Process Address Space

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Summary of last lectures

- Tools: building, exploring, and debugging Linux kernel
- Core kernel infrastructure
    - syscall, module, kernel data structures
- Process management & scheduling
- Interrupt & interrupt handler
- Kernel synchronization
- Memory management

Today: process address space

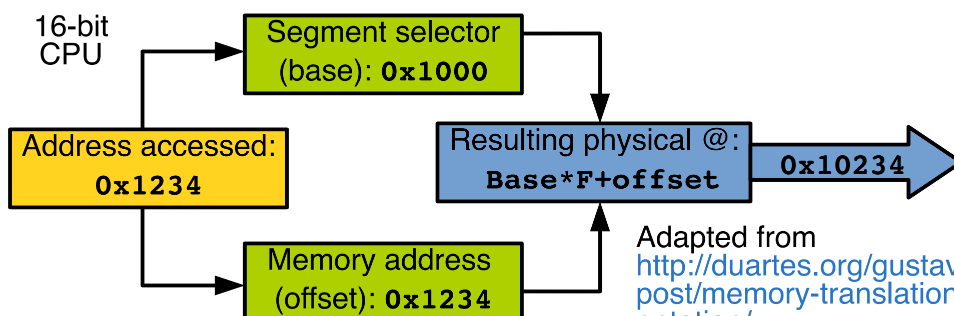
- Address space
- Memory descriptor: `mm_struct`
- Virtual Memory Area (VMA)
- VMA manipulation
- Page tables

Address space

- The memory that a process can access
  - Illusion that the process can access 100% of the system memory
  - With virtual memory, can be much larger than the actual amount of physical memory
- Defined by the process page table set up by the kernel

Address space

- A memory address is an index within the address spaces:
  - Identify a specific byte
- Each process is given a flat 32/64-bits address space
  - Not segmented



Adapted from http://duartes.org/gustavo/blog/post/memory-translation-and-segmentation/

Address space

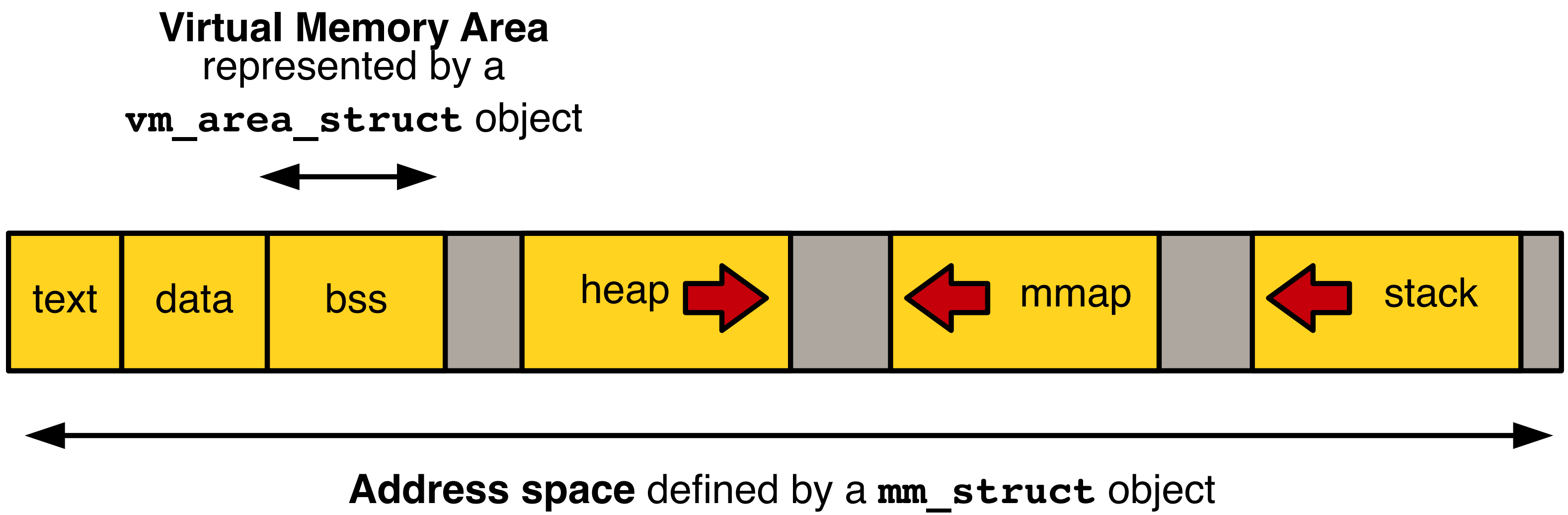
- **Virtual Memory Areas (VMA)**
  - Interval of addresses that the process has the right to access
  - Can be dynamically added or removed to the process address space
  - Associated permissions: read, write, execute
  - *Illegal access → segmentation fault*

```
$ cat /proc/1/maps      # or sudo pmap 1
55fe3bf02000-55fe3bff9000 r-xp 00000000 fd:00 1975429  /usr/lib/systemd/systemd
55fe3bffa000-55fe3c021000 r--p 000f7000 fd:00 1975429  /usr/lib/systemd/systemd
55fe3c021000-55fe3c022000 rw-p 0011e000 fd:00 1975429  /usr/lib/systemd/systemd
55fe3db4a000-55fe3ddfd000 rw-p 00000000 00:00 0        [heap]
7f7522769000-7f7522fd9000 rw-p 00000000 00:00 0
7f7523150000-7f7523265000 r-xp 00000000 fd:00 1979800  /usr/lib64/libm-2.25.so
7f7523265000-7f7523464000 ---p 00115000 fd:00 1979800  /usr/lib64/libm-2.25.so
7f7523464000-7f7523465000 r--p 00114000 fd:00 1979800  /usr/lib64/libm-2.25.so
7f7523465000-7f7523466000 rw-p 00115000 fd:00 1979800  /usr/lib64/libm-2.25.so
```

