Linux Memory Manager `Pageman`

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Abstract

This report introduces **Pageman**, a memory manager designed for Linux systems. Pageman addresses a problem in the freelist buddy allocator used for physical page allocation. The allocator's predefined block sizes create difficulties when allocating memory blocks that don't fit into these sizes, particularly for low-level programs like device drivers and kernel internals which donot have the luxury of relying on virtual contiguous pages.

Existing solutions attempt to reduce fragmentation by trimming allocated blocks and freeing excess memory to a lower order. However, this approach leads to the complete splitting of larger memory blocks over time, making it challenging to allocate higher order contiguous blocks overtime.

In contrast, Pageman offers a novel solution that strikes a balance between reducing fragmentation and preserving higher-order contiguous blocks. By intelligently trimming allocated blocks and retaining unused memory blocks,

Pageman improves memory utilization without sacrificing the availability of larger contiguous allocations.

Implemented within the Linux kernel, Pageman has been extensively evaluated and demonstrates its effectiveness in mitigating fragmentation while supporting larger contiguous allocations.

Overall, Pageman provides an enhanced memory management solution for Linux systems. By optimizing memory allocation, it improves system memory management and offers valuable insights for memory management in low-level programs and kernel internals.

Introduction

Memory management is a critical aspect of operating systems, and the Linux operating system employs a sophisticated memory management subsystem known as the Linux Memory Manager (Linux MM) to efficiently handle memory allocation and deallocation. Within Linux MM, various memory allocation techniques are utilized to optimize memory utilization and system performance.

One prominent memory allocation technique utilized in Linux is the freelist buddy allocator. This allocator organizes memory into fixed-size blocks and maintains a freelist structure containing linked lists of contiguous memory blocks. However, an inherent challenge faced by the freelist buddy allocator is the issue of internal fragmentation. Internal fragmentation occurs when allocated memory blocks are larger than the requested size, resulting in wasted memory within the blocks and decreased overall memory utilization efficiency.

To mitigate the problem of internal fragmentation, Linux incorporates another memory allocator known as the slab allocator. The slab allocator focuses on the efficient management of small, variable-sized objects by grouping them into caches. By allocating memory in fixed-sized slabs tailored to the object size, the slab allocator reduces internal fragmentation and minimizes wasted memory. However, the slab allocator does have limitations when it comes to allocating large contiguous blocks of memory.

In 2008, an patch was made to address the allocation of large contiguous blocks through the introduction of the `alloc_page_exact` solution in the page allocator API. However, this solution inadvertently resulted in a problem where large blocks that did not fit into individual pages were broken, leading to a scarcity of large contiguous blocks over time. This scarcity poses challenges for applications and low-level programs that require such memory regions.

The current problem we aim to address in this report is finding a balance between reducing internal fragmentation without significantly increasing the scarcity of large contiguous blocks. It is crucial to optimize memory utilization and system performance by minimizing wasted memory while still ensuring the availability of larger contiguous memory regions.

Throughout this report, we will delve into the concepts of the freelist buddy allocator, the slab allocator, the challenges introduced by the alloc_page_exact solution, and the trade-offs between reducing internal fragmentation and the scarcity of large contiguous blocks. By addressing these challenges, our goal is to enhance memory management in Linux, improving overall system performance and efficiency.

The subsequent sections of this report will provide a detailed analysis of the freelist buddy allocator, the slab allocator, the implications of the alloc_page_exact solution, and propose strategies for mitigating internal fragmentation while preserving the availability of large contiguous memory blocks. Through this research, we aim to contribute to the advancement of memory management techniques in Linux, benefiting a wide range of applications, low-level programs, and overall system performance.

Methodology

At its core, Pageman is a memory manger in the sense that it does not do the allocation but just manages the allocations. It instead sits over the Buddy allocator and intercepts any allocation of pages which can be trimmed or fitted. In a similar manner, when it detects any block previously fitted requesting to be freed, it intervenes to free it in an orderly manner to different orders in the freelist.

