Memory management in Linux

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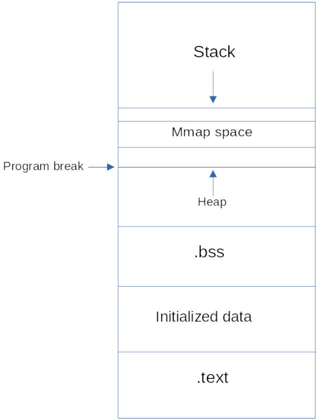
Process memory space



Process memory space

- Virtual memory map
  - Allocation and freeing of automatic variables on stack.
  - Mapping of zero pages to bss section to initialize static variables.
  - Malloc acquires memory through `brk/sbrk` and `mmap` system calls.

bss: Block Started by Symbol

Next up *Memory descriptor*

struct mm_struct(simplified)

```c
struct mm_struct
{
    struct{
        struct vm_are_struct *mmap;
        struct rb_root mm_rb;
        struct vm_are_struct *mmap_cache;
        atomic_t mm_users;
        int map_count;
        unsigned long start_code, end_code;
        unsigned long start_data, end_data;
        unsigned long start_brk, brk;
        unsigned long start_stack;
        struct mm_rss_stat rss_stat;
        unsigned long total_vm;
        spinlock_t page_table_lock;
    }
}
```

Some less talked about topics in C

- Allocation of dynamic memory on stack with alloca.
  - Allocates `size` bytes of space in the stack frame of the caller.

  ```
  #include <alloca.h>
  void *alloca(size_t size)
  ```
- Also introduction of variable sized arrays in C99.

```
for(i=0; i < n; i++)
{
    char foo[n+i];

    /* use foo */
}
```

- On each iteration, foo is dynamically created and automatically cleaned up when it falls out of scope.

Next up *paging*

Paging

What does a page represent?

- Kernel treats physical pages as the basic unit of memory management.
- Although processor can address anything as small as a byte or a word but the MMU deals in pages.
- Word size of a processor is an ambiguously defined term but usually it corresponds to the max size of the general purpose registers of the processor.

Page representation in software

```c
struct page {
    unsigned long flags;
    atomic_t _refcount; /* References to this page */
    atomic_t _mapcount; /* References by a page table*/
    unsigned long private;
    struct address_space *mapping;
    pgoff_t index;
    struct list_head lru;
}
```

simplified version

Organization of struct page

```
struct page {
    unsigned long flags;
    union {
        struct { /* For page cache and anonymous pages */
            ....
        };
        struct { /* Slab, slob, and slub*/
            ....
        };
        struct { /* Tail pages of compound pages */
            ....
        };
        struct { /* Page table pages */
            ....
        }; /* Followed by _mapcount, _refcount etc.*/
    }
}
```

struct page: Page cache and anonymous pages

```
struct page {
    unsigned long flags;
    struct {
        struct list_head lru;
        struct address_space *mapping;
        pgoff_t index;
        unsigned long private;
    };
    atomic_t _mapcount;
    atomic_t _refcount;
    unsigned long memcg_data;
}
```

struct page: Tail pages of compound pages

```c
struct page {
    unsigned long flags;
    struct {
        unsigned long compound_head;
        unsigned char compound_dtor;
        unsigned char compound_order;
        atomic_t compound_mapcount;
        unsigned int compound_nr;
    };
    atomic_t _mapcount;
    atomic_t _refcount;
    unsigned long memcg_data;
}
```

struct page: Page table pages

```
struct page {
    unsigned long flags;
    struct {
        unsigned long _pt_pad_1;
        pgtable_t pmd_huge_pte;
        unsigned long _pt_pad_2;
        struct mm_struct *pt_mm; /* For x86 pgds only */
        spinlock_t *ptl;
    };
    atomic_t _mapcount;
    atomic_t _refcount;
    unsigned long memcg_data;
}
```

Page flags

- There can be upto 28 page flags on a 64-bit system.
  - For eg. PG_dirty, PG_head, PG_mlocked, PG_active etc.
- The flags variable is declared an unsigned long so on:
  - 32-bit systems it is 32 bits long.
  - 64-bit systems it is 64 bits long.
- The higher bits in the flags variable have been used to store the node and zone information of each page on NUMA systems.

Page flags layout

- No sparsemem:

```
- |        NODE       | ZONE | ... | FLAGS |
```

- classic sparse with space for node:

```
- | SECTION | NODE | ZONE | ... | FLAGS |
```

- classic sparse no space for node:

```
- | SECTION |     ZONE     | ... | FLAGS |
```

- Also the variants with `last_cpu_id` exist.