Address space

- **VMAs can contain:**
  - Mapping of the executable file code *(text section)*
  - Mapping of the executable file initialized variables *(data section)*
  - Mapping of the zero page for uninitialized variables *(bss section)*
  - Mapping of the zero page for the *user-space stack*
  - Text, data, bss for each *shared library* used
  - Memory-mapped files, shared memory segment, anonymous mappings (used by malloc)

Address space



Memory descriptor: `mm_struct`

- Address space in linux kernel: `struct mm_struct`

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

struct mm_struct {
    struct vm_area_struct *mmap;            /* list of VMAs */
    struct rb_root        mm_rb;            /* rbtree of VMAs */
    pgd_t                 *pgd;             /* page global directory */
    atomic_t              mm_users;         /* address space users */
    atomic_t              mm_count;         /* primary usage counters */
    int                   map_count;        /* number of VMAs */
    struct rw_semaphore   mmap_sem;         /* VMA semaphore */
    spinlock_t            page_table_lock;  /* page table lock */
    struct list_head      mmlist;           /* list of all mm_struct */
    unsigned long         start_code;       /* start address of code */
    unsigned long         end_code;         /* end address of code */
    unsigned long         start_data;       /* start address of data */
    unsigned long         end_data;         /* end address of data */
    unsigned long         start_brk;   /* start address of heap */
    unsigned long         end_brk;     /* end address of heap */
    unsigned long         start_stack; /* start address of stack */
    /* ... */
```

Memory descriptor: `mm_struct`

```
    unsigned long           arg_start;    /* start of arguments */
    unsigned long           arg_end;      /* end of arguments */
    unsigned long           env_start;    /* start of environment */
    unsigned long           total_vm;     /* total pages mapped */
    unsigned long           locked_vm;    /* number of locked pages */
    unsigned long           flags;        /* architecture specific data */
    spinlock_t              ioctx_lock;   /* Asynchronous I/O list lock */
    /* ... */
};
```

- `mm_users`: number of processes (threads) using the address space
- `mm_count`: reference count:
  - +1 if `mm_users` > 0
  - +1 if the kernel is using the address space

Memory descriptor: `mm_struct`

- `mmap` and `mm_rb` are respectively a linked list and a tree containing all the VMAs in this address space
    - List used to iterate over all the VMAs in an ascending order
    - Tree used to find a specific VMA
- All `mm_struct` are linked together in a doubly linked list
    - Through the `mmlist` field if the `mm_struct`

Allocating a memory descriptor

- A task memory descriptor is located in the `mm` field of the corresponding `task_struct`