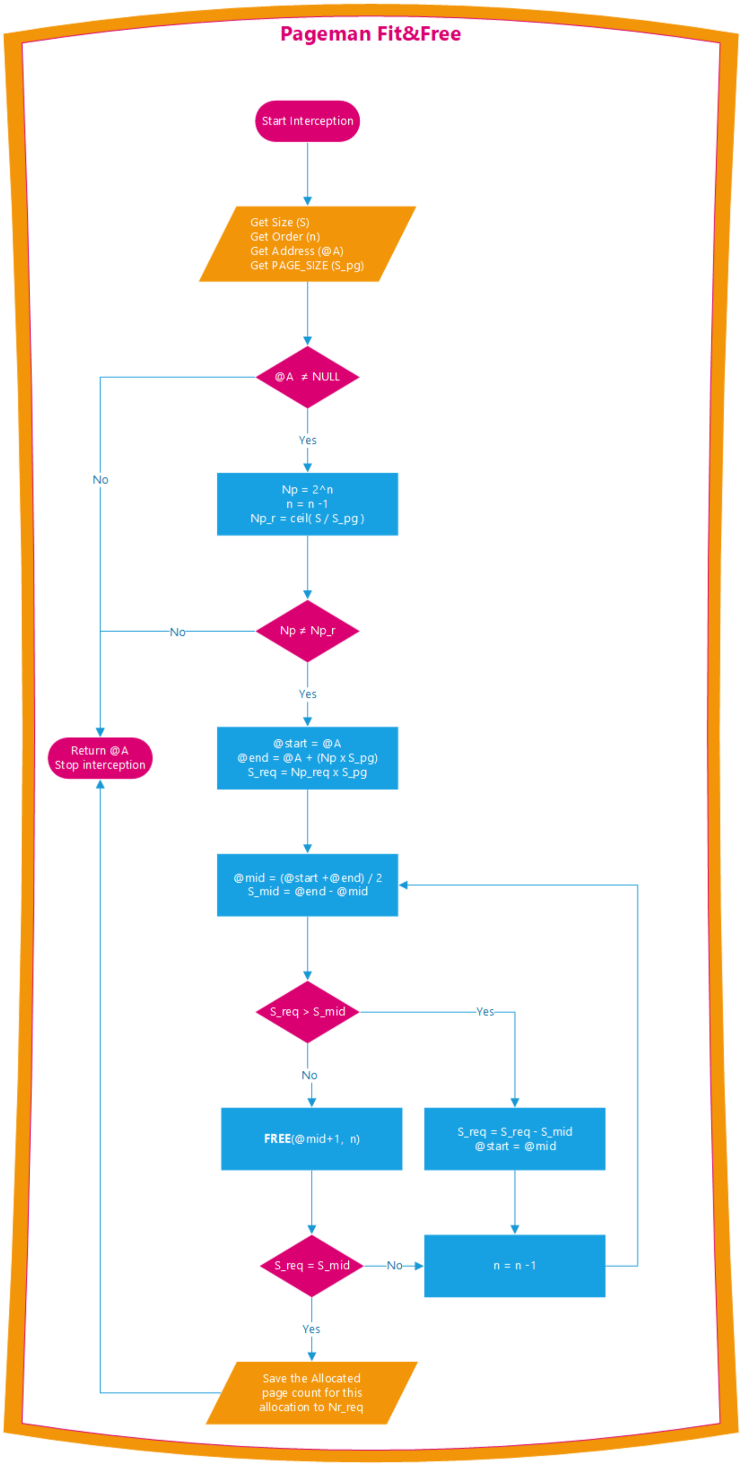
Pageman uses two pretty similar algorithms which are the **Fit&Free** during the allocation and the **Free&Fit** during the free stage. To better understand, we will place ourselves in a general scenario. Before we proceed, we need to define some variables and functions which we will be used below.

variable	Full Name	Type	Meaning
S	Size	Integer	It represents the size in Bytes of the requested allocation
n	Order	Integer	It represents the nearest power of 2 for which is greater than or equals to the size
@A	Address	Pointer	It represents the address of the start of the allocated block
S_pg	Size of a RAM PAGE	Number	This is the size of a RAM page

variable	Full Name	Type	Meaning
Np	Total Number of pages	Number	This refers to the 2^n or the number of pages which were allocated by the buddy allocator
Np_req (or Np_r)	Number of Required Pages	Number	This refers to the minimum amount of pages to fit the allocation size
S_req	Required Size	Number	This is the Size of the block minimum the amount of page required
S_mid	Half size span	Number	This is half of the size of block

Function	Argument1	Argument2	Use
ceil	Real Number		Returns the smallest integer greater than the argument
FREE	Pointer	Order	Frees from the address given to a freelist at a particular order

A call to the `alloc_pages_exact`, `alloc_pages_exact`, `__kmalloc_large_node` from the kernel subsystems i.e all page allocation apis which takes in a size as parameter. We proceed as follows.

