Operating Systems II

Memory Management

Why Memory Management?

- Force tasks to communicate over fixed interfaces.
- Security and protection of tasks from one another (and kernel).
- Trick applications to provide more memory than available.
- When sharing memory, provides synchronization amongst operations.

MM Responsibilities

- Allocate blocks of the system’s primary (or executable) memory on request
- Ensure exclusive control of allocated blocks
- Provide a means for cooperating processes to share blocks
- Automatically move data between the primary and secondary memories

Demand Paged Virtual Memory

- Architecture-Independent Memory model.
  - This model is adapted for specific implementation.
- Each process is allocated it’s own virtual address space.
  - Processes reference virtual addresses.
  - System maps each reference into a physical address.
- The kernel *and* hardware together ensure that the virtual and physical addresses are correctly corresponding.

Page by Page

- All memory management in the kernel is done on the basis of a page.
  - For the i386, a page is typically 4K (4096 bytes).
- The virtual addressing space is 32 bits wide
  - 4 Gb of virtual address space for a task.
  - Up to 2^{20} pages per task.

Virtual Address Space

- A virtual address space is broken into two sections.
  - User segment (3 Gb) to contain the applications code and data. Addressable by the user.
    - Unmapped virtual addresses are simply not used.
  - Kernel segment (1 Gb) permanently mapped and associated with fixed physical memory addresses used by the kernel.
- System calls execute in kernel segment (mode).

Virtual Address Space

- Each of these segments are further broken down into sectors.
  - *Code* and *Data* sectors.
- The kernel segment (physical pages) are mapped after the user segment.
  - The boundary is described by `TASK_SIZE` macro.

Kernel to/from User

- From the kernel, there are several macros defined to allow access to the user segment of a processes virtual address space...
  - get_user(val, ptr) /* read scalar value */
  - put_user(val, ptr) /* write scalar value */
  - copy_from_user(to, from, n)
  - copy_to_user(to, from, n)
  - strncpy_from_user(to, from, n)
  - strnlen_user(str, n) /* length of string (max n) */
  - clear_user(mem, len)

access_ok() ?

- The access_ok() macro allows the kernel to query a virtual address to see if it is legitimate for the task.
- Each of the kernel -> user memory access macros have a __ equivalent (e.g. __get_access(val, ptr)) that performs the action without the address check.
- WHY?

Let's Get Physical!

- Converting addresses from virtual to physical is a three level process in an architecture independent model.
  - It can be less in a *real* implementation depending on what the hardware supports.
  - This is dictated by the hardware's MMU...
  - For the x86 it only supports a two level conversion of the address.

Virtual to Physical

Page Directories

- Kernel has to manage page directories (and tables) for both the user and kernel segments of the processes.
- Short identifiers
  - pgd - page directory, pmd - page middle directory
- The data types are `pgd_t` and `pmd_t` respectively.
  - Defined as structs to avoid mistaken casts to int.

Page Directory Support

- `pgd_val(), pmd_val()`
  - Allow access to the real value of the directory entry.
- `pgd_alloc(), pmd_alloc()`
  - Provide a memory page for the respective directory.
- `pgd_free(), pmd_free()`
  - The directory entries are freed

Page Directory Support

- `pgd_clear(), pmd_clear()`
  - Deletes the entry in the page directory.
- `pgd_none(), pmd_none()`
  - Test whether a directory entry is valid
- `pgd_present(), pmd_present()`
  - Negation result of the p{gm}d_none() macro
- `pgd_bad(), pmd_bad()`
  - Check the correctness of the entries that refer to subsequent page structs (directory, mid directory, table)

Page Directory Support

- `pgd_page(), pmd_page()`
  - Return reference to next level page structure
- `pgd_offset()`
  - Return reference to page directory for the given address.
- `pmd_offset()`
  - Return the reference to page middle directory for the given address.
- `set_pgd(), set_pmd()`
  - Fill the page directory with entries.

The Page Table

- The Page table is the lowest level of the memory model.
- An entry in the page table is defined as `pte_t` structure.
- This is the final mapping, so it addresses a page in the physical memory.

Page Table Support

- `pte_val()`
  - Returns the value of a page table entry.
- `pte_alloc()`
  - Using an entry of the pmd, returns the referenced page table. Creates one if non-existant.
- `pte_free()`
  - Free the page table and makes sure it does not contain an initialized value.

Page Table Support

- `pte_page()`
  - Returns reference to physical page
- `pte_offset()`
  - Given an intermediate page directory and virtual address, returns associated page table.
- `set_pte()`
  - Sets the given position of the page table entry.