```
/* linux/include/linux/sched.h */

struct task_struct {
    struct thread_info          thread_info;
    /* ... */
    const struct sched_class    *sched_class;
    struct sched_entity         se;
    struct sched_rt_entity      rt;
    /* ... */
    struct mm_struct            *mm;
    struct mm_struct            *active_mm;
    /* ... */
};
```

Allocating a memory descriptor

- Current task memory descriptor: `current->mm`
- During `fork()`, `copy_mm()` is making a copy of the parent memory descriptor for the child
  - `copy_mm()` calls `dup_mm()` which calls `allocate_mm()` → allocates a `mm` struct object from a slab cache
- Two threads sharing the same address space have the `mm` field of their `task_struct` pointing to the same `mm_struct` object
  - Threads are created using the `CLONE_VM` flag passed to `clone()` → `allocate_mm()` is not called

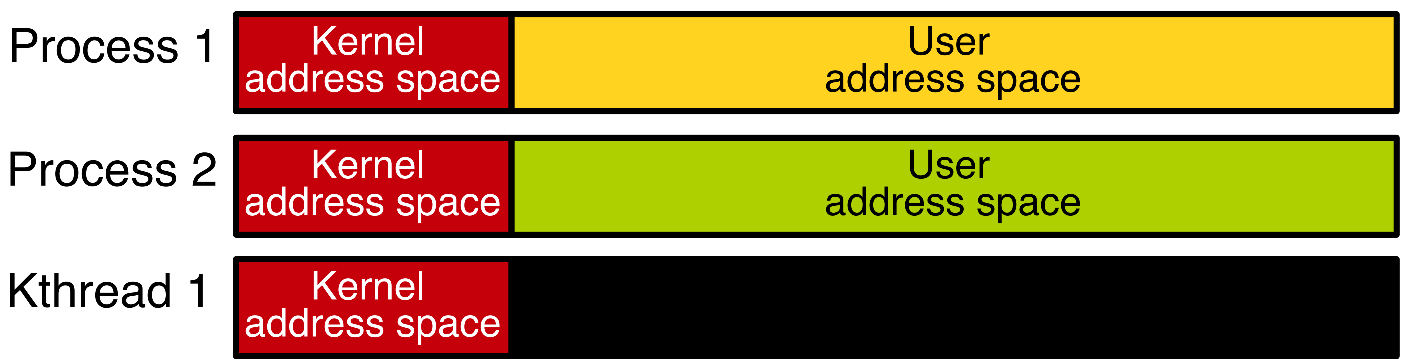
Destroying a memory descriptor

- When a process exits, `do_exit()` is called and it calls `exit_mm()`
    - Performs some housekeeping/statistics updates and calls `mmput()`

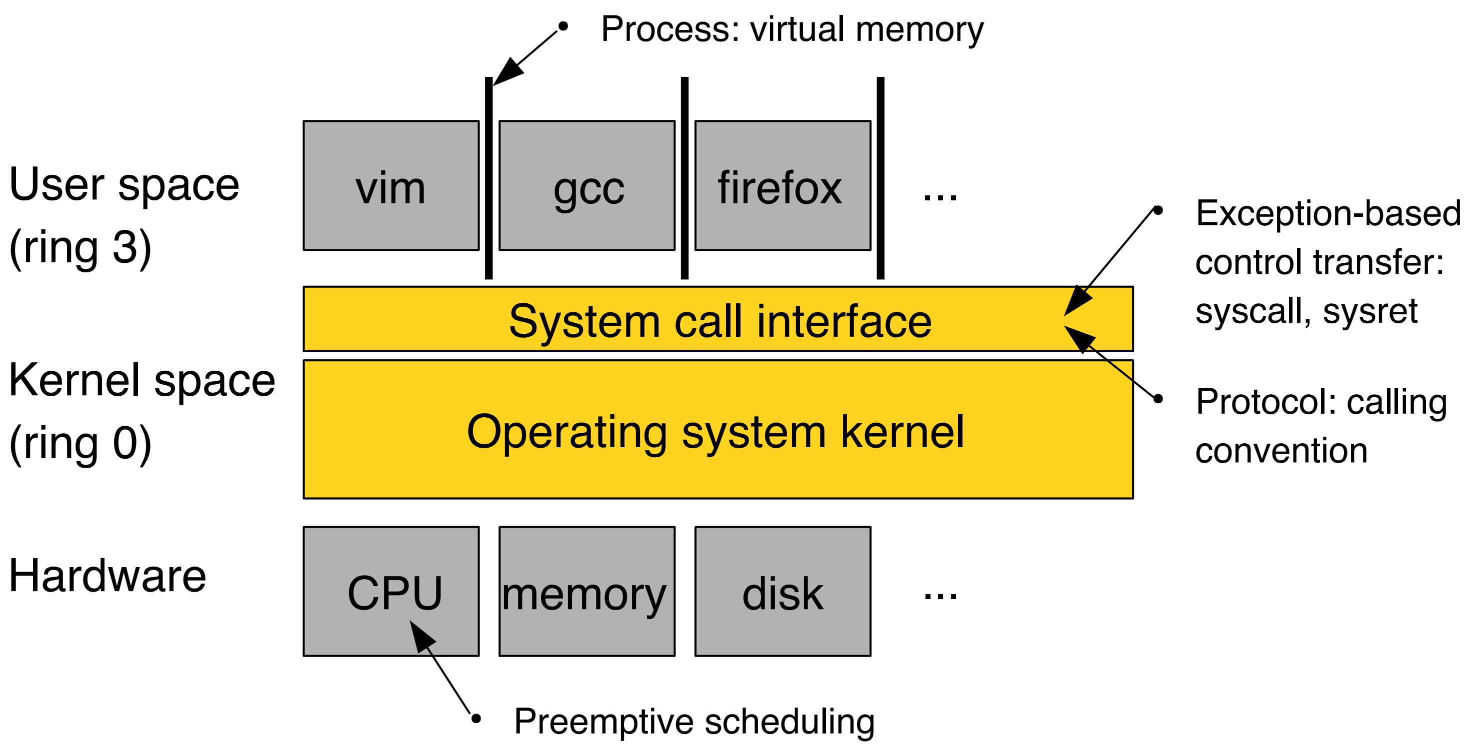