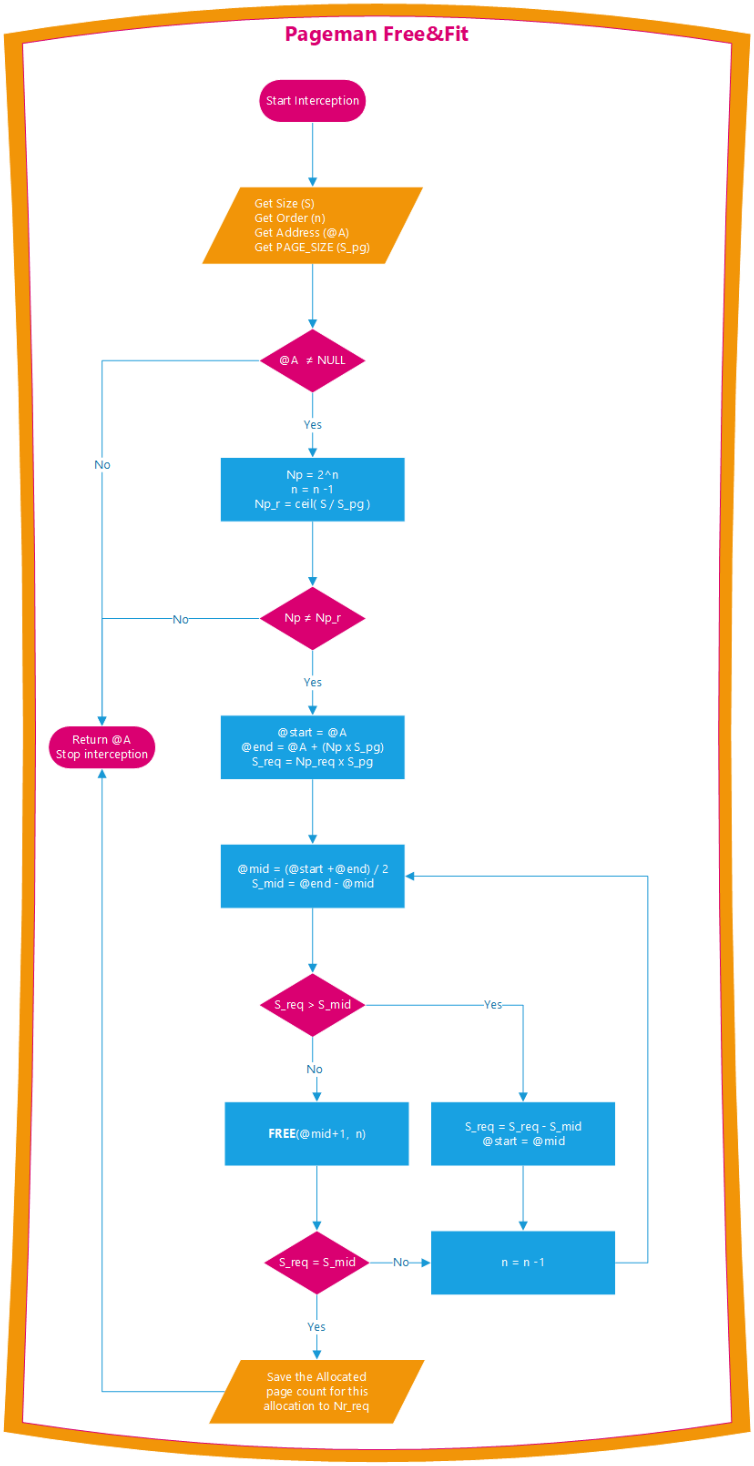


Pageman Fit&Free
Start Interception
Get Size (S)
Get Order (n)
Get Address (@A)
Get PAGE_SIZE (S_pg)
@A ≠ NULL
Yes
No
Np = 2^n
n = n -1
Np_r = ceil(S / S_pg)
Np ≠ Np_r
No
Yes
Return @A
Stop interception
@start = @A
@end = @A + (Np x S_pg)
S_req = Np_req x S_pg
@mid = (@start +@end) / 2
S_mid = @end - @mid
S_req > S_mid
Yes
No
FREE(@mid+1, n)
S_req = S_req - S_mid
@start = @mid
S_req = S_mid
No
n = n -1
Yes
Save the Allocated
page count for this
allocation to Nr_req

- We can note

that we continually half the allocated block till while freeing the unused blocks to their ideal order till we are left with a number of pages which can be allocated - If the minimum number of pages is equals to the allocated number, we donot do anything.

Analogously, any call to `free_pages_exact`, `kfree` from the kernel subsystems i.e Any page freeing APIs, we first check if we trimmed the blocked to be freed and in that case, we launch the Free&Fit algorithm as shown below.



Pageman Free&Fit
Start Interception
Get Size (S)
Get Order (n)
Get Address (@A)
Get PAGE_SIZE (S_pg)
@A ≠ NULL
Yes
No
Np = 2^n
n = n -1
Np_r = ceil(S / S_pg)
Np ≠ Np_r
No
Yes
Return @A
Stop interception
@start = @A
@end = @A + (Np x S_pg)
S_req = Np_req x S_pg
@mid = (@start +@end) / 2
S_mid = @end - @mid
S_req > S_mid
Yes
No
FREE(@mid+1, n)
S_req = S_req - S_mid
@start = @mid
S_req = S_mid
No
n = n -1
Yes
Save the Allocated
page count for this
allocation to Nr_req

- We can note

that we half the allocated space and free it to its ideal order until we are done

Here we reach the end of this rather short introduction and finally talk about the implementation of the whole system.

Implementation

The implementation was done on a linux machine with the following specs |Computer|Lenovo Thinkpad T460s| |–|–| |Firmware version| N1CET89W (1.57)| |Memory|12.0GiB| |Processor|Intel® Core™ i7-6600U × 4| |Graphics|Intel® HD Graphics 520 (SKL GT2)| |Disk Capacity|2TB| |Linux Distro|Ubuntu 23.04| |OS Type|64-bit| |Kernel Version| Linux 6.2.0-20-generic|

The project was carried out on a custom built **linux kernel version 6.5.3.**

0. Prerequisites

The following steps were carried out to setup the system

```
# The following libraries were installed during the setup process

# Updating the system libraries
sudo update
sudo upgrade

# Installing linux headers for compilation
sudo apt install build-essential dkms linux-headers-$(uname -r)

# Installing C, git, make and perl
sudo apt install git gcc make perl

# Additional libraries for compilation
sudo apt-get install libncurses-dev flex bison openssl libssl-dev dkms libelf-dev libudev-de
sudo apt install dwarves
```

1. Building a Linux kernel from source

- Download and extraction of the kernel

```
# Changing to the home directory and creating our working directory manager
cd ~
mkdir manager
cd manager

# Download the kernel archive file
wget https://cdn.kernel.org/pub/linux/kernel/v6.x/linux-6.5.3.tar.xz

# Extract the extraction
```

```
tar -xf manager/linux-6.5.3.tar.xz

# Navigating to the kernel code
cd manager/linux-6.5.3
```

- Building the kernel image and modules

```
# Copying the current system modules in an attempt to build a clone
sudo lsmod > /tmp/lsmod.now

# After putting our terminal in fullscreen, we edit the configuration of our kernel
make menuconfig
```

The last command opens a minimalist menu driven interface to tweak some of the kernel configurations.