Page size

Definitions

from arch/arm64/include/asm/page-defs.h

```
#define PAGE_SHIFT (CONFIG_ARM64_PAGE_SHIFT)
#define PAGE_SIZE (1 << PAGE_SHIFT)
```

Kconfig options for page size

- Configuring page sizes by config options.
- from arch/arm64/Kconfig

```
config ARM64_PAGE_SHIFT
    int
    default 16 if ARM64_64K_PAGES
    default 14 if ARM64_16K_PAGES
    default 12 /* For 4KB pages */
```

Constraints with increase size of struct page

- Size of page struct on arm64 is usually ~ 60 bytes(0x3C).
- Any increase in struct page size is felt around a million times.

Let's calculate

- In a 4GB RAM system with 4KB pages we will have 2^20 physical pages.
- That means around 60 MB would be consumed by page structures.

Memory Folios

- Pages are going to be replaced by memory folios soon.

Next up Kernel stack

Kernel Stack

- Problem and Solution

Kernel Stack

Problem at hand

- Each process has its own stack for use when it is running in the kernel; in current kernels, that stack is sized at either 8KB or (on 64-bit systems) 16KB of memory.
- The stack lives in directly-mapped kernel memory, so it must be physically contiguous. That requirement alone can be problematic since, as memory gets fragmented, finding two or four physically contiguous pages can become difficult.

Userspace view

- Can be viewed from userspace with:
  - `cat /proc/<pid>/stack`.

Kernel stack (continued)

Things to lookout for

- Check autmatic variable allocation to avoid stack overflows.
- Recursion not allowed in the kernel.

Defaults currently set.

- Size of stack: Configured by `THREAD_SIZE` macro.
  - Defined in `arch/arm64/include/asm/memory.h`
- For `arm64` the default size is:
  - `16KB` if `KASAN` is disabled
  - `32KB` if `KASAN` is enabled.

Solution

- Virtual mapping of stacks

Common memory allocation APIs

- kmalloc : contiguous physical addresses.
- vmalloc : contiguous virtual addresses(may not be physically contiguous)
- kvmalloc : Calls kmalloc and if it fails calls vmalloc.

Common use cases.

- kmalloc : the most commonly used API to get subpage sized memory.
- vmalloc : only valid use case in the kernel at the moment is to allocate memory when kernel modules are loaded.

kmalloc internals

```
void *kmalloc(size_t size, gfp_t flags)
```

- It might allocate more than the programmer asked for but it will atleast allocate the requested size.
- Max and min allocation capping are explained later using code.
- Declared with `__always_inline` to boost the fastpath allocations.
  - This attribute inlines the function independent of any restrictions that otherwise apply to inlining
- Notice the difference with `inline` here since we don't want to leave it at compiler's discretion or the optimization level specified.

kmalloc: min and max limits on allocation

- Min: 8 bytes
- Max: 4 MB, well actually 2 MB(explained later).

`from include/linux/slab.h`

```
#define MAX_ORDER 11
#define KMALLOC_SHIFT_HIGH (PAGE_SHIFT+1) // 13
#define KMALLOC_SHIFT_MAX (MAX_ORDER+PAGE_SHIFT-1) // 22
#define KMALLOC_SHIFT_LOW 3
```

kmalloc: min and max limits on allocation

from include/linux/slab.h

```
/* Maximum allocatable size = 4MB */
#define KMALLOC_MAX_SIZE (1 << KMALLOC_SHIFT_MAX)
/* Max size for which we can use a slab cache = 8KB */
#define KMALLOC_CACHE_SIZE (1 << KMALLOC_SHIFT_HIGH)
/* Max order allocatable via the slab allocator = 10 */
#define KMALLOC_MAX_ORDER (KMALLOC_SHIFT_MAX - PAGE_SHIFT)
/* Minimum allocatable size = 8 bytes */
#define KMALLOC_MIN_SIZE (1 << KMALLOC_SHIFT_LOW)
```

Allocation flags

- Action modifiers: Specify how the kernel is supposed to allocate memory.
- Zone modifiers: Specify from which zone to allocate the memory.
- Type modifiers: Combination of action and zone modifiers as needed by a certain type of memory.

Examples

- Action modifiers: `__GFP_WAIT`, `__GFP_NOFAIL`, `__GFP_COMP` etc.
- Zone modifiers: `__GFP_DMA`, `__GFP_HIGHMEM` etc.
- Type modifiers: `GFP_ATOMIC`, `GFP_KERNEL`, `GFP_USER` etc.