```
void mmput(struct mm_struct *mm) {
    might_sleep();
    if (atomic_dec_and_test(&mm->mm_users))
        __mmput(mm);
}
static inline void __mmput(struct mm_struct *mm) {
    /* ... */
    mmdrop(mm);
}
static inline void mmdrop(struct mm_struct *mm) {
    if (unlikely(atomic_dec_and_test(&mm->mm_count)))
        __mmdrop(mm);
}
void __mmdrop(struct mm_struct *mm) {
    /* ... */
    free_mm(mm);
}
```

The `mm_struct` and kernel threads

- Kernel threads do not have a user-space address space
  - `mm` field of a kernel thread `task_struct` is `NULL`



The `mm_struct` and kernel threads



The `mm_struct` and kernel threads

- However kernel threads still need to access the kernel address space
  - When a kernel thread is scheduled, the kernel notice its `mm` is `NULL` so it keeps the previous address space loaded (page tables)
  - Kernel makes the `active_mm` field of the kernel thread to point on the borrowed `mm_struct`
  - It is okay because the kernel address space is the same in all tasks

Review: Segmentation in x86

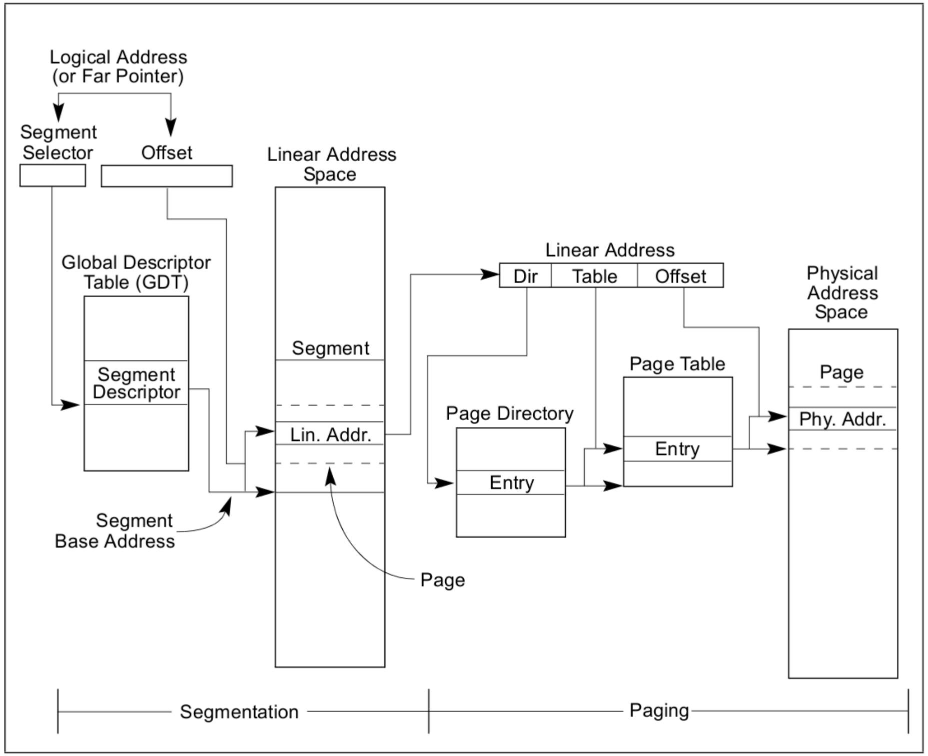