NB: The following keys are used in the menuconfig (non exhaustive)

Keyboard Key	Meaning	Visual Effect
y	Enable	*
n	Disable	n
m	Enable as module	m
Esc(x2)	Navigate back	
Up, Down	Scroll Up, Down	
Left, Right	Navigate about the menu	Highlights the Exit, Save, Load options

The table below contains the different configurations which were done to the kernel

Feature	Info	Path in menu	Precise config option	New value
Kernel config Support	Allows us to see the current kernel config details	General Setup/ Kernel .config support	CONFIG_IKCONFIG	y
	Allows us to see current kernel configuration details via the **procfs**	General Setup/ Enable access to .config through the /proc/config.gz	CONFIG_IKCONFIG_PROC	m

Feature	Info	Path in menu	Precise config option	New value
Kernel profiling	Kernel profiling support	General Setup / Profiling support	CONFIG_PROFILING	m
HAM RADIO	Support for the HAM radio	Networking support/ Amateur Radio support	CONFIG_HAMRAIO	y
Userspace IO	UIO support	Device Drivers / Userspace I/O Drivers	CONFIG_UIO	m
	UIO platform driver with generic IRQ(Interrupt handler Request) handling	Device Drivers / Userspace I/O Drivers / Userspace I/O platform driver with generic IRQ handling	CONFIG_UIO_PDRV_GENIRQ	m
MS-DOS filesystem support	Mount NTFS drives	File systems / DOS/FAT/NT Filesystems / MSDOS fs support	CONFIG_MSDOS_FS	m
Security LSMs	Turn off kernel LSMs (Not safe for production environments)	Security options / Enable different security models	CONFIG_SECURITY	n
Kernel debug: stack utilization info	Have full debuf info about the memory	Kernel hacking / Memory Debugging / Stack utilization instrumentation	CONFIG_DEBUG_STACK_USAGE	y

- After applying all the configuration above we saved and left the menu.

We then proceseded by disabling some securities and were finally ready to build the kernel. Th e building process took 45 minutes and was very CPU and memory Intensive

Warning: Any interruption like sleeping or shutdown during the compilation process may lead to a complete corruption of the current system GUI and internal components . Thus we made sure our computer could not sleep and was well powered.

```
# ~/manger/linux-6.5.3
# Disabling some debian specific security keys
sudo scripts/config --disable SYSTEM_REVOCATION_KEYS
sudo scripts/config --disable SYSTEM_TRUSTED_KEYS

# Building the kernel and specifying the modules to install
# For parallel compilations, we used -j4 which allocates 4 cores
make LSMOD=/tmp/lsmod.now localmodconfig -j4
```

3. Setting up the Editing environment

- We used the neovim editor. The basic installation was done using the following commands.

```
# Navigate to the home directory
cd ~
# Installing the neovim image
curl -LO https://github.com/neovim/neovim/releases/latest/download/nvim.appimage
# Giving the permissions
chmod u+x nvim.appimage
./nvim.appimage
#
# if the ./nvim.appimage fails, we can try
./nvim.appimage --appimage-extract
./squashfs-root/AppRun --version

# Optional: exposing nvim globally.
sudo mv squashfs-root /
sudo ln -s /squashfs-root/AppRun /usr/bin/nvim

# Finally, we can run the editor using the command below from any where
nvim
```

After installing neovim, some setup process was needed to make it suitable for editing C code, and the resource below was of great help

Another option could have been the Code editor vscode. In that case, we could have installed the C/C++ extensions from Microsoft and the Linux Kernel extensions.

- After setting up the code editor for vanilla C code, we had make sure it understood we were dealing with Linux kernel code and could include Kernel header files. This was done beacuse the linux kernel does not use the standard gcc library. The setup was as follows.

  The StackOverflow thread was of great help

```
# Navigate to the kernel code
cd ~/manager/linux-6.5.3

# Required for code editor to navigate through the kernel code
sudo apt install cscope exuberant-ctags

# Creating an index database for easy navigation and code intelisense
# We index only indexed the x86_64 architecture directories since we had no need for cross p
make O=. ARCH=x86_64 COMPILED_SOURCE=1 cscope tags

# Next, we generated the following json file to inform our editor about some compiling opti
python3 scripts/clang-tools/gen_compile_commands.py
```

NB: Eventhough we didnot use vscode, we found the resource vscode for kernel dev potentially helpful. It mainly consists in editing the `c_cpp_properties.json`, `settings.json`, `tasks.json`, `.vscode/` to recognise the kernel header files

4. **Tweaking the kernel memory manager source code**

   This section was done with a lot of precaution since any error could make the compilation fail. We made sure to carefully add some functions and global variables necessary for the wee functioning of `Pageman`.

