# Linux Kernel Programming
# **Memory Management**

Pierre Olivier

Systems Software Research Group @ Virginia Tech

March 28, 2017

# Outline

1. Pages and zones
2. Low-level memory allocator
3. `kmalloc()` and `vmalloc()`
4. Slab layer
5. Stack, high memory and per-cpu allocation

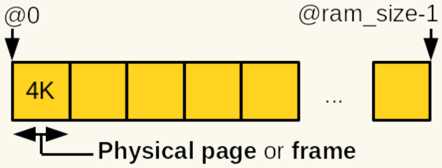
# Outline

# Pages and zones

## Pages

- Memory allocation in the kernel is different from user space
  - How to handle memory allocation failures?
  - In some situations the kernel cannot sleep
  - Etc.
- The **page** is the basic unit for memory management by the MMU, and thus the kernel
  - Page size is machine dependent
    - Typical values for x86 are **4K**, 2M, and 1G
    - Get the page size on your machine:

```
getconf PAGESIZE
```



# Pages and zones

## Pages: `struct page`

- Each **physical page** is represented by a **`struct page`**
  - Most of the pages are used for (1) kernel/userspace memory (*anonymous mapping*) or (2) file mapping

- Simplified version:

```
struct page {
  unsigned long flags;
  unsigned counters;
  atomic_t _mapcount;
  unsigned long private;
  struct address_space *mapping;
  pgoff_t index;
  struct list_head lru;
  void *virtual;
}
```

- More info on `struct page`: [1]

- `flags`: page status (permission, dirty, etc.)
- `counters`: usage count
- `private`: private mapping
- `mapping`: file mapping
- `index`: offset within mapping
- `virtual`: virtual address

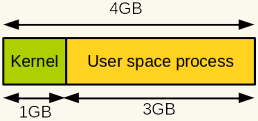
# Pages and zones

## Pages (2)

- The kernel uses `struct page` to keep track of the owner of the page
  - User-space process, kernel statically/dynamically allocated data, page cache, etc.
- **There is one `struct page` object per physical memory page**
  - `sizeof(struct page)` with regular kernel compilation options: 64 bytes
  - Assuming 8GB of RAM and 4K-sized pages: 128MB reserved for `struct page` objects (∼1.5%)

# Pages and zones
## Zones

- Because of hardware limitations, **only certain physical pages can be used in certain contexts**
  - Example: on x86 some DMA-enabled devices can only access the lowest 16M part of physical memory
  - On x86_32 the kernel address space area sometimes cannot map all physical RAM (1/3 model)

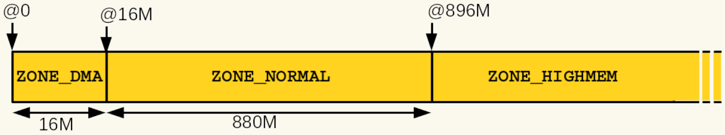



- Physical memory is divided into **zones**:
  - `ZONE_DMA`: pages with which DMA can be used
  - `ZONE_DMA32`: memory for other DMA limited devices
  - `ZONE_NORMAL`: page always mapped in the address space
  - `ZONE_HIGHMEM`: pages only mapped temporary
- Zones layout is completely architecture dependent

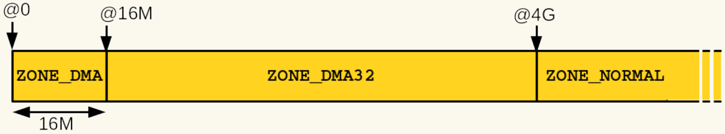
# Pages and zones

## Zones (2)

- x86_32 zones layout:




- x86_64 zones layout:




- Some memory allocation requests must be served in specific zones
- While the kernel tries to avoid it, general allocations requests can be served from any zone if needed

# Pages and zones

## Zones (3)

- Each zone is represented by a `struct zone` object
  - Defined in `include/linux/mmzone.h`
  - Simplified version with notable fields:

```
struct zone {
  unsigned long       watermark[NR_WMARK];
  const char          *name;
  spinlock_t          lock;
  struct free_area    free_area[MAX_ORDER];
  /* ... */
}
```

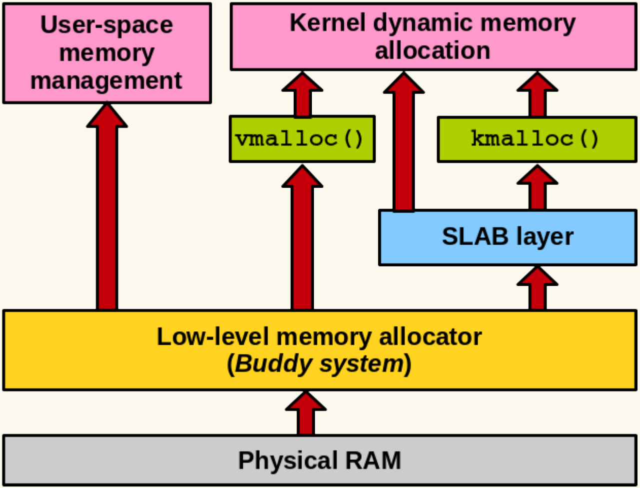
- `watermark` minimum, low and high watermarks used for per-area memory allocation
- `lock`: protects against concurrent access
- `free_area`: list of free pages to serve memory allocation requests