Commonly used type modifier flags

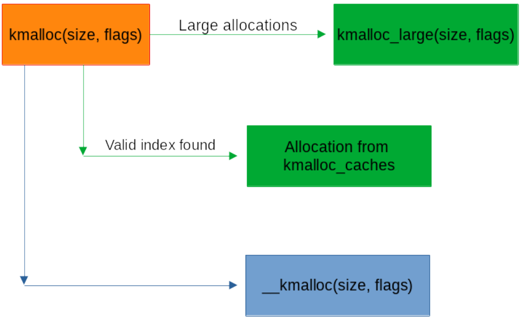
- `GFP_KERNEL`: Normal allocation and might block. To be used in process context when we can sleep.
- `GFP_ATOMIC`: High priority and cannot sleep. Can be used in interrupt handlers.
- `GFP_USER`: Might block. Used to allocate memory for userspace processes.

GFP stands get free pages

Expansion of common modifiers

- `GFP_ATOMIC`: `(__GFP_HIGH)`
- `GFP_KERNEL`: `(__GFP_WAIT|__GFP_IO|__GFP_FS)`
- `GFP_USER`: `(__GFP_WAIT|__GFP_IO|__GFP_FS)`

kmalloc code flow



Legend:

Green: Compile time optimized paths.
Blue: Non-compile time optimized paths.

kmalloc code walkthrough

```
static void *kmalloc(size_t size, gfp_t flags)
{
    if (__builtin_constant_p(size)) {
        unsigned int index;
        if (size > KMALLOC_MAX_CACHE_SIZE)
            return kmalloc_large(size, flags);
        index = kmalloc_index(size);

        if (!index)
            return ZERO_SIZE_PTR;

        return kmem_cache_alloc_trace(
            kmalloc_caches[kmalloc_type(flags)][index],
            flags, size);
    }
    return __kmalloc(size, flags);
} /* from include/linux/slab.h */
```

kmalloc code walkthrough(continued)

__builtin_constant_p

- You can use the built-in function `__builtin_constant_p` to determine if a value is known to be constant at compile time and hence that GCC can perform constant-folding on expressions involving that value.

Ref link

What is constant-folding?

- Expressions with constant operands can be evaluated at compile time, thus improving run-time performance and reducing code size by avoiding evaluation at compile-time.
- Programmers generally do not write expressions such as `(3 + 5)` directly, but these expressions are relatively common after macro expansion and other optimizations such as constant propagation.
- Since kmalloc would be inlined at all places due to **`__always_inline`** attribute we can optimize a lot of compile time determined constant size allocations.

Constant folding

Constant propagation

kmalloc code walkthrough(continued)

- `KMALLOC_MAX_CACHE_SIZE`
  - Max size for which we use a slab cache.
  - For SLUB its value is 8KB.

```
static void *kmalloc_large(size_t size, gfp_t flags)
{
    unsigned int order = get_order(size);
    return kmalloc_order_trace(size, flags, order);
}
```

kmalloc code walkthrough(continued)

```
static void *kmalloc_order_trace(size, flags, order)
{
    return kmalloc_order(size, flags, order);
}
```

Argument types omitted intentionally.

kmalloc code walkthrough(continued)

```
void *kmalloc_order(size, flags, order)
{
    void *ret;
    struct page *page;

    flags |= __GFP_COMP;
    page = alloc_pages(flags, order);
    ret = page ? page_address(page) : NULL;
    ret = kasan_kmalloc_large();
    kmemleak_alloc(ret, size, 1, flags);
    return ret;
}
EXPORT_SYMBOL(kmalloc_order)
```

kmalloc code walkthrough(continued)

kmalloc_index()

- Figure out which kmalloc slab an allocation of a certain size belongs to.

```
#define kmalloc_index(s) __kmalloc_index(s, true)
```

kmalloc code walkthrough(continued)

`from include/linux/slab.h`

```
unsigned int __kmalloc_index(size, size_is_constant)
{
    /* 0 = zero alloc */
    /* 1 = 65 to 96 bytes */
    /* 2 = 129 to 192 bytes */
    /* n = 2^(n-1)+1 to 2^n bytes */
}
```

Let's checkout `kmalloc_info` to understand this.

ZERO_SIZE_PTR

- ZERO_SIZE_PTR will be returned for zero sized kmalloc requests.

```
#define ZERO_SIZE_PTR ((void *)16)
#define ZERO_OR_NULL_PTR(x) ((unsigned long)(x) <= \
                (unsigned long)ZERO_SIZE_PTR)
```

kmalloc code walkthrough(continued)

```
static void *kmem_cache_alloc_trace(
            the_kmem_cache, flags, size)
{
    void *ret = kmem_cache_alloc(the_kmem_cache, flags);
    ret = kasan_malloc(the_kmem_cache, ret, size, flags);

    return ret;
}
```