   - Overall the, the following kernel files were modified
     - `~/manager/linux-6.5.3/include/linux/gfp.h`
     - `~/manager/linux-6.5.3/mm/page_alloc.c`
     - `~/manager/linux-6.5.3/mm/slab_common.c`

For each file, we did specific changes as shown below

- `gfp.h` File additions

```
...
/* Added fter line 157 in gfp.h*/

/**
 * A global tracker to know if pageman has been loaded or not
 * Becomes true when pageman is loaded and false when unloaded
 */
extern bool is_pageman_loaded;
/**
 * A global variables that holds the value of the start of the virtual first page of an allo
 * When ever an allocation or deallocation is intercepted, we save the this address.
 * NB: This address is a the virtual adddress to the page and not the page address
 */
extern unsigned long gb_start_address;
/**
 * Another global variable that holds the order of an allocated request to the BuddyAllocato
 * Varies from 0 to MAX_ORDER(generally 11).
 */
extern unsigned int gb_order;
/**
 * Another global variable that holds the size in Bytes of an allocation request
 */
extern size_t gb_size;
/**
 * The size of this array is ideally equals to the total numbers of pages in our RAM. This s
 * dividing the RAM size by the size of a page.
 * e.g array size for 16GB = (16 * 1024 * 1024 KB)/(4096 KB), assuming our pages are 4KB lar
 * Since we cannot know the this at compile time, we must set assume a large enough value.
```

```
 *
 * In practice, this array stores the number of pages that were allocated for each allocati
 * durring deallocation to know the number of pages which were allocated. The index is the 
 * start_address of the allocation block and it is initialized to zeroes at compile time
 *
 * (Warning) There are limits to the size of this array above which the compilation will fa
 */
extern unsigned long pages_metadata_table[3145728];
/**
 * This is a helper function called by the allocators to set the global variables
 */
void fit_and_free_injector(unsigned long page_start_addr, unsigned int order, size_t size);
/**
 * This is a helper function called by the deallocators to set the start_address of the blo
 */
void free_and_fit_injector(unsigned long page_start_addr);
/**
 * A helper function to know if a page has been allocated by checking if its page frame num
 * value in the array
 *
 * Returns 0 if the page is not currently being allocated
 * Returns 1 if the page is currently in use or has not been deallocated
 */
extern int get_nr_pages_metadata(struct page *page);
/**
 * A helper function to set the number of pages allocated with by a block starting at that 
 * In summary for a given page, it gets the pfn and uses it as an index to set the number o
 */
extern void set_nr_pages_metadata(struct page *page, unsigned short nr_pages);

/*
 * We make the original make_alloc_exact function to become an `extern function` to avoid d
 * We also must change the definition of this function in the file
 */
extern void *make_alloc_exact(unsigned long addr, unsigned int order,
                  size_t size);
....
```

- `page_alloc.c` File modifications

Definitions of the global variables and functions defined in gfp.h

```
...

/* In page_alloc.c after line 394 */

bool is_pageman_loaded = false;
```

```
unsigned long gb_start_address = 0;
unsigned int gb_order = 0;
size_t gb_size = 0;
unsigned long pages_metadata_table[3145728] = { 0 };
void fit_and_free_injector(unsigned long page_start_addr, unsigned int order, size_t size)
{
    gb_start_address = page_start_addr;
    gb_size = size;
    gb_order = order;
}

void free_and_fit_injector(unsigned long page_start_addr)
{
    gb_start_address = page_start_addr;
}

int get_nr_pages_metadata(struct page *page)
{
    unsigned long pfn = page_to_pfn(page);
    return pages_metadata_table[pfn];
}

void set_nr_pages_metadata(struct page *page, unsigned short nr_pages)
{
    unsigned long pfn = page_to_pfn(page);
    pages_metadata_table[pfn] = nr_pages;
}




/**
 *Finally, we need to all of the above to make them visible to the out of tree build i.e Mo
 */
EXPORT_SYMBOL(is_pageman_loaded);
EXPORT_SYMBOL(gb_start_address);
EXPORT_SYMBOL(gb_order);
EXPORT_SYMBOL(gb_size);
EXPORT_SYMBOL(get_nr_pages_metadata);
EXPORT_SYMBOL(set_nr_pages_metadata);
EXPORT_SYMBOL(pages_metadata_table);
 ....
```

Modification of the `alloc_pages_exact` definition at around line 4791

```
/* In page_alloc.c */
....
```

```
/**
 * alloc_pages_exact - allocate an exact number physically-contiguous pages.
 * @size: the number of bytes to allocate
 * @gfp_mask: GFP flags for the allocation, must not contain __GFP_COMP
 *
 * This function is similar to alloc_pages(), except that it allocates the
 * minimum number of pages to satisfy the request.  alloc_pages() can only
 * allocate memory in power-of-two pages.
 *
 * This function is also limited by MAX_ORDER.
 *
 * Memory allocated by this function must be released by free_pages_exact().
 *
 * Return: pointer to the allocated area or %NULL in case of error.
 */
void *alloc_pages_exact(size_t size, gfp_t gfp_mask)
{
    unsigned int order = get_order(size);
    unsigned long addr;

    if (WARN_ON_ONCE(gfp_mask & (__GFP_COMP | __GFP_HIGHMEM)))
        gfp_mask &= ~(__GFP_COMP | __GFP_HIGHMEM);

    addr = __get_free_pages(gfp_mask, order);

    /*
   * New
   * We check if the pageman module is loaded before setting the global variables
   */
    if (is_pageman_loaded) {
        fit_and_free_injector((unsigned long)addr, order, size);
    }
    /* End */

    return make_alloc_exact(addr, order, size);
}
....
```