# Outline

1. Pages and zones
2. Low-level memory allocator
3. `kmalloc()` and `vmalloc()`
4. Slab layer
5. Stack, high memory and per-cpu allocation

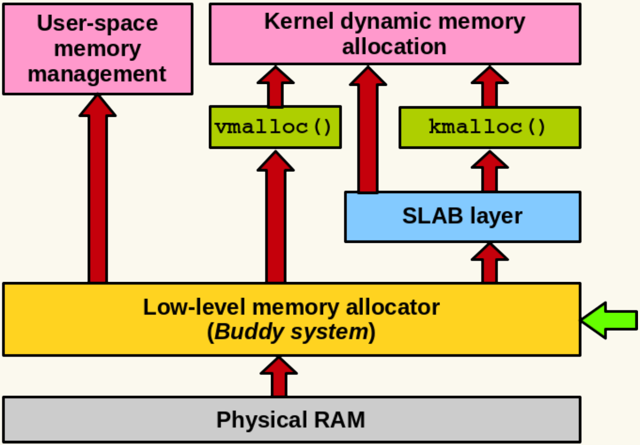
# Low-level memory allocator

## Memory allocation: general overview



# Low-level memory allocator

## Memory allocation: general overview



# Low-level memory allocator

## Getting pages

- Low-level mechanisms allocating memory with page-sized granularity
- Interface in `include/linux/gfp.h`
  - Core function:

```
struct page * alloc_pages(gfp_t gfp_mask, unsigned int order);
```

    - Allocates $2^{order}$ contiguous pages ($1 << order$)
    - Returns the **address of the first allocated `struct page`**
    - To actually use the allocated memory, need to convert to virtual address:

```
void * page_address(struct page *page);
```

  - To allocate and get the virtual address directly:

```
unsigned long __get_free_pages(gfp_t gfp_mask, unsigned int order);
```

# Low-level memory allocator

## Getting pages (2)

- To get a single page:

```
struct page * alloc_page(gfp_t gfp_mask);
unsigned long __get_free_page(gfp_t gfp_mask);
```

- To get a page filled with zeros:

```
unsigned long get_zeroed_page(gfp_t gfp_mask);
```

  - Needed for pages given to user space
    - A page containing user space data (process A) that is freed can be later given to another process (process B)
    - We don't want process B to read information from process A

# Low-level memory allocator

## Freeing pages

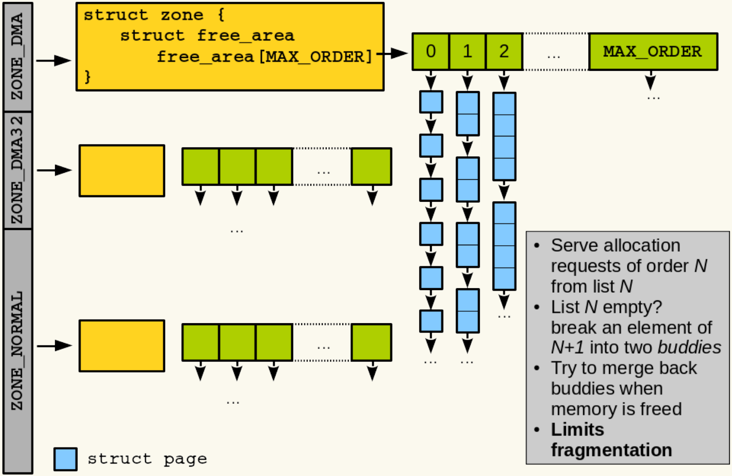
- Freeing pages - low level API:

```
void __free_pages(struct page *page, unsigned int order);
void free_pages(unsigned long addr, unsigned int order);
void __free_page(struct page *page);
void free_page(unsigned long addr);
```

  - Free only the pages you allocate!
    - Otherwise: corruption

# Low-level memory allocator

## Buddy system




- Serve allocation requests of order *N* from list *N*
- List *N* empty? break an element of *N+1* into two *buddies*
- Try to merge back buddies when memory is freed
- **Limits fragmentation**

# Low-level memory allocator

## Usage example

```c
#include <linux/module.h>
#include <linux/kernel.h>
#include <linux/init.h>
#include <linux/gfp.h>

#define PRINT_PREF    "[LOWLEVEL]: "
#define PAGES_ORDER_REQUESTED 3
#define INTS_IN_PAGE (PAGE_SIZE/sizeof(int))

unsigned long virt_addr;

static int __init my_mod_init(void)
{
  int *int_array;
  int i;

  printk(PRINT_PREF "Entering module.\n");

  virt_addr = __get_free_pages(GFP_KERNEL,
      PAGES_ORDER_REQUESTED);
  if(!virt_addr) {
    printk(PRINT_PREF "Error in allocation\n
      ");
    return -1;
  }

  int_array = (int *)virt_addr;
  for(i=0; i<INTS_IN_PAGE; i++)
    int_array[i] = i;

  for(i=0; i<INTS_IN_PAGE; i++)
    printk(PRINT_PREF "array[%d] = %d\n", i,
       int_array[i]);

  return 0;
}

static void __exit my_mod_exit(void)
{
  free_pages(virt_addr,
      PAGES_ORDER_REQUESTED);
  printk(PRINT_PREF "Exiting module.\n");
}

module_init(my_mod_init);
module_exit(my_mod_exit);
```