Page Table Flags

- Flags in the page table entry indicate
  - The legal access modes into the page.
  - The pages status.
- A page’s status can give vital information for how memory management is performed.

Page Table Flags

- PAGE_NONE – No physical memory page associated with entry.
- PAGE_SHARED – All types of access permitted.
- PAGE_READONLY – No writing. “Copy-on-Write” can be used.
- PAGE_KERNEL – kernel segment only allowed access.
- PAGE_KERNEL_RO – kernel read-only access.

Modifier Functions

- `pte_modify()` – modify the descriptor
- `pte_present()` – tests presence attribute
- `pte_dirty()` – tests dirty attribute
- `pte_read()` – tests read attribute
- `pte_exec()` – tests exec attribute
- `pte_young()` – tests age attribute

Modifier Functions

- `pte_mkexec(), pte_exprotect()`
  - Sets execute attribute
- `pte_mkdirty(), pte_mkclean()`
  - Sets dirty attribute
- `pte_mkread(), pte_mkwrite()`
  - Sets read attribute
- `pte_mkyoung(), pte_mkold()`
  - Sets age attribute

Task’s Virtual Space

- A task’s virtual space is divided between user and kernel segments.
- Since the user segment contains data and code belonging to a task it must be unique to the task.
  - This can be done using different directories or page tables for a process.
- fork - copies the page directory, tables, and pages
- clone - shares the same memory structure.

Structure of User Segment

- This is dependent on the binary format being executed. (a.out, ELF, S19, ...)
- Contains the code of user program, data space for execution, and any shared libraries used.
- This also includes program filename, environment, arguments, ...

Virtual Memory Areas

- Shared libraries and applications are sometimes large. Even if it can fit in the addressable space, it is wasteful to load.
- Virtual memory can also provide a mechanism for sharing memory.
  - Quicker to write to a memory location than to perform a system call.
- Read Only data can be shared between tasks (Copy_on_write).
- Just because memory is requested, it may not be needed!

vm_area_struct

- vm_start, vm_end – beginning and ending of virtual memory.
- vm_page_prot – protection attributes of area.
- vm_flags – memory type.
- vm_file – file or device mapped to virtual memory.
- vm_opps – structure of function pointers (handlers for page errors).

Operational Details

- The virtual memory structs for a task can be stored in both an AVL tree and a singly linked list for management.
- If you try to access any of the addresses that are defined by this virtual memory area, then the appropriate function is called.

Operational Details (cont.)

- open
  - Memory region is added to the set of regions owned by the task.
- close
  - Memory region is removed from the set of regions owned by the task.
- nopage(area, address, write_access)
  - Obtains physical page, copies data, corrects page directory/page table. Invoked by Page Fault exception handler

do_mmap_pgoff()

- Creates a new VM area.
- Arguments include:
  - The file to map and offset into the file.
  - Address to start searching for free linear interval.
  - Length of the file to map.
  - Any permissions and memory region flags.

Kernel Segment

- On an interrupt 0x80, the processor sets registers to allow kernel memory access.
  - Likewise, resets registers on return to user task
- Memory management in the kernel is in some ways easier than in the user segment.
  - No shared libraries
  - All memory is always kept in physical pages.
  - All tasks share the same kernel segment!
- Still have to deal with dynamic memory.