Figure 3-1. Segmentation and Paging

Review: Privilege levels of a segment

- CPL (current privilege level)
  - the privilege level of currently executing program
  - bits 0 and 1 in the `%cs` register
- RPL (requested privilege level)
  - an override privilege level that is assigned to a segment selector
  - a segment selector is a part (16-bit) of segment registers (e.g., `ds`, `fs`), which is an index of a segment descriptor and RPL
- DPL (descriptor privilege level)
  - the privilege level of a segment

Review: How isolation is enforced in x86?

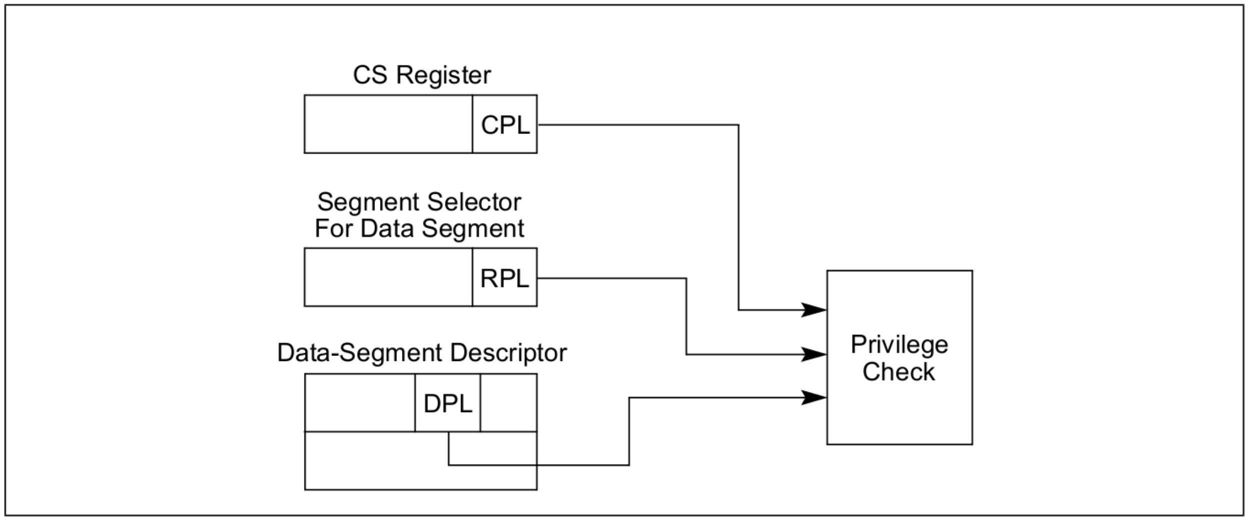


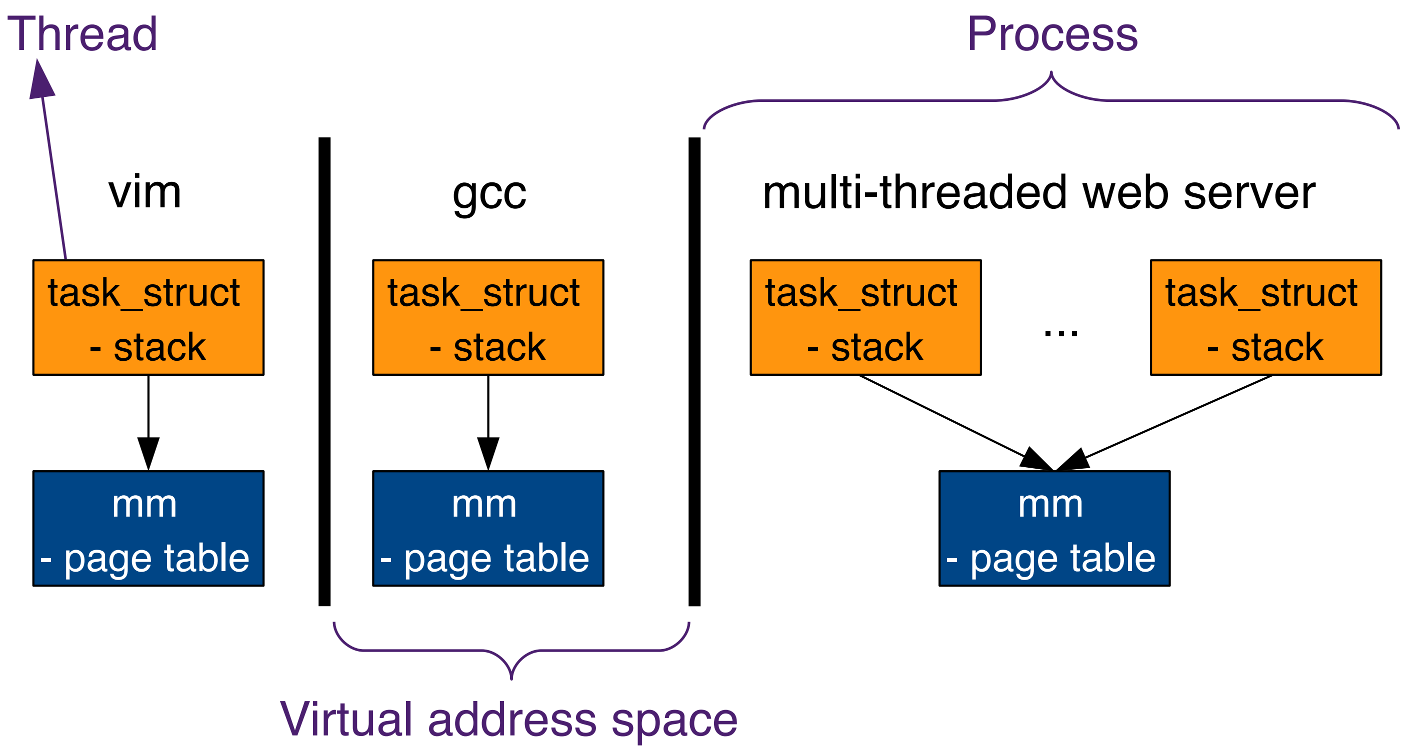
Figure 5-4. Privilege Check for Data Access

- Access is granted if `RPL` >= `CPL` and `DPL` >= `CPL`

Review: How to switch b/w rings (ring 0 ↔ ring 3)?

- Controlled transfer: system call
  - `int`, `sysenter` or `syscall` instruction set CPL to 0; change to KERNEL_CS and KERNEL_DS segments
  - set CPL to 3 before going back to user space; change to USER_CS and USER_DS segments

`mm_struct` vs. `task_struct`



Virtual Memory Area (VMA)

- Each line corresponds to one VMA