# Outline

# kmalloc() and vmalloc()

## kmalloc() usage and kfree()

- kmalloc() allocates byte-sized chunks of memory
- Allocated memory is **physically contiguous**
- Usage similar to userspace malloc()
  - Returns a pointer to the first allocated byte on success
  - Returns NULL on error
- Declared in includes/linux/slab.h:

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

- Usage example:

```
struct my_struct *ptr;

ptr = kmalloc(sizeof(struct my_struct), GFP_KERNEL);
if(!ptr) {
  /* handle error */
}
```

# kmalloc() and vmalloc()
## Kmalloc flags

- gfp_t type (unsigned int in include/linux/types.h)
  - *get free page* [2]
- Specify options for the allocated memory
  1. **Action modifiers**
     - How should the memory be allocated? (for example, can the kernel sleep during allocation?)
  2. **Zone modifiers**
     - From which zone should the allocated memory come
  3. **Type flags**
     - Combination of action and zone modifiers
     - Generally preferred compared to direct use of action/zone

# kmalloc() and vmalloc()
## Kmalloc flags: action modifiers

- **Action modifiers:**

| Flag | Description |
|---|---|
| __GFP_WAIT | Allocator can sleep |
| __GFP_HIGH | Allocator can access emergency pools |
| __GFP_IO | Allocator can start disk IO |
| __GFP_FS | Allocator can start filesystem IO |
| __GFP_NOWARN | Allocator does not print failure warnings |
| __GFP_REPEAT | Allocator repeats the allocation if it fails, the allocation can potentially fail |
| __GFP_NOFAIL | Allocator indefinitely repeats the allocation, which cannot fail |

# kmalloc() and vmalloc()

## Kmalloc flags: action modifiers (2)

| Flag | Description |
|---|---|
| __GFP_NORETRY | Allocator does not retry if the allocation fails |
| __GFP_NOMEMALLOC | Allocation does not fall back on reserves |
| __GFP_HARDWALL | Allocator enforces "hardwall" cpuset boundaries |
| __GFP_RECLAIMABLE | Allocator marks the pages reclaimable |
| __GFP_COMP | Allocator adds compound page metadata (used by hugetlb code) |

- Several action modifiers can be specified together:

```
ptr = kmalloc(size, __GFP_WAIT | __GFP_FS | __GFP_IO);
```

  - Generally, **type modifiers are used instead**

# kmalloc() and vmalloc()

## Kmalloc flags: zone modifiers

- **Zone modifiers:**

| Flag | Description |
| --- | --- |
| __GFP_DMA | Allocates **only** from ZONE_DMA |
| __GFP_DMA32 | Allocates **only** from ZONE_DMA32 |
| __GFP_HIGHMEM | Allocated from ZONE_HIGHMEM or ZONE_NORMAL |

- __GFP_HIGHMEM: OK to use high memory, normal works too
- No flag specified?
  - Kernel allocates from ZONE_NORMAL or ZONE_DMA with a strong preference for ZONE_NORMAL
- Cannot specify __GFP_HIGHMEM to kmalloc() or __get_free_pages()
  - These function return a virtual address
  - Addresses in ZONE_HIGHMEM might not be mapped yet

# kmalloc() and vmalloc()
## Kmalloc flags: type flags

- **GFP_ATOMIC**: high priority allocation that cannot sleep
  - Use in interrupt context, while holding locks, etc.
  - Modifier flags: (__GFP_HIGH)
- **GFP_NOWAIT**: same as GFP_ATOMIC but does not fall back on emergency memory pools
  - More likely to fail
  - Modifier flags: (0)
- **GFP_NOIO**: can block but does not initiate disk IO
  - Used in block layer code to avoid recursion
  - Modifier flags: (__GFP_WAIT)
- **GFP_NOFS**: can block and perform disk IO, but does not initiate filesystem operations
  - Used in filesystem code
  - Modifier flags: (__GFP_WAIT | __GFP_IO)

# kmalloc() and vmalloc()

## Kmalloc flags: type flags (2)

- **GFP_KERNEL**: default choice, can sleep and perform IO
  - Modifier flags: (__GFP_WAIT | __GFP_IO | __GFP_FS)
- **GFP_USER**: normal allocation, might block, for user-space memory
  - Modifier flags: (__GFP_WAIT | __GFP_IO | __GFP_FS)
- **GFP_HIGHUSER**: allocation for user-space memory, from ZONE_HIGHMEM
  - Modifier flags: (__GFP_WAIT | __GFP_IO | __GFP_FS | __GFP_HIGHMEM)
- **GFP_DMA**: served from ZONE_DMA
  - Modifier flags: (__GFP_DMA)

# kmalloc() and vmalloc()

## Kmalloc flags: which flag to use?

| Context | Solution |
|---|---|
| Process context, can sleep | GFP_KERNEL |
| Process context, cannot sleep | GFP_ATOMIC or allocate at a different time |
| Interrupt handler | GFP_ATOMIC |
| Softirq | GFP_ATOMIC |
| Tasklet | GFP_ATOMIC |
| Need to handle DMA, can sleep | (GFP_DMA \| GFP_KERNEL) |
| Need DMA, cannot sleep | (GFP_DMA \| GFP_ATOMIC) |