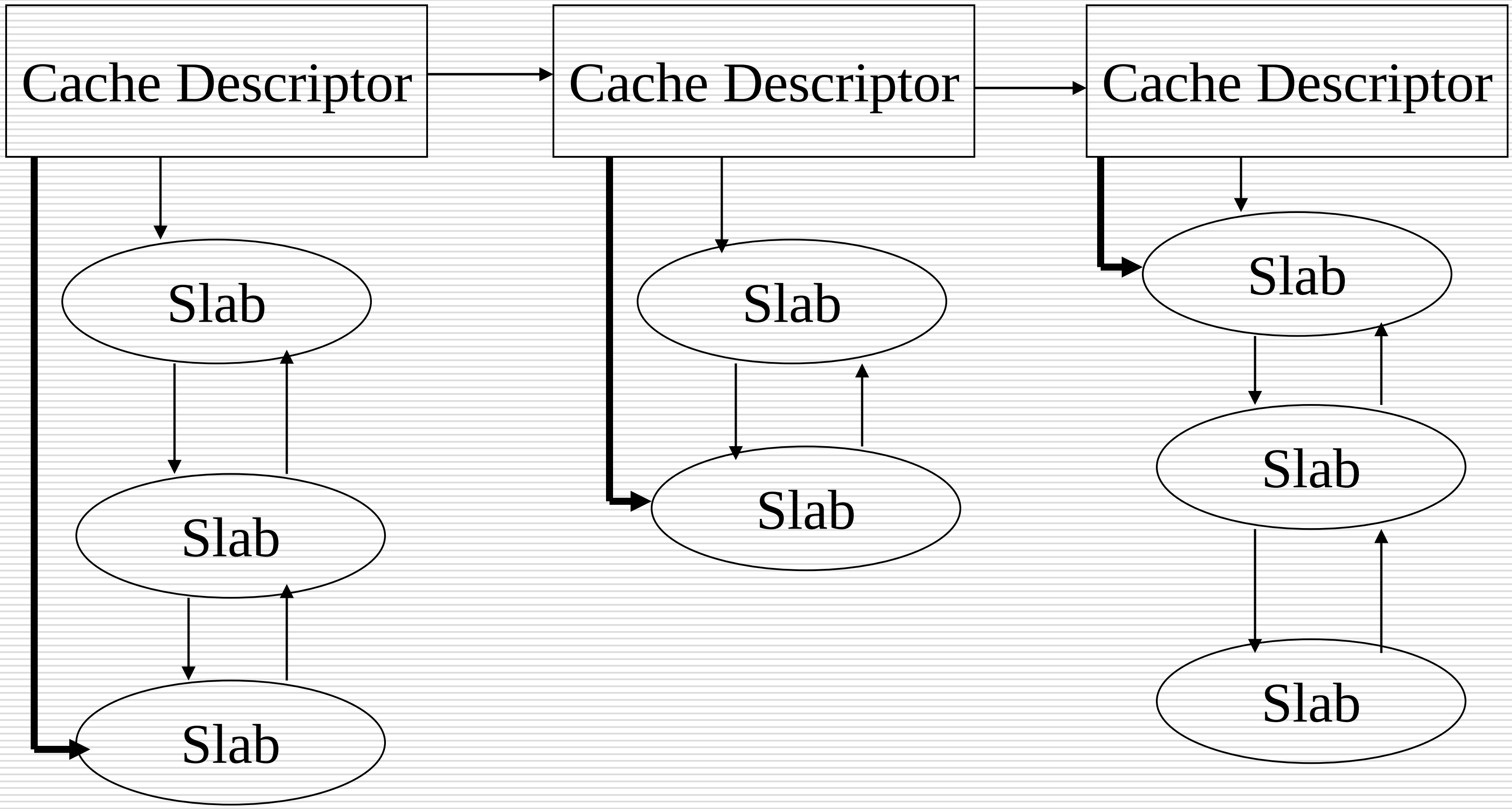
Kernel's Dynamic Memory

- Once up, the kernel can acquire memory through
  - `kmalloc(size, priority)`
  - maximum of 128K
  - Does not clear the allocated memory
- Free the memory through
  - `kfree(obj)`
- Dynamic memory in the kernel is performed on a slab basis instead of pages.

Slabs

- A Caching mechanism exists for managing different sizes of slabs.
- Each of the slabs can be a multiple of a memory page in size.
  - Starting from 64 bytes up to 128K
- Depending on the memory space, the slab management structure can be inside or outside the slab.

Slab Caches


Cache Descriptor
Cache Descriptor
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Slab Allocation

- `kmem_cache_create(name, size, offset, flags, `**`ctor()`**`, `**`dtor()`**`)`
  - `name` – name of the cache
  - `size` – creates a cache for objects of this size.
  - `offset` – any special alignment needed.
  - `ctor()` and `dtor()` – construct and destruct functions to call on (de)allocating objects.

Slab Allocation (cont.)

- `kmem_cache_destroy()`
  - Closes the cache and releases all associated memory.
- `kmem_cache_shrink()`
  - Shrink the size of a cache.
- `kmem_cache_alloc()`
  - Allocate an object from the cache.
- `kmem_cache_free()`
  - Free an object back into the cache.

Paging

- Paging can occur either to a fixed length file or to a partition.
  - Page file or swap partition.
- Pages of physical memory that have been altered need writing to the swap memory.
- Pages that have not been altered can just be discarded.
- Why is kernel memory never swapped?

Partition vs. File

- For swapping, a partition is more efficient than a file.
  - Partition is in consecutive blocks, thus no searching for blocks.
  - File can be split across non-consecutive blocks resulting in longer lookups.
  - Filesystem block size may not correspond to a page size!
- Swap file is more flexible! Easier to allocate a file than a partition after initial setup.