Showing the kmalloc slab caches

```
$ sudo cat /proc/slabinfo
```

```
kmalloc-8k   <- 8KB = KMALLOC_MAX_CACHE_SIZE
kmalloc-4k
kmalloc-2k
kmalloc-1k
kmalloc-512
kmalloc-256
kmalloc-192 <- Non-power 2 sized kmalloc cache
kmalloc-128
kmalloc-96  <- Non-power 2 sized kmalloc cache
kmalloc-64
kmalloc-32
kmalloc-16
kmalloc-8  <- 8 bytes = KMALLOC_MIN_SIZE
```

kmalloc code walkthrough(continued)

if CONFIG_ZONE_DMA is defined

```
enum kmalloc_cache_type kmalloc_type(flags)
{
    if(likely((flags & (__GFP_DMA|__GFP_RECLAIM)) == 0))
        return KMA_NORMAL;

    return flags & __GFP_DMA ? KMA_DMA : KMA_RECLAIM;
}
```

KMA: KMALLOC

kmalloc code walkthrough(continued)

```
void *__kmalloc(size, flags)
{
    struct kmem_cache *s;
    void *ret;

    if(unlikely(size > KMALLOC_MAX_CACHE_SIZE))
        return kmalloc_large(size, flags);

    s = kmalloc_slab(size, flags);
    ret = slab_alloc(s, flags, _RET_IP_);
    ret = kasan_malloc(s, ret, size, flags);

    return ret;
}
EXPORT_SYMBOL(__kmalloc);
```

kmalloc code walkthrough(continued)

```
struct kmem_cache *kmalloc_slab(size, flags)
{
/* Find the kmem_cache structure that serves a
 * given size of allocation. Refers to a look up
 * table for sizes < 192 bytes and does an fls for
 * sizes > 192. Look up table is called size_index.
 * Similar to kmalloc_index */
/* I think these two routines can be merged */
}
```

fls: find last(most-significant) bit set.

kmalloc code walkthrough(continued)

from mm/slub.c

```
static void *slab_alloc(kmem_cache, flags,
            addr, size)
{
    return slab_alloc_node(kmem_cache, flags,
            NUMA_NO_NODE, addr, size);
}
```

kmalloc code walkthrough(continued)

from mm/slub.c

```
static void *slab_alloc_node(kmem_cache, flags,
            addr, size)
{
    /*read tid and cpu_slab ptr*/
    /*read freelist and slab page*/
    /*fastpath*/
    void *new_object = get_freepointer_safe(s, object);
    /*make sure we are on the right cpu*/
    prefetch_freepointer(kmem_cache_ptr, next_object);
    /*slowpath*/
    return __slab_alloc(kmem_cache_ptr, flags, node
            addr, kmem_cache_cpu_ptr);
}
```

Fastpath: kmalloc code walkthrough(continued)

```
void *get_freepointer_safe(kmem_cache_ptr, void *object)
{
    unsigned long freeptr_addr;
    void *p;

    freeptr_addr = (unsigned long)object + kcp->offset;
    copy_from_kernel_nofault(&p, (void **)freeptr_addr,
            sizeof(p));
    return p;
}
```

kcp: kmem_cache_ptr

Fastpath: kmalloc code walkthrough(continued)

```
long copy_from_kernel_nofault(dst, src, size)
{
    /* Assuming a black box for now.*/
}
```

Fastpath: kmalloc code walkthrough(continued)

```
void prefetch_freepointer(kmem_cache_ptr, void *obj)
{
    prefetch(obj + kcp->offset);
}

void prefetch(void *ptr)
{
    asm volatile("prfm pldl1keep, %a0\n" : : "p" (ptr));
}
```

- `%a`: for generating absolute addresses instead of labels.
- `"p"` : This is called a modifier in inline asm syntax.
  - An operand that is a valid memory address is allowed.
  - This is for “load address” and “push address” instructions.

prfm

- Instruction format `prfm <type><target><policy>`.
- `prfm` stands for Prefetch memory.
- `pldl1keep` can be divided into 3 parts:
  - `pld` : Type: Prefetch for load. Could be:
    - `pst` : Prefetch for store.
    - `pli` : Prefetch for instructions.
  - `l1/L1` : Target: Target is L1 cache.
    - Could be L1/L2/L3.
  - `keep` : Policy: Allocated in the cache normally.
    - Could be `strm` which is for data that is used only once.

Slowpath: kmalloc code walkthrough(continued)

```
void *__slab_alloc(kcp, flags, node,
        addr, kmem_cache_cpu_ptr)
{

}
```

To be continued with kfree()

- Thanks for attending!
- Let's do some Q & A.

kfree API

```c
void kfree(const void *ptr);
```

kfree codewalkthrough

from mm/slub.c

```
void kree(const void *x)
{
    struct page *page;
    void *object = (void *)x;

    /* handling if x is zero or null ptr*/

    page = virt_to_head_page(x);

    /* handling if page is not PageSlab*/

    slab_free(page->slab_cache, page, object, NULL,
        1, _RET_IP);
}
EXPORT_SYMBOL(kfree);
```