- Other types and modifier are declared and documented in include/linux/gfp.h

# kmalloc() and vmalloc()

## kfree

- Memory allocated with kmalloc() needs to be freed with kfree()
- include/linux/slab.h:

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

- Example:

```
struct my_struct ptr;

ptr = kmalloc(sizeof(struct my_struct));
if(!ptr) {
  /* handle error */
}

/* work with ptr */

kfree(ptr);
```

- **Do not free memory that has already been freed**
  - Leads to corruption

# kmalloc() and vmalloc()
## vmalloc()

- **`vmalloc()` allocates *virtually* contiguous pages that are not guarantee to map to *physically* contiguous ones**
  - Page table is modified → no problems from the programmer usability standpoint
- Buffers related to communication with the hardware generally need to be physically contiguous
  - But most of the rest do not, for example user-space buffers
- However, most of the kernel uses `kmalloc()` for **performance reasons**
  - Pages allocated with `kmalloc()` are directly mapped
  - Less overhead in virtual to physical mapping setup and translation
- `vmalloc()` is still needed to allocate large portions of memory

# kmalloc() and vmalloc()

## vmalloc() (2)

- **vmalloc() usage:**
- Similar to user-space malloc()
  - include/linux/vmalloc.h:

```
void *vmalloc(unsigned long size);
void vfree(const void *addr);
```

- Example:

```
struct my_struct *ptr;

ptr = vmalloc(sizeof(struct my_struct));
if(!ptr) {
  /* handle error */
}

/* work with ptr */

vfree(ptr);
```

# kmalloc() and vmalloc()

## vmalloc(): kmalloc() allocated size limitation

```c
#include <linux/module.h>
#include <linux/kernel.h>
#include <linux/init.h>
#include <linux/slab.h>

#define PRINT_PREF "[KMALLOC_TEST]: "

static int __init my_mod_init(void)
{
  unsigned long i;
  void *ptr;

  printk(PRINT_PREF "Entering module.\n");

  for(i=1;;i*=2) {
    ptr = kmalloc(i, GFP_KERNEL);
    if(!ptr) {
      printk(PRINT_PREF "could not
     allocate %lu bytes\n", i);
      break;
    }
    kfree(ptr);
  }

  return 0;
}
```

```c
static void __exit my_mod_exit(void)
{
  printk(KERN_INFO "Exiting module.\n");
}

module_init(my_mod_init);
module_exit(my_mod_exit);

MODULE_LICENSE("GPL");
```

Virginia Tech

# kmalloc() and vmalloc()

## vmalloc(): kmalloc() allocated size limitation (2)

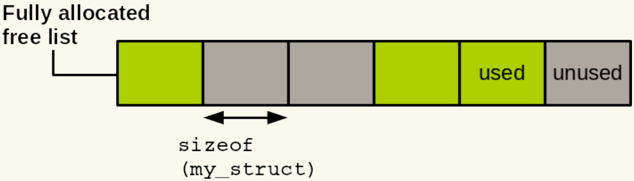
```
pierre@bulbi: ~/Desktop/VM
root@debian:~# insmod kmalloc_test.ko
[   12.949562] kmalloc_test: loading out-of-tree module taints kernel.
[   12.950338] [KMALLOC_TEST]: Entering module.
[   12.950746] ------------[ cut here ]------------
[   12.951171] WARNING: CPU: 1 PID: 2071 at mm/page_alloc.c:3541 __alloc_pages_s
lowpath+0x9de/0xb10
[   12.951894] Modules linked in: kmalloc_test(O+)
[   12.952320] CPU: 1 PID: 2071 Comm: insmod Tainted: G           O    4.10.4 #5
[   12.952908] Hardware name: QEMU Standard PC (i440FX + PIIX, 1996), BIOS Ubunt
u-1.8.2-1ubuntu2 04/01/2014
[   12.953315] Call Trace:
[   12.953315]  dump_stack+0x4d/0x66
[   12.953315]  __warn+0xc6/0xe0
[   12.953315]  warn_slowpath_null+0x18/0x20
[   12.953315]  __alloc_pages_slowpath+0x9de/0xb10
[   12.953315]  ? get_page_from_freelist+0x514/0xa80
[   12.953315]  ? serial8250_console_putchar+0x22/0x30
[   12.953315]  ? wait_for_xmitr+0x90/0x90
[   12.953315]  __alloc_pages_nodemask+0x183/0x1f0
[   12.953315]  alloc_pages_current+0x9e/0x150
[   12.953315]  kmalloc_order_trace+0x29/0xe0
[   12.953315]  __kmalloc+0x18c/0x1a0
[   12.953315]  ? __free_pages+0x13/0x20
[   12.953315]  my_mod_init+0x23/0x49 [kmalloc_test]
[   12.959278]  ? 0xffffffffa0002000
[   12.959278]  do_one_initcall+0x3e/0x160
[   12.959278]  ? kmem_cache_alloc_trace+0x33/0x150
[   12.959278]  do_init_module+0x5a/0x1c9
[   12.959278]  load_module+0x1dd4/0x23f0
[   12.959278]  ? __symbol_put+0x40/0x40
[   12.959278]  ? kernel_read_file+0x19e/0x1c0
[   12.959278]  ? kernel_read_file_from_fd+0x44/0x70
[   12.959278]  SYSC_finit_module+0xba/0xc0
[   12.959278]  SyS_finit_module+0x9/0x10
[   12.959278]  entry_SYSCALL_64_fastpath+0x13/0x94
[   12.959278] RIP: 0033:0x7f7ef56495b9
[   12.959278] RSP: 002b:00007fff22a92f78 EFLAGS: 00000206 ORIG_RAX: 0000000000
00139
[   12.959278] RAX: ffffffffffffffda RBX: 00007f7ef590a620 RCX: 00007f7ef56495b9
[   12.959278] RDX: 0000000000000000 RSI: 000055a2bd49b3d9 RDI: 0000000000000003
[   12.959278] RBP: 0000000000001021 R08: 0000000000000000 R09: 00007f7ef590cf20
[   12.959278] R10: 0000000000000003 R11: 0000000000000206 R12: 000055a2bf0091c0
[   12.959278] R13: 000055a2bf0091b0 R14: 0000000000001018 R15: 00007f7ef590a678
[   12.971803] ---[ end trace 3bed3649938d2598 ]---
[   12.972456] [KMALLOC_TEST]: could not allocate 8388608 bytes
root@debian:~#
```