Swap Space

- Within the kernel, `MAX_SWAPFILES` (8 is reasonable) defines the maximum number of space space entries allowed.
- To map a new swap space, the system call `sys_swapon(char* specialfile, int flags)` is invoked.
  - `specialfile` points to the swap device/file.
  - `flags` indicates the priority of swap device.
- `sys_swapoff(char *specialfile)` to remove the swap space.

swap_info table

- Each swap device added creates an entry in the swap_info table. Entries contain
  - flags – Is the swap space available?
  - swap_device – device number if swap partition.
  - sdev_lock – synchronization lock for swap space.
  - swap_file – file pointer if swap file used.
  - swap_vfsmnt – mount point of the swap space.
  - swap_map – table of swap space pages.
  - prio – priority of the swap space.
  - next – priority list of swap spaces.
  - pages - #pages that can be written to.

Swap Management

- For each page of memory in swap, a `mem_map_t` structure is used.
- Different fields include:
  - `list` - All swap pages are kept in a doubly linked circular list. One list for used, clean, and dirty pages.
  - `mapping` - Points to the address_space object which the page belongs.
  - `count` - number of users of the page in swap.

Physical Page Management

- Page frames are often 4Kb on Intel architecture.
- The kernel must keep track of the current status of each frame.
  - Is the page free?
  - process or kernel pages?
- An array of page frame descriptors is used for each page (`struct page`).

Page Frame Descriptors

- Each descriptor has several fields:
  - count - equals 0 if the frame is free, >0 otherwise.
  - flags - an array of 32 bits for the frame status.
    - Example flag values:
      - `PG_locked` - page cannot be swapped out.
      - `PG_reserved` - page reserved for kernel or unuseable.
      - `PG_slab` - included in a slab.

The mem_map Array

- All page frame descriptors are stored in the `mem_map` array.
- Descriptors are less than 64 bytes, so about 4 pages of memory are needed for each Mb of RAM.
- The `virt_to_page()` macro computes the number of the page frame whose address is passed as a parameter.
  - `#define virt_to_page(addr) (__pa(addr) >> PAGE_SHIFT)`
  - `__pa` macro converts logical address to physical.

Requesting Page Frames

- Main routine for requesting page frames:
  - `__get_free_pages(gfp_mask, order)`
  - request 2^{order} contiguous page frames.
- `gfp_mask` specifics how to look for page frames
  - `GFP_WAIT` - Allows kernel to discard page frame contents to satisfy request.
  - `GFP_IO` - Allows kernel to write pages to disk to free pages frames for new request.
  - `GFP_HIGH/MED/LOW` - Request priority.

Releasing Page Frames

- Main routine for freeing pages is: `free_pages(addr, order)`
  - Check descriptor of frame at addr.
  - If not reserved -> decrement the count field.
  - If count == 0 -> free 2^{order} contiguous frames
  - `free_pages_ok()` inserts 1st page into list of free page frames.

External Fragmentation

- External fragmentation is a problem when small blocks of free page frames are scattered between allocated page frames.
- Becomes impossible to allocate large blocks of contiguous page frames.
- Solution:
  - Use paging HW to group non-contiguous page frames into contiguous linear (virtual) addresses, or …
  - Track free blocks of contiguous frames & attempt to avoid splitting large free blocks to satisfy requests.

The Buddy System

- Free page frames are grouped into lists of blocks containing 2^n contiguous page frames.
  - Maintaining 11 lists of 1, 2, 4, ..., 1024 contiguous page frames can often service ALL memory size requests.
  - Physical address of 1st frame in a block is a multiple of the group size
    - e.g. multiple of $16*2^{12}$ for a 16 page frame block.

Buddy Allocation

- Example: Need to allocate 65 contiguous page frames.
  - Look in the list of free 128 page frame blocks.
  - If free block exists, allocate it
  - Else, if free block found in 256 page frame list, split it into 2 128-page frame blocks. Allocate one block, and put remaining block into the lower order list.
- What is the worst case fragmentation?

Buddy De-Allocation

- When blocks of page frames are released the kernel tries to merge pairs of “buddy” blocks of size b into blocks of size 2b.
- Two blocks are buddies if:
  - They have equal size b.
  - They are located at contiguous physical addresses.
  - The address of the first page frame in the first block is aligned on a multiple of $2b*2^{12}$
- The process repeats by attempting to merge buddies of size 2b, 4b, 8b etc…

Buddy Data Structures

- Different zones used for page frames.
- An array of MAX_ORDER * elements (one for each group size) of type free_area_struct.
  - free_area[order] contains a free_list and a bitmap for groups of blocks and 2^{order} page frames.
- MAX_ORDER is set to maximum required size.