```
$ cat /proc/1/maps  # or sudo pmap 1
55fe3bf02000-55fe3bff9000 r-xp 00000000 fd:00 1975429  /usr/lib/systemd/systemd
55fe3bffa000-55fe3c021000 r--p 000f7000 fd:00 1975429  /usr/lib/systemd/systemd
55fe3c021000-55fe3c022000 rw-p 0011e000 fd:00 1975429  /usr/lib/systemd/systemd
55fe3db4a000-55fe3ddfd000 rw-p 00000000 00:00 0        [heap]
7f7522769000-7f7522fd9000 rw-p 00000000 00:00 0
7f7523150000-7f7523265000 r-xp 00000000 fd:00 1979800  /usr/lib64/libm-2.25.so
7f7523265000-7f7523464000 ---p 00115000 fd:00 1979800  /usr/lib64/libm-2.25.so
7f7523464000-7f7523465000 r--p 00114000 fd:00 1979800  /usr/lib64/libm-2.25.so
7f7523465000-7f7523466000 rw-p 00115000 fd:00 1979800  /usr/lib64/libm-2.25.so

# r = read
# w = write
# x = execute
# s = shared
# p = private (copy on write)
```

Virtual Memory Area (VMA)

- Each VMA is represented by an object of type `vm_area_struct`

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

struct vm_area_struct {
    struct                      mm_struct *vm_mm; /* associated address space (mm_struct) */
    unsigned long               vm_start;         /* VMA start, inclusive */
    unsigned long               vm_end;           /* VMA end, exclusive */
    struct vm_area_struct       *vm_next;         /* list of VMAs */
    struct vm_area_struct       *vm_prev;         /* list of VMAs */
    pgprot_t                    vm_page_prot;     /* access permissions */
    unsigned long               vm_flags;         /* flags */
    struct rb_node              vm_rb;            /* VMA node in the tree */
    struct list_head            anon_vma_chain;   /* list of anonymous mappings */
    struct anon_vma             *anon_vma;        /* anonmous vma object */
    struct vm_operation_struct *vm_ops;           /* operations */
    unsigned long               vm_pgoff;         /* offset within file */
    struct file                 *vm_file;         /* mapped file (can be NULL) */
    void                        *vm_private_data; /* private data */
    /* ... */
}
```

Virtual Memory Area (VMA)

- The VMA exists over `[vm start, vm end)` in the corresponding address space → size in bytes: `vm_end` - `vm_start`
- Address space is pointed by the `vm_mm` field (of type `mm_struct`)
- Each VMA is unique to the associated `mm_struct`
    - Two processes mapping the same file will have two different `mm_struct` objects, and two different `vm_area_struct` objects
    - Two threads sharing a `mm_struct` object also share the `vm_area_struct` objects

VMA flags

Flag	Effect on the VMA and Its Pages
`VM_READ`	Pages can be read from.
`VM_WRITE`	Pages can be written to.
`VM_EXEC`	Pages can be executed.
`VM_SHARED`	Pages are shared.
`VM_MAYREAD`	The `VM_READ` flag can be set.
`VM_MAYWRITE`	The `VM_WRITE` flag can be set.
`VM_MAYEXEC`	The `VM_EXEC` flag can be set.
`VM_MAYSHARE`	The `VM_SHARE` flag can be set.

VMA flags

Flag	Effect on the VMA and Its Pages
`VM_GROWSDOWN`	The area can grow downward.
`VM_GROWSUP`	The area can grow upward.
`VM_SHM`	The area is used for shared memory.
`VM_DENYWRITE`	The area maps an unwritable file.
`VM_EXECUTABLE`	The area maps an executable file.
`VM_LOCKED`	The pages in this area are locked.
`VM_IO`	The area maps a device's I/O space.
`VM_SEQ_READ`	The pages seem to be accessed sequentially.

VMA flags

Flag	Effect on the VMA and Its Pages
`VM_RAND_READ`	The pages seem to be accessed randomly.
`VM_DONTCOPY`	This area must not be copied on fork().
`VM_DONTEXPAND`	This area cannot grow via mremap().
`VM_RESERVED`	This area must not be swapped out.
`VM_ACCOUNT`	This area is an accounted VM object.
`VM_HUGETLB`	This area uses hugetlb pages.
`VM_NONLINEAR`	This area is a nonlinear mapping.

VMA flags

- Combining `VM_READ`, `VM_WRITE` and `VM_EXEC` gives the permissions for the entire area, for example:
  - Object code is `VM_READ` and `VM_EXEC`
  - Stack is `VM_READ` and `VM_WRITE`
- `VM_SEQ_READ` and `VM_RAND_READ` are set through the `madvise()` system call
  - Instructs the file pre-fetching algorithm read-ahead to increase or decrease its pre-fetch window

VMA flags

- `VM_HUGETLB` indicates that the area uses pages larger than the regular size
    - 2M and 1G on x86
    - Larger page size → less TLB miss → faster memory access

VMA operations

- `vm_ops` in `vm_area_struct` is a struct of function pointers to operate on a specific VMA

```
/* linux/include/linux/mm.h */
struct vm_operations_struct {
    /* called when the area is added to an address space */
    void (*open)(struct vm_area_struct * area);

    /* called when the area is removed from an address space */
    void (*close)(struct vm_area_struct * area);

    /* invoked by the page fault handler when a page that is
     * not present in physical memory is accessed*/
    int (*fault)(struct vm_area_struct *vma, struct vm_fault *vmf);

    /* invoked by the page fault handler when a previously read-only
     * page is made writable */
    int (*page_mkwrite)(struct vm_area_struct *vma, struct vm_fault *vmf);
    /* ... */
}
```

VMA manipulation: `find_vma()`

```
/* linux/mm/mmap.c */

/* Look up the first VMA which satisfies  addr < vm_end,  NULL if none. */
struct vm_area_struct *find_vma(struct mm_struct *mm, unsigned long addr)
{
    struct rb_node *rb_node;
    struct vm_area_struct *vma;

    /* Check the cache first. */
    vma = vmacache_find(mm, addr);
    if (likely(vma))
        return vma;

    rb_node = mm->mm_rb.rb_node;

    while (rb_node) {
        struct vm_area_struct *tmp;

        tmp = rb_entry(rb_node, struct vm_area_struct, vm_rb);
```