- Max size: 8MB

# Outline

# Slab layer
## Presentation

- Allocating/freeing data structures is done very often in the kernel
- **Free lists:**
  - Block of pre-allocated memory for a given type of data structure




  - **Allocation cache**
    - "Allocating" from the free list is just picking a free slot
    - "Freeing" from the free list is setting back the slot state to free
  - Faster than frequent `{k|v}malloc()` and `{k|v}free()`
- Issue with ad-hoc free lists: no global control

# Slab layer

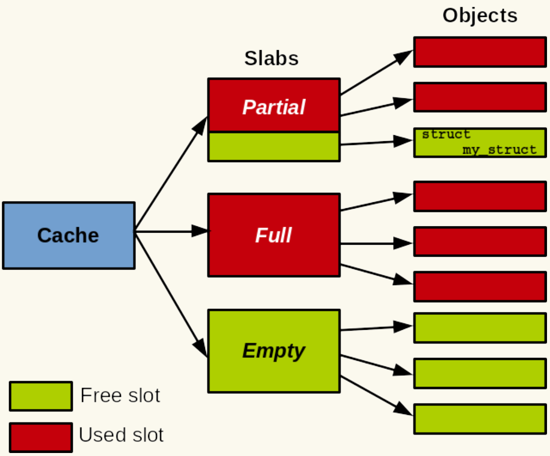
## Presentation (2)

- **Slab layer/slab allocator**: Linux's generic allocation caching interface
- Basic principles:
  - Frequently used data structures are allocated and freed often $\rightarrow$ needs to be cached
  - Frequent allocation/free generates memory fragmentation
    - Caching allocation/free operations in large chunks of contiguous memory reduces fragmentation
  - An allocator aware of data structure size, page size, and total cache size is more efficient
  - Part of the cache can be made per-cpu to operate without a lock
  - Allocator should be NUMA-aware and implement cache-coloring

# Slab layer
## Presentation (3)

- The slab layer introduces defines the concept of **caches**
  - One cache per type of data structure supported
    - Example: one cache for `struct task_struct`, one cache for `struct inode`, etc.
- Each cache contains one or several **slabs**
  - One or several physically contiguous pages
- Slabs contain **objects**
  - The actual data structure slots
- A slab can be in one of three states:
  - Full: all slots used
  - Partial: some, not all slots used
  - Empty: all slots free
- Allocation requests are served from partial slabs if present, or empty slabs $\rightarrow$ **reduces fragmentation**
  - A new empty slab is actually allocated in case the cache is full

# Slab layer
## Presentation (4)



# Slab layer
## Usage

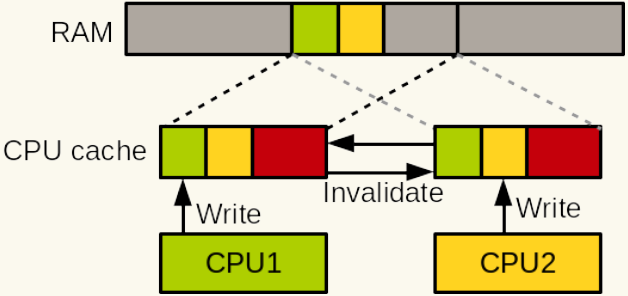
- A new cache is created using:

```
struct kmem_cache *kmem_cache_create(const char *name,
                                     size_t size,
                                     size_t align,
                                     unsigned long flags,
                                     void (*ctor)(void *));
```

- `name`: cache name
- `size`: data structure size
- `align`: offset of the first element within the page (can put 0)
- `ctor`: constructor called when a new data structure is allocated
  - Rarely used, can put `NULL`
- `flags`: settings controlling the cache behavior