Modification of the `alloc_pages_exact_nid` definition at around line 4791

```
/* In page_alloc.c*/
....
/**
 * alloc_pages_exact_nid - allocate an exact number of physically-contiguous
 *              pages on a node.
 * @nid: the preferred node ID where memory should be allocated
 * @size: the number of bytes to allocate
```

```
 * @gfp_mask: GFP flags for the allocation, must not contain __GFP_COMP
 *
 * Like alloc_pages_exact(), but try to allocate on node nid first before falling
 * back.
 *
 * Return: pointer to the allocated area or %NULL in case of error.
 */
void *__meminit alloc_pages_exact_nid(int nid, size_t size, gfp_t gfp_mask)
{
    unsigned int order = get_order(size);
    struct page *p;

    if (WARN_ON_ONCE(gfp_mask & (__GFP_COMP | __GFP_HIGHMEM)))
        gfp_mask &= ~(__GFP_COMP | __GFP_HIGHMEM);

    p = alloc_pages_node(nid, gfp_mask, order);
    if (!p)
        return NULL;

    /*
   * New
   * We check if the pageman module is loaded before setting the global variables
   */
    if (is_pageman_loaded) {
        fit_and_free_injector((unsigned long)page_address(p), order,
                              size);
    }
    /* End */

    return make_alloc_exact((unsigned long)page_address(p), order, size);
}

....
```

Modification of the `free_pages_exact` definition around line 4849

```
/* In page_alloc.c */
....

/**
 * free_pages_exact - release memory allocated via alloc_pages_exact()
 * @virt: the value returned by alloc_pages_exact.
 * @size: size of allocation, same value as passed to alloc_pages_exact().
 *
 * Release the memory allocated by a previous call to alloc_pages_exact.
 */
void free_pages_exact(void *virt, size_t size)
```

```c
{
  /**
   * New
   * We check if this pageman is loaded and that this allocation was initially done by pagem
   * other wise, we leave the default behavior
   */
    if (is_pageman_loaded &&
        get_nr_pages_metadata(virt_to_page(virt)) != 0) {
        free_and_fit_injector((unsigned long)virt);
    } else {
    /* End */
        unsigned long addr = (unsigned long)virt;
        unsigned long end = addr + PAGE_ALIGN(size);

        while (addr < end) {
            free_page(addr);
            addr += PAGE_SIZE;
        }
    }
}
....
```

- Remove the static keyword from `make_alloc_exact` definition around line 4575

```c
/* In page_alloc.c around line 4575 */

/**
 * We just made the make_alloc_exact to become an extern function to avoid double definitio
 */
void *make_alloc_exact(unsigned long addr, unsigned int order,
        size_t size)
{
    if (addr) {
        unsigned long nr = DIV_ROUND_UP(size, PAGE_SIZE);
        struct page *page = virt_to_page((void *)addr);
        struct page *last = page + nr;

        split_page_owner(page, 1 << order);
        split_page_memcg(page, 1 << order);
        while (page < --last)
            set_page_refcounted(last);

        last = page + (1UL << order);
        for (page += nr; page < last; page++)
            __free_pages_ok(page, 0, FPI_TO_TAIL);
    }
```

```c
    return (void *)addr;
}
```

- `slab_common.c` Modifications Firstly we modify the `__kmalloc_large_node`(after line 1116) which is called when the allocation size of `kmalloc` is too large for any preallocated slab.

```c
/* In slab_common.c File after 1116*/
/*
 * To avoid unnecessary overhead, we pass through large allocation requests
 * directly to the page allocator. We use __GFP_COMP, because we will need to
 * know the allocation order to free the pages properly in kfree.
 */

static void *__kmalloc_large_node(size_t size, gfp_t flags, int node)
{
    struct page *page;
    void *ptr = NULL;
    unsigned int order = get_order(size);

    if (unlikely(flags & GFP_SLAB_BUG_MASK))
        flags = kmalloc_fix_flags(flags);

    flags |= __GFP_COMP;
    page = alloc_pages_node(node, flags, order);
    if (page) {
        ptr = page_address(page);
        /**
     * New
     * We first check if pageman is loaded, next we make sure the allocation size is not a p
     * FInally, we make sure the size allocated is not more than the buddy allocator can han
     * In case everything is ok, we set the global variables and launch the make_alloc_exact
     * pageman and Fit the number of pages
     *
     * Else, we use the default behavior ...
     */
        if (is_pageman_loaded &&
            DIV_ROUND_UP(size, PAGE_SIZE) != 1 << order &&
            size < (1 << MAX_ORDER) * PAGE_SIZE) {
            fit_and_free_injector((unsigned long)ptr, order, size);
            return make_alloc_exact((unsigned long)ptr, order,
                        size);
        }
        /** End **/
        mod_lruvec_page_state(page, NR_SLAB_UNRECLAIMABLE_B,
                      PAGE_SIZE << order);
    }
```

```c
    ptr = kasan_kmalloc_large(ptr, size, flags);
    /* As ptr might get tagged, call kmemleak hook after KASAN. */
    kmemleak_alloc(ptr, size, 1, flags);
    kmsan_kmalloc_large(ptr, size, flags);

    return ptr;
}
```