VMA manipulation: `find_vma()`

```
        if (tmp->vm_end > addr) {
            vma = tmp;
            if (tmp->vm_start <- addr)
                break;
            rb_node = rb_node->rb_left;
        } else
            rb_node = rb_node->rb_right;
    }

    if (vma)
        vmacache_update(addr, vma);
    return vma;
}
```

VMA manipulation

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

/* Look up the first VMA which satisfies  addr < vm_end,  NULL if none. */
struct vm_area_struct *find_vma(struct mm_struct *mm, unsigned long addr);

/*
 * Same as find_vma, but also return a pointer to the previous VMA in *pprev.
 */
struct vm_area_struct *
find_vma_prev(struct mm_struct *mm, unsigned long addr,
              struct vm_area_struct **pprev);

/* Look up the first VMA which intersects the interval start_addr..end_addr-1,
   NULL if none.  Assume start_addr < end_addr. */
struct vm_area_struct * find_vma_intersection(struct mm_struct * mm,
              unsigned long start_addr, unsigned long end_addr);
```

Creating an address interval

- `do_mmap()` is used to create a new linear address interval:
  - Can result in the creation of a new VMAs
  - Or a merge of the create area with an adjacent one when they have the same permissions

```
/*
 * The caller must hold down_write(&current->mm->mmap_sem).
 */
unsigned long do_mmap(struct file *file, unsigned long addr,
            unsigned long len, unsigned long prot,
            unsigned long flags, vm_flags_t vm_flags,
            unsigned long pgoff, unsigned long *populate,
            struct list_head *uf);
```

Creating an address interval

- `prot` specifies access permissions for the memory pages

Flag	**Effect on the new interval**
`PROT_READ`	Corresponds to `VM_READ`
`PROT_WRITE`	Corresponds to `VM_WRITE`
`PROT_EXEC`	Corresponds to `VM_EXEC`
`PROT_NONE`	Cannot access page

Creating an address interval

- `flags` specifies the rest of the VMA options

Flag	Effect on the new interval
`MAP_SHARED`	The mapping can be shared.
`MAP_PRIVATE`	The mapping cannot be shared.
`MAP_FIXED`	The new interval must start at the given address addr.
`MAP_ANONYMOUS`	The mapping is not file-backed, but is anonymous.
`MAP_GROWSDOWN`	Corresponds to `VM_GROWSDOWN`.

Creating an address interval

- `flags` specifies the rest of the VMA options

Flag	Effect on the new interval
`MAP_DENYWRITE`	Corresponds to `VM_DENYWRITE`.
`MAP_EXECUTABLE`	Corresponds to `VM_EXECUTABLE`.
`MAP_LOCKED`	Corresponds to `VM_LOCKED`.
`MAP_NORESERVE`	No need to reserve space for the mapping.
`MAP_POPULATE`	Populate (prefault) page tables.
`MAP_NONBLOCK`	Do not block on I/O.

Creating an address interval

- On error `do_mmap()` returns a negative value
- On success
  - The kernel tries to merge the new interval with an adjacent one having same permissions
  - Otherwise, create a new VMA
  - Returns a pointer to the start of the mapped memory area
- `do_mmap()` is exported to user-space through `mmap2()`

```
void *mmap2(void *addr, size_t length, int prot,
            int flags, int fd, off_t pgoffset);
```

Removing an address interval

- Removing an address interval is done through do munmap()