# Slab layer
## Usage: flags

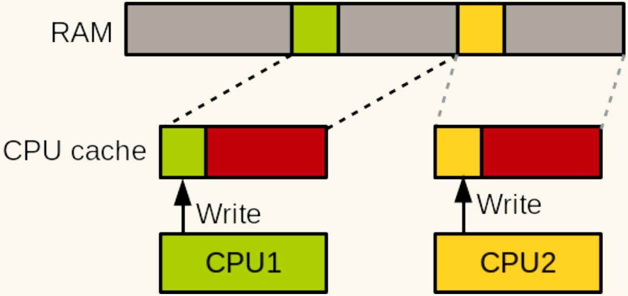
- SLAB_HW_CACHEALIGN
  - Each object in a slab is aligned to a cache line
    - Prevent *false sharing*:



# Slab layer

## Usage: flags

- `SLAB_HW_CACHEALIGN`
  - Each object in a slab is aligned to a cache line
    - Prevent *false sharing*:




- Increased memory footprint

# Slab layer

## Usage: flags (2)

- `SLAB_POISON`
  - Fill the slab with know values (`a5a5a5a5`) to detect accesses to uninitialized memory
- `SLAB_RED_ZONE`
  - Extra padding around objects to detect buffer overflows
- `SLAB_PANIC`
  - Slab layer panics if the allocation fails
- `SLAB_CACHE_DMA`
  - Allocation made from DMA-enabled memory

# Slab layer

## Usage: allocating from the cache, cache destruction

- **Allocating from the cache:**

```
void *kmem_cache_alloc(struct kmem_cache *cachep, gfp_t flags);
```

- **To free an object:**

```
void kmem_cache_free(struct kmem_cache *cachep, void *objp);
```

- **To destroy a cache:**

```
int kmem_cache_destroy(struct kmem_cache *cachep);
```

- `kmem_cache_destroy()` should only be called when:
  - All slabs in the cache are empty
  - Nobody is accessing the cache during the execution of `kmem_cache_destroy()`
    - Implement synchronization

# Slab layer

## Usage example

```
#include <linux/module.h>
#include <linux/kernel.h>
#include <linux/init.h>
#include <linux/slab.h>

#define PRINT_PREF  "[SLAB_TEST] "

struct my_struct {
  int int_param;
  long long_param;
};

static int __init my_mod_init(void)
{
  int ret = 0;
  struct my_struct *ptr1, *ptr2;
  struct kmem_cache *my_cache;

  printk(PRINT_PREF "Entering module.\n");

  my_cache = kmem_cache_create("pierre-
      cache", sizeof(struct my_struct),
    0, 0, NULL);
  if(!my_cache)
    return -1;
```

```
  ptr1 = kmem_cache_alloc(my_cache,
      GFP_KERNEL);
  if(!ptr1){
    ret = -ENOMEM;
    goto destroy_cache;
  }

  ptr2 = kmem_cache_alloc(my_cache,
      GFP_KERNEL);
  if(!ptr2){
    ret = -ENOMEM;
    goto freeptr1;
  }

  ptr1->int_param = 42;
  ptr1->long_param = 42;
  ptr2->int_param = 43;
  ptr2->long_param = 43;
```

# Slab layer

## Usage example (2)

```
  printk(PRINT_PREF "ptr1 = {%d, %ld} ; ptr2 = {%d, %ld}\n", ptr1->int_param,
    ptr1->long_param, ptr2->int_param, ptr2->long_param);

  kmem_cache_free(my_cache, ptr2);

freeptr1:
  kmem_cache_free(my_cache, ptr1);

destroy_cache:
  kmem_cache_destroy(my_cache);

  return ret;
}

static void __exit my_mod_exit(void)
{
  printk(KERN_INFO "Exiting module.\n");
}

module_init(my_mod_init);
module_exit(my_mod_exit);

MODULE_LICENSE("GPL");
```

# Slab layer

## Slab allocator variants and additional info

- **Slab allocator variants**:
  - **SLOB** (Simple List Of Blocks):
    - Used in early Linux version (from 1991)
    - Low memory footprint → used in embedded systems
  - **SLAB**:
    - Integrated in 1999
    - Cache-friendly
  - **SLUB**:
    - Integrated in 2008
    - Scalability improvements (amongst other things) over SLAB on many-cores
- More info: [5, 3, 4]

# Outline

# Stack, high memory and per-cpu allocation

## Allocating on the stack

- Each process has:
  - A user-space stack for execution in user space
  - A kernel stack for execution in the kernel
- User-space stack is large and grows dynamically
- **Kernel stack is small and has a fixed-size**
  - Generally 8KB on 32-bit architectures and 16KB on 64-bit
- What about interrupt handlers?
  - Historically using the kernel stack of the interrupted process
  - Now using a per-cpu stack (1 single page) dedicated to interrupt handlers
  - Same thing for softirqs
- **Reduce kernel stack usage to a minimum**
  - Local variables & function parameters

# Stack, high memory and per-cpu allocation

## High memory allocation

- On x86_32, physical memory above 896MB is not permanently mapped within the kernel address space
  - Because of the limited size of the address space and the 1G/3G kernel/user-space physical memory split
- **Before usage, pages from highmem must be mapped after allocation**
  - Recall that allocation is done through `alloc_pages()` with the `GFP_HIGHMEM` flag
- **Permanent mapping (`include/linux/highmem.h`):**

```
void *kmap(struct page *page);
```