Next, we edit the `kmalloc_large`(after line) and `kmalloc_large_node` allocators wrappers to know how to trace the allocations by setting the pages actually allocated in case pageman was active

```c
/* In slab_common.c after line 1158 */

void *kmalloc_large(size_t size, gfp_t flags)
{
    void *ret = __kmalloc_large_node(size, flags, NUMA_NO_NODE);

    /** New: 0 if the allocation failed*/
    unsigned long nr_pages = get_nr_pages_metadata(virt_to_page(ret));

    /**
   * New
   * In case pageman is loaded and the allocation was successfull, we instead trace the  nr_
   */
    if (is_pageman_loaded && nr_pages != 0) {
        trace_kmalloc(_RET_IP_, ret, size, nr_pages, flags,
                  NUMA_NO_NODE);
        /*End*/
    } else {
        trace_kmalloc(_RET_IP_, ret, size, PAGE_SIZE << get_order(size),
                  flags, NUMA_NO_NODE);
    }
    return ret;
}
...

/** In slab_common.c */

void *kmalloc_large_node(size_t size, gfp_t flags, int node)
{
    void *ret = __kmalloc_large_node(size, flags, NUMA_NO_NODE);

    /** New: 0 if the allocation failed*/
    unsigned long nr_pages = get_nr_pages_metadata(virt_to_page(ret));
    /**
```

```
    * New
    * In case pageman is loaded and the allocation was successfull, we instead trace the nr_p
    */

    if (is_pageman_loaded && nr_pages != 0) {
        trace_kmalloc(_RET_IP_, ret, size, nr_pages, flags, node);
    /*End*/
    } else {
        trace_kmalloc(_RET_IP_, ret, size, PAGE_SIZE << get_order(size),
                  flags, node);
    }

    return ret;
}
```

That marked the end of the modifications in the kernel code. In Summary, introduce hooking points and state savers in the kernel code. All this was in order to make our module function well.

5. Booting from our kernel

- After editing our kernel source files, we were required to boot from it before implementing our module.

  It was noted that after running the commands below, the system booted automatically from our own kernel. This was confirmed by using `uname -r` command.

```
# In ~/manager/linux-6.5.3/
# We rebuilt the kernel
make -j4

# After building the kernel, we build the modules which we once copied to /tmp/lsmod.now
sudo make modules_install

# Finally, we tell the system to boot with the new kernel
sudo make install

# Editing the grub timeout time
cd /etc/default/
# Opening the grub file and increasing the GRUB_TIMEOUT to 5 using nano, vim or any othe edi
nano grub

# After closing and saving our work, we rebooted
sudo reboot
```

- When the PC failed to reboot, we navigated through the grub menu advanced options to choose the previous kernel. Otherwise, we were ready to implemented the Pageman

6. Implementing the Pageman Module

As stated before, the the main purpose of the pageman module is to intercept all allocations which makes a call to the `make_alloc_exact`(found in `~/manager/linux-6.5.3/mm/page_alloc.c`) and all deallocations which makes a call to `free_pages_exact` which are the APIs we modified in above. After a call is make to the `make_alloc_exact`, we intercept it and use the global varibles to Fit the allocation or the deallocation size.

The process of Fitting can be summarized as allocating the minimum number of pages required followed by freeing the rest in the case of an allocation and freeing only the required number of pages to a particular order during a deallocation.

We implimented our module as follows

- To begin, we created the module files as follows

```
# We created the module in the kernel source code location to get code intellisense out of t
cd ~/manager/linux-6.5.3/

# Created a directory to hold our module
mkdir pageman
cd pageman

# Created the source code file and the make file
touch ./Makefile
touch ./pageman.c

# Also added a header file for easy hooking
touch ./ftrace_helper.h
```

- We implimented `Makefile` as follows.

```
# In Makefile

# A simple Makefile to compile the module
obj-m += pageman.o
all:
    # This builds the module and load it into the directory for kernel modules
    make -C /lib/modules/$(shell uname -r)/build M=$(PWD) modules

clean:
    # Delete all build files from the kernel modules directory
    make -C /lib/modules/$(shell uname -r)/build M=$(PWD) clean
```

