Linux

- **Kernel mapping of physical memory**
  - Uses 1GB or 2MB huge pages when possible
  - Direct mapping, ioremap() for device memory ranges
- **Explicit hugepage usage – HugeTLBfs**
  - Pre-allocated in pools, accessible by several interfaces
  - Private or shared, no splitting, no swapping
  - Multiple sizes supported; page table sharing support
- **Transparent hugepage usage – THP**
  - Allocated implicitly, possible to prefer or disallow by hints
  - Anonymous, private (except fork+COW), can be split back to base pages and then swapped out
  - Shmem/tmpfs support – controlled via mount parameter
HugeTLBfs Usage

- **SysV shared memory segment**
  - `shmid = shmget(key, SIZE, SHM_HUGETLB | ...);
    addr = shmat(shmid, NULL, 0);
  - Since 3.8: alternative flags SHM_HUGE_2MB, SHM_HUGE_1GB, and SHM_HUGE_SHIFT

- **Anonymous mmap()**
  - `addr = mmap(NULL, SIZE, PROT_*,
    MAP_PRIVATE | MAP_ANONYMOUS | MAP_HUGETLB, -1, 0);
  - Since 3.8: same alternative flags as shmget()

- **Mount a special virtual filesystem**
  - `mount -t hugetlbfs none /dev/hugepages -o <pagesize=2M>
  - fd = open("/dev/hugepages/1", O_CREAT | O_RDWR, 0755);
    addr = mmap(NULL, SIZE, PROT_*, MAP_SHARED, fd, 0);

- **Use libhugetlbfs library – man libhugetlbfs(7)**
  - `get_huge_pages(), get_hugepage_region()`
  - LD_PRELOAD for legacy applications
  - Text, data, malloc(), shared memory backed by hugepages

- **Useful tools: hugeadm, hugectl**
HugeTLBfs Internals

- **Hugetlb pages reserved on mmap()**
  - Reservation system tracks
  - Cheaper mmap(), potentially better NUMA placement

- **Private mappings can fork() + COW fault at any time**
  - Potential copies not reserved – fork() won’t fail
  - COW will try to allocate without reserve, but that can fail
    - Child COW alloc fails → SIGBUS
    - Parent COW alloc fails → child’s mapping removed, fault → SIGBUS

- **Reservations don’t guarantee NUMA placement**

- **Shared page tables**
  - Scenario: many processes mapping the same region of 2MB hugepages
  - Each 1GB large region (fully populated or not) would have 4KB pmd-level page table for each process
  - This page table will be shared when mappings are properly aligned, reducing the memory usage
  - Example: Memory usage of (system running Oracle) by page tables 150GB without vs 1GB with HugeTLB
THP

- First page fault in each huge-page aligned part of vma (last-level page table does not yet exist)
  - Read fault → map a shared “THP zero page” first
- During `mmap()` with MAP_POPULATE
- Khugepaged merge small pages into THP in the background
- If allocating huge page fails, fallback to mapping a page table with a single PTE entry for a base page
- COW – alloc+copy whole huge page, fallback to alloc+copy many base pages mapped by PTEs
- THP may be mapped by ptes partially – mprotect, unmap
- Fault in resp. merging policy fine tuning
  - `madvise(MADV_HUGEPAGE, MADV_NOHUGEPAGE)`
  - `prctl(PR_SET_THP_DISABLE)`
  - Global setting - `/sys/kernel/mm/transparent_hugepage/`
    - allways, madvise, never for global setting
    - allways, madvise, never, defer, defer+madvise for khugepaged
  - Shmem controlled by mount option
    - allways, advise, never, within_size
THP - khugepaged

- Kernel thread to scan address space
- `/sys/kernel/mm/transparent_hugepage/khugepaged/*`
- Merges sparsely populated PMD
  - `max_ptes_none` – how much more to allocate
  - `max_ptes_swap` – how much to swap in
  - `pages_to_scan, scan_sleep_millisecs` – how much/often to scan
- **Pros**
  - Fault in is latency sensitive while deferred context might try harder
  - VMAs might grow over time (e.g. stack, shmem file)
  - Reduces memory fragmentation
- **Cons**
  - Background interference – e.g. mmap_sem lock contention
  - Jumps in too late for short lived mappings
THP related statistics

/proc/meminfo
AnonHugePages: 1929216 kB
ShmemHugePages, ShmemPmdMapped

/proc/vmstat
thp_fault_alloc 174171
thp_fault_fallback 61457
thpCollapse_alloc 35893
thpCollapse_alloc_failed 703
thp_file_alloc 0
thp_file_mapped 0

/sys/kernel/mm/transparent_hugepage/khugepaged
full_scans: 751
pages_collapsed: 26272
Memory cgroup controller

- Hierarchical accounting of user memory (page faults) and opt-in kernel allocations \_\_GFP\_ACCOUNT (e.g. kernel stacks)
- Represented by struct mem_cgroup
  - Page counters for charges
  - Own LRUs – mem_cgroup::nodeinfo – per NUMA node
- Memory is charged when the page is added to the LRU list or in the page allocator for kernel allocations - try\_charge()
  - Charge is propagated up the hierarchy
  - Performs direct reclaim on the memcg which hits hard limit - mem\_cgroup\_shrink\_node()
    - shrink\_node\_memcg() - iterates over all lruvecs under given mem\_cgroup in a round robin manner
    - Code shared with the standard reclaim – some exceptions, we wait for Dirty pages, swappiness is not ignored even under hard memory pressure etc...
  - Schedules “background” reclaim when high limit is reached – reclaim\_high() when returning to the user space
- Low/Min limit protects memory cgroup from reclaim
Memory cgroup controller

• Charge fails and marks OOM context when the reclaim fails
  • Only kills tasks from the memcg hierarchy
• Memcg OOM killer can be handled from userspace
  • `echo 1 > memory.oom_control` – disables oom killer, the kernel will notify listener on this file and waits for situation to change - `mem_cgroup_oom_synchronize()`
  • Admin may increase the limit or kill a task manually
• Only page faults are triggering memcg OOM killer
  `pagefault_out_of_memory()`
  • Used to trigger it from the charge path but this could deadlock easily – charge context can hold locks which might be needed for OOM to make a forward progress
Questions?
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