  - Works on low and high memory
  - Maps (update the page table) and return the given
  - **May sleep**, use only in process context
  - Number of permanent mappings is limited, unmap when done:

```
void kunmap(struct page *page);
```

# Stack, high memory and per-cpu allocation

## High memory allocation: usage example

```
#include <linux/module.h>
#include <linux/kernel.h>
#include <linux/init.h>
#include <linux/gfp.h>
#include <linux/highmem.h>

#define PRINT_PREF     "[HIGHMEM]: "
#define INTS_IN_PAGE   (PAGE_SIZE/sizeof(
      int))

static int __init my_mod_init(void)
{
  struct page *my_page;
  void *my_ptr;
  int i, *int_array;

  printk(PRINT_PREF "Entering module.\n");

  my_page = alloc_page(GFP_HIGHUSER);
  if(!my_page)
    return -1;

  my_ptr = kmap(my_page);
  int_array = (int *)my_ptr;
```

```
  for(i=0; i<INTS_IN_PAGE; i++) {
    int_array[i] = i;
    printk(PRINT_PREF "array[%d] = %d\n", i,
      int_array[i]);
  }

  kunmap(my_page);
  __free_pages(my_page, 0);

  return 0;
}

static void __exit my_mod_exit(void)
{
  printk(PRINT_PREF "Exiting module.\n");
}

module_init(my_mod_init);
module_exit(my_mod_exit);
```

Virginia Tech

# Stack, high memory and per-cpu allocation

## High memory allocation: temporary mappings

- **Temporary mappings**
  - Also called ***atomic mappings*** as they can be used from interrupt context
  - Uses a per-cpu pre-reserved slot

```
void *kmap_atomic(struct page *page);
```

  - Disables kernel preemption
  - Unmap with:

```
void kunmap_atomic(void *addr);
```

- **Do not sleep while holding a temporary mapping**
- After `kunmap_atomic()`, the next temporary mapping will overwrite the slot

# Stack, high memory and per-cpu allocation

## High memory allocation: temporary mappings usage example

```c
#include <linux/module.h>
#include <linux/kernel.h>
#include <linux/init.h>
#include <linux/gfp.h>
#include <linux/highmem.h>

#define PRINT_PREF    "[HIGHMEM_ATOMIC]: "
#define INTS_IN_PAGE  (PAGE_SIZE/sizeof(int))

static int __init my_mod_init(void)
{
  struct page *my_page;
  void *my_ptr;
  int i, *int_array;

  printk(PRINT_PREF "Entering module.\n");

  my_page = alloc_page(GFP_HIGHUSER);
  if(!my_page)
    return -1;

  my_ptr = kmap_atomic(my_page);
  int_array = (int *)my_ptr;
  for(i=0; i<INTS_IN_PAGE; i++) {
    int_array[i] = i;
    printk(PRINT_PREF "array[%d] = %d\n", i, int_array[i]);
  }

  kunmap_atomic(my_ptr);
  __free_pages(my_page, 0);

  return 0;
}

static void __exit my_mod_exit(void)
{
  printk(PRINT_PREF "Exiting module.\n");
}

module_init(my_mod_init);
module_exit(my_mod_exit);
```

# Stack, high memory and per-cpu allocation

## Per-CPU allocation

- **Per-cpu data: data that is unique to each CPU (i.e. each core)**
  - No locking required
  - Implemented through arrays in which each index corresponds to a CPU:

```c
unsigned long my_percpu[NR_CPUS]; /* NR_CPUS contains the number of cores */
```

```c
int cpu;

cpu = get_cpu();    /* get current CPU, disable kernel preemption */
my_percpu[cpu]++;   /* access the data */
put_cpu();          /* re-enable kernel preemption */
```

- Disabling kernel preemption (`get_cpu()`/`put_cpu()`) while accessing per-cpu data is necessary:
  - Preemption then reschedule on another core → `cpu` not valid anymore
  - Another task preempting the current one might access the per-cpu data → race condition

# Stack, high memory and per-cpu allocation

## Per-CPU allocation: the *percpu* API

- Linux provides an API to manipulate per-cpu data: *percpu*
  - In `include/linux/percpu.h`
- **Compile-time per-cpu data structure usage**:
  - Creation:

```
DEFINE_PER_CPU(type, name);
```

  - To refer to a per-cpu data structure declared elsewhere:

```
DECLARE_PER_CPU(name, type);
```

  - Data manipulation:

```
get_cpu_var(name)++;  /* increment 'name' on this CPU */
put_cpu_var(name);    /* Done, disable kernel preemption */
```

  - Access another CPU data:

```
per_cpu(name, cpu)++; /* increment name on the given CPU */
```

    - **Need to use locking!**

# Stack, high memory and per-cpu allocation

## Per-CPU allocation (2)

- **Per-cpu data at runtime**:
  - Allocation:

```
struct my_struct *my_var = alloc_percpu(struct my_struct);
if(!my_var) {
  /* allocation error */
}
```

  - Manipulation:

```
get_cpu_var(my_var)++;
put_cpu_var(my_var);
```

  - Deallocation:

```
free_percpu(my_var);
```

- Benefits of per-cpu data:
  - Removes/minimizes the need for locking
  - Reduces cache thrashing
    - Processor access local data so there is less cache coherency overhead (invalidation) in multicore systems