```
/* linux/include/linux/mm.h */
int do_munmap(struct mm_struct *, unsigned long, size_t);
```

- Exported to user-space through munmap()

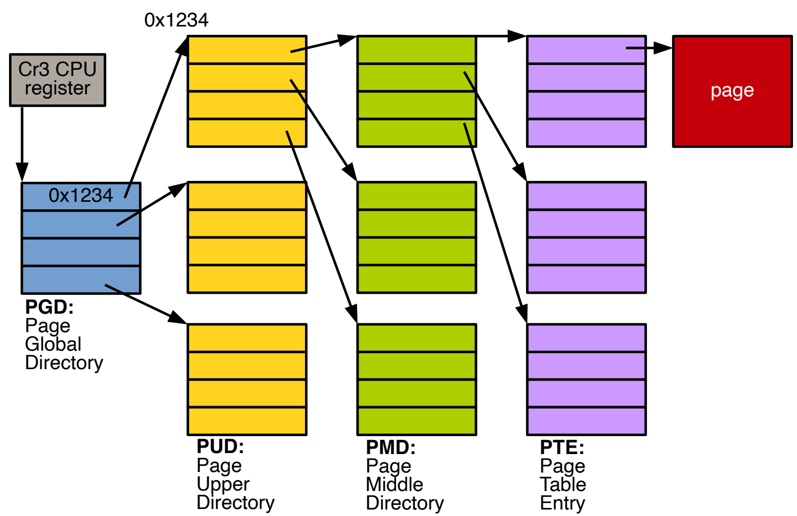
```
int munmap(void *addr, size_t len);
```

Page tables

- Linux enables paging early in the boot process
  - All memory accesses made by the CPU are virtual and translated to physical addresses through the page tables
  - Linux set the page tables and the translation is made automatically by the hardware (MMU) according to the page tables content
- The address space is defined by VMAs and is sparsely populated
  - One address space per process → one page table per process
  - Lots of “empty” areas

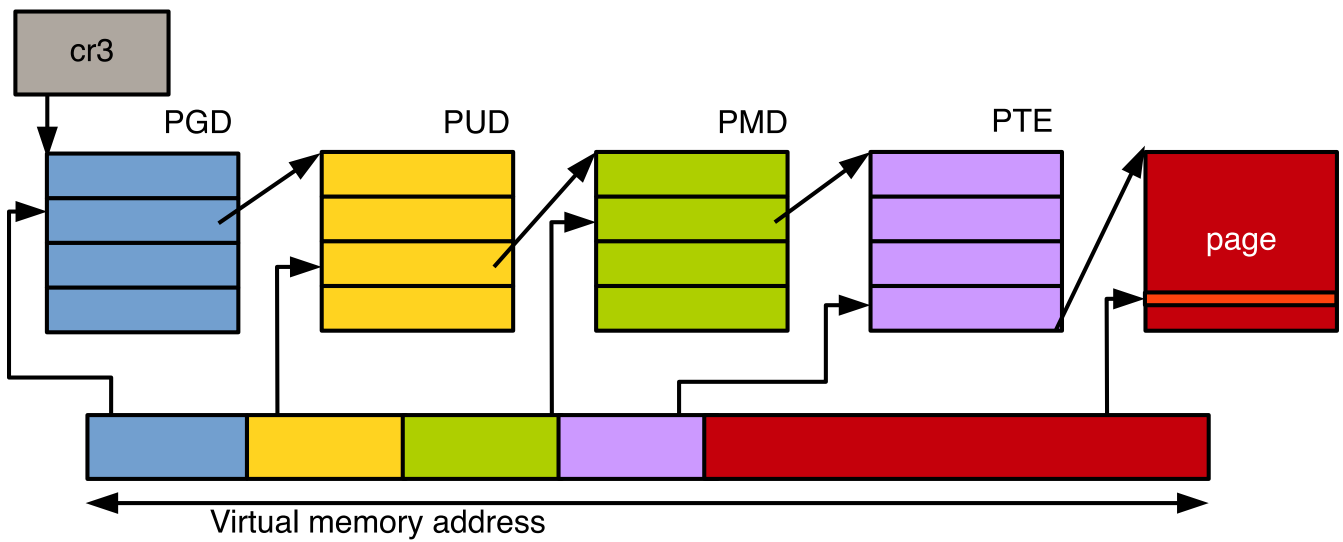
Page tables

```
/* linux/include/linux/mm types.h */
struct mm_struct {
    struct vm_area_struct *mmap;           /* list of VMAs */
    struct rb_root        mm_rb;           /* rbtree of VMAs */
    pgd_t                 *pgd;            /* page global directory */
    /* ... */
};
```



Page tables

- Address translation is performed by the hardware (MMU)



Virtual address map in linux

```
0000000000000000 - 00007fffffffffff (=47 bits) user space, different per mm
hole caused by [47:63] sign extension
ffff800000000000 - ffff87ffffffffff (=43 bits) guard hole, reserved for hypervisor
ffff880000000000 - ffffc7ffffffffff (=64 TB)   **direct mapping of all phys. memory**
ffffc80000000000 - ffffc8ffffffffff (=40 bits) hole
ffffc90000000000 - ffffe8ffffffffff (=45 bits) vmalloc/ioremap space
ffffe90000000000 - ffffe9ffffffffff (=40 bits) hole
ffffea0000000000 - ffffeaffffffffff (=40 bits) virtual memory map (1TB)
... unused hole ...
ffffec0000000000 - fffffbffffffffff (=44 bits) kasan shadow memory (16TB)
... unused hole ...
                    vaddr_end for KASLR
fffffe0000000000 - fffffe7fffffffff (=39 bits) cpu_entry_area mapping
fffffe8000000000 - fffffeffffffffff (=39 bits) LDT remap for PTI
ffffff0000000000 - ffffff7fffffffff (=39 bits) %esp fixup stacks
... unused hole ...
ffffffef00000000 - fffffffeffffffff (=64 GB)   EFI region mapping space
... unused hole ...
ffffffff80000000 - ffffffff9fffffff (=512 MB) kernel text mapping, from phys 0
ffffffffa0000000 - fffffffffeffffff (1520 MB) module mapping space
[fixmap start]   - ffffffffff5fffff          kernel-internal fixmap range
ffffffffff600000 - ffffffffff600fff (=4 kB)   legacy vsyscall ABI
ffffffffffe00000 - ffffffffffffffff (=2 MB)   unused hole
```

Further readings

- Introduction to Memory Management in Linux
- 20 years of Linux virtual memory
- Linux Kernel Virtual Memory Map
- Kernel page-table isolation
- Addressing Meltdown and Spectre in the kernel
- Meltdown and Spectre
- Meltdown Attack Lab

Further readings

- Supporting bigger and heterogeneous memory efficiently
  - AutoNUMA, Transparent Hugepage Support, Five-level page tables
  - Heterogeneous memory management
- Optimization for virtualization
  - Kernel same-page merging (KSM)
  - MMU notifier

Next class

- Virtual File System