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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/
- **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

- **Syscalls 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_to_pfn()` – 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 0x0000000100000000-0x000000403fffefff] 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 pfn_to_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`

```
[    0.000000] ACPI: SRAT: Node 0 PXM 0 [mem 0x00000000-0xbfffffff]
[    0.000000] ACPI: SRAT: Node 0 PXM 0 [mem 0x100000000-0x103fffffff]
[    0.000000] ACPI: SRAT: Node 1 PXM 1 [mem 0x1040000000-0x203fffffff]
[    0.000000] ACPI: SRAT: Node 2 PXM 2 [mem 0x2040000000-0x303fffffff]
[    0.000000] ACPI: SRAT: Node 3 PXM 3 [mem 0x3040000000-0x403fffffff]
[    0.000000] NUMA: Node 0 [mem 0x00000000-0xbfffffff] + [mem 0x100000000-0x103fffffff] -> [mem 0x00000000-0x103fffffff]
[    0.000000] NODE_DATA(0) allocated [mem 0x103ffde000-0x103fffffff]
[    0.000000] NODE_DATA(1) allocated [mem 0x203ffde000-0x203fffffff]
[    0.000000] NODE_DATA(2) allocated [mem 0x303ffde000-0x303fffffff]
[    0.000000] 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

        ```
        0000000 – BFFFFFFF user space
        C000000 – F7xxxxxx kernel (direct mapping)
        F7xxxxx – FF7FE0000 vmalloc
        FF80000 – FFC000000 kmap
        ```
    - 64b – negative address space kernel, positive userspace

      ```
      0000000000000000 – 00007FFFFFFFFFFF – user space
      FFFF880000000000 – FFFFC7FFFFFFFFFF – direct mapping
      FFFFC90000000000 – FFFFE8FFFFFFFFFF – 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**

```
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 maped 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 unmap 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 mappnig – `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()`)

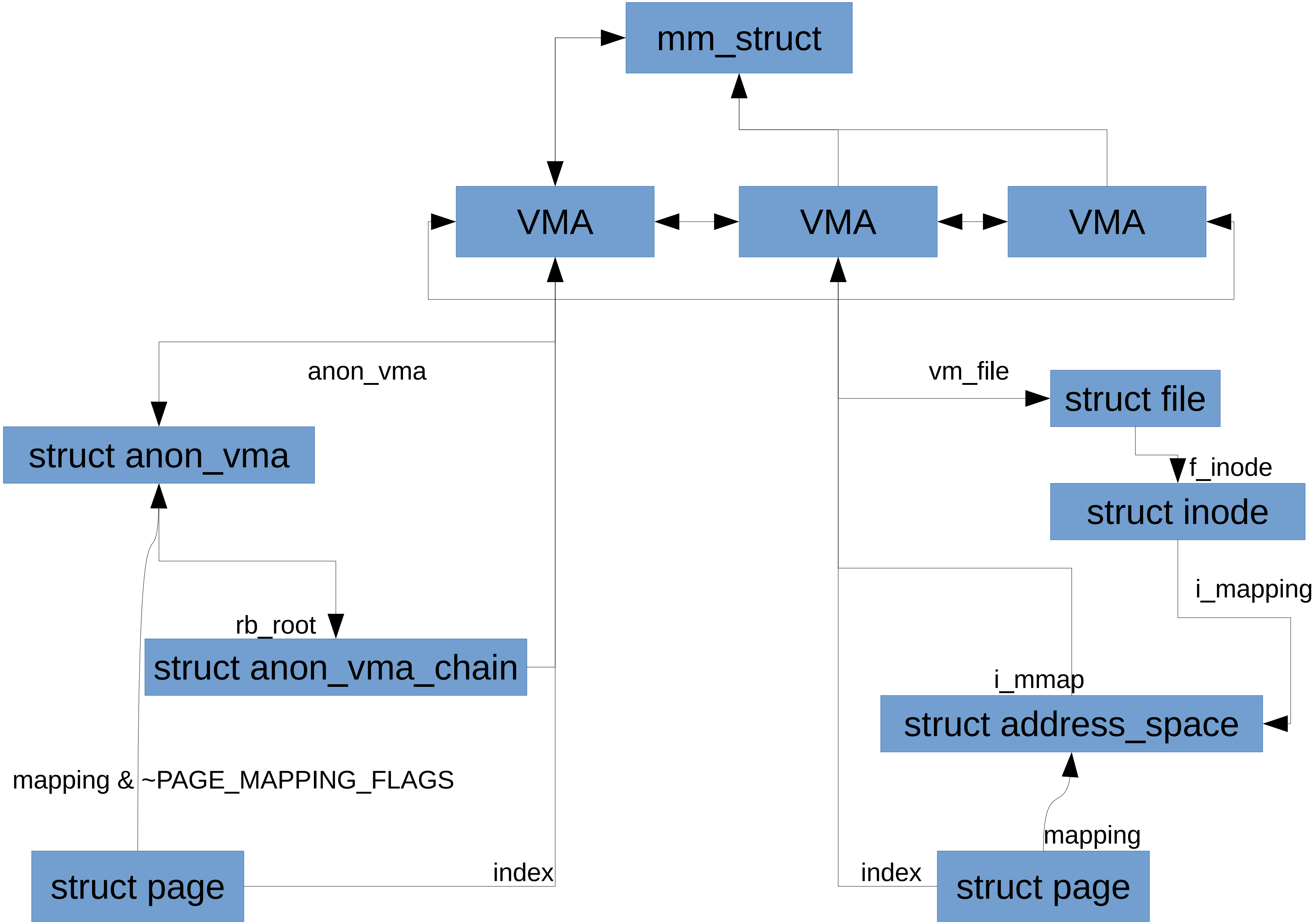
page → VMA mappings

- **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^{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 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()`

```
$ cat /proc/buddyinfo
Node 0, zone      DMA      1      0      1      0      1      1      1      0      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_CLUSTER_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`**

```
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

```
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);`
  - Sice 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
thp_collapse_alloc 35893
thp_collapse_alloc_failed 703
thp_file_alloc 0
thp_file_mapped 0
```

```
thp_split_page 5542
thp_split_page_failed 4
thp_deferred_split_page 199
thp_split_pmd 26504
thp_split_pud 0
thp_zero_page_alloc 1
thp_zero_page_alloc_failed 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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