# Stack, high memory and per-cpu allocation

## Per-CPU allocation: usage example (static)

```c
#include <linux/module.h>
#include <linux/kernel.h>
#include <linux/init.h>
#include <linux/percpu.h>
#include <linux/kthread.h>
#include <linux/sched.h>
#include <linux/delay.h>
#include <linux/smp.h>

#define PRINT_PREF "[PERCPU] "
struct task_struct *thread1, *thread2, *thread3;
DEFINE_PER_CPU(int, my_var);

static int thread_function(void *data)
{
  while(!kthread_should_stop()) {
    int cpu;
    get_cpu_var(my_var)++;
    cpu = smp_processor_id();
    printk("cpu[%d] = %d\n", cpu, get_cpu_var(my_var));
    put_cpu_var(my_var);
    msleep(500);
  }
  do_exit(0);
}
```

```c
static int __init my_mod_init(void)
{
  int cpu;

  printk(PRINT_PREF "Entering module.\n");

  for(cpu=0; cpu<NR_CPUS; cpu++)
    per_cpu(my_var, cpu) = 0;

  wmb();

  thread1 = kthread_run(thread_function, NULL, "percpu-thread1");
  thread2 = kthread_run(thread_function, NULL, "percpu-thread2");
  thread3 = kthread_run(thread_function, NULL, "percpu-thread3");

  return 0;
}
```

# Stack, high memory and per-cpu allocation

## Per-CPU allocation: usage example (static) (2)

```
static void __exit my_mod_exit(void)
{
  kthread_stop(thread1);
  kthread_stop(thread2);
  kthread_stop(thread3);
  printk(KERN_INFO "Exiting module.\n");
}

module_init(my_mod_init);
module_exit(my_mod_exit);

MODULE_LICENSE("GPL");
```

# Stack, high memory and per-cpu allocation

## Per-CPU allocation: usage example (dynamic)

```c
#include <linux/module.h>
#include <linux/kernel.h>
#include <linux/init.h>
#include <linux/percpu.h>
#include <linux/kthread.h>
#include <linux/sched.h>
#include <linux/delay.h>
#include <linux/smp.h>

#define PRINT_PREF "[PERCPU] "
struct task_struct *thread1, *thread2, *
      thread3;
void *my_var2;

static int thread_function(void *data)
{
  while(!kthread_should_stop()) {
    int *local_ptr, cpu;
    local_ptr = get_cpu_ptr(my_var2);
    cpu = smp_processor_id();
    (*local_ptr)++;
    printk("cpu[%d] = %d\n", cpu, *
      local_ptr);
    put_cpu_ptr(my_var2);
    msleep(500);
  }
  do_exit(0);
}
```

```c
static int __init my_mod_init(void)
{
  int *local_ptr;
  int cpu;
  printk(PRINT_PREF "Entering module.\n");

  my_var2 = alloc_percpu(int);
  if(!my_var2)
    return -1;

  for(cpu=0; cpu<NR_CPUS; cpu++) {
    local_ptr = per_cpu_ptr(my_var2, cpu);
    *local_ptr = 0;
    put_cpu();
  }

  wmb();

  thread1 = kthread_run(thread_function,
      NULL, "percpu-thread1");
  thread2 = kthread_run(thread_function,
      NULL, "percpu-thread2");
  thread3 = kthread_run(thread_function,
      NULL, "percpu-thread3");

  return 0;
}
```

# Stack, high memory and per-cpu allocation

## Per-CPU allocation: usage example (dynamic) (2)

```
static void __exit my_mod_exit(void)
{
  kthread_stop(thread1);
  kthread_stop(thread2);
  kthread_stop(thread3);

  free_percpu(my_var2);

  printk(KERN_INFO "Exiting module.\n");
}

module_init(my_mod_init);
module_exit(my_mod_exit);

MODULE_LICENSE("GPL");
```

# Stack, high memory and per-cpu allocation

## Choosing the right allocation method

- Need physically contiguous memory?
  - `kmalloc()` or low-level allocator, with flags:
    - `GFP_KERNEL` if sleeping is allowed
    - `GFP_ATOMIC` otherwise
- Need large amount of memory, not physically contiguous:
  - `vmalloc()`
- Frequently creating/destroying large amount of the same data structure:
  - Use the slab layer
- Need to allocate from high memory?
  - Use `alloc_page()` then `kmap()` or `kmap_atomic()`

# Bibliography I

[1] Cramming more into struct page.
https://lwn.net/Articles/565097/.
Accessed: 2017-03-12.

[2] Gfp_kernel or slab_kernel?
https://lwn.net/Articles/23042/.
Accessed: 2017-03-18.

[3] The slub allocator.
https://lwn.net/Articles/229984/.
Accessed: 2017-03-18.

[4] Bonwick, J., et al.
The slab allocator: An object-caching kernel memory allocator.
In *USENIX summer* (1994), vol. 16, Boston, MA, USA.

[5] Lameter, C.
Slab allocators in the linux kernel: Slab, slob, slub.
LinuxCon/Dsseldorf 2014,
http://events.linuxfoundation.org/sites/events/files/slides/slaballocators.pdf.
Accessed: 2017-03-18.