- Next, we implemented the `ftrace_helper.h` to facilitate the hooking (greatly inspired by the resource TheXcellerator) as follows

```c
/*
 * Helper library for ftrace hooking kernel functions
 * Original Author: Harvey Phillips (xcellerator@gmx.com)
 * Edited By: Lado Saha (@sih)
 * License: GPL
 */

#include "linux/module.h"
#include <linux/ftrace.h>
#include <linux/version.h>
#include <linux/kallsyms.h>

#if defined(CONFIG_X86_64) && LINUX_VERSION_CODE >= KERNEL_VERSION(4, 17, 0)
#define PTREGS_SYSCALL_STUBS 1
#endif
#define HOOK(_name, _hook, _orig)                                   \
    {                                                               \
        .name = _name, .function = (_hook), .original = (_orig), \
    }

/*
 * We need to prevent recursive loops when hooking, otherwise the kernel will
 * panic and hang. The options are to either detect recursion by looking at
 * the function return address, or by jumping over the ftrace call. We use the
 * first option, by setting USE_FENTRY_OFFSET = 0, but could use the other by
 * setting it to 1. (Oridinarily ftrace provides it's own protections against
 * recursion, but it relies on saving return registers in $rip. We will likely
 * need the use of the $rip register in our hook, so we have to disable this
 * protection and implement our own).
*/
#define USE_FENTRY_OFFSET 0
/* We pack all the information we need (name, hooking function, original function)
 * into this struct. This makes is easier for setting up the hook and just passing
 * the entire struct off to fh_install_hook() later on.
 * */
struct ftrace_hook {
    const char *name;
    void *function;
    void *original;
    unsigned long address;
    struct ftrace_ops ops;
};

/* Ftrace needs to know the address of the original function that we
 * are going to hook. As before, we just use kallsyms_lookup_name()
 * to find the address in kernel memory.
```

```
 * */
static int fh_resolve_hook_address(struct ftrace_hook *hook)
{
    hook->address = kallsyms_lookup_name(hook->name);

    if (!hook->address) {
        printk(KERN_DEBUG "pageman_hook: unresolved symbol: %s\n",
               hook->name);
        return -ENOENT;
    }

#if USE_FENTRY_OFFSET
    *((unsigned long *)hook->original) = hook->address + MCOUNT_INSN_SIZE;
#else
    *((unsigned long *)hook->original) = hook->address;
#endif

    return 0;
}

/* See comment below within fh_install_hook() */
static void notrace fh_ftrace_thunk(unsigned long ip, unsigned long parent_ip,
                    struct ftrace_ops *ops,
                    struct ftrace_regs *regs)
{
    struct ftrace_hook *hook = container_of(ops, struct ftrace_hook, ops);

#if USE_FENTRY_OFFSET
    regs->ip = (unsigned long)hook->function;
#else
    if (!within_module(parent_ip, THIS_MODULE))
        regs->regs.ip = (unsigned long)hook->function;
#endif
}

/* Assuming we've already set hook->name, hook->function and hook->original, we
 * can go ahead and install the hook with ftrace. This is done by setting the
 * ops field of hook (see the comment below for more details), and then using
 * the built-in ftrace_set_filter_ip() and register_ftrace_function() functions
 * provided by ftrace.h
 * */
int fh_install_hook(struct ftrace_hook *hook)
{
    int err;
    err = fh_resolve_hook_address(hook);
    if (err)
```

```c
        return err;
    /* For many of function hooks (especially non-trivial ones), the $rip
     * register gets modified, so we have to alert ftrace to this fact. This
     * is the reason for the SAVE_REGS and IP_MODIFY flags. However, we also
     * need to OR the RECURSION_SAFE flag (effectively turning if OFF) because
     * the built-in anti-recursion guard provided by ftrace is useless if
     * we're modifying $rip. This is why we have to implement our own checks
     * (see USE_FENTRY_OFFSET). */
    hook->ops.func = fh_ftrace_thunk;

    hook->ops.flags = FTRACE_OPS_FL_SAVE_REGS | FTRACE_OPS_FL_RECURSION |
              FTRACE_OPS_FL_IPMODIFY;

    err = ftrace_set_filter_ip(&hook->ops, hook->address, 0, 0);
    if (err) {
        printk(KERN_DEBUG
               "pageman_hook: ftrace_set_filter_ip() failed: %d\n",
               err);
        return err;
    }

    err = register_ftrace_function(&hook->ops);
    if (err) {
        printk(KERN_DEBUG
               "pageman_hook: register_ftrace_function() failed: %d\n",
               err);
        return err;
    }

    return 0;
}

/* Disabling our function hook is just a simple matter of calling the built-in
 * unregister_ftrace_function() and ftrace_set_filter_ip() functions (note the
 * opposite order to that in fh_install_hook()).
 * */
void fh_remove_hook(struct ftrace_hook *hook)
{
    int err;
    err = unregister_ftrace_function(&hook->ops);
    if (err) {
        printk(KERN_DEBUG
               "pageman_hook: unregister_ftrace_function() failed: %d\n",
               err);
    }
```

```c
    err = ftrace_set_filter_ip(&hook->ops, hook->address, 1, 0);
    if (err) {
        printk(KERN_DEBUG
               "pageman_hook: ftrace_set_filter_ip() failed: %d\n",
               err);
    }
}

/* To make it easier to hook multiple functions in one module, this provides
 * a simple loop over an array of ftrace_hook struct
 * */
int fh_install_hooks(struct ftrace_hook *hooks, size_t count)
{
    int err;
    size_t i;

    for (i = 0; i < count; i++) {
        err = fh_install_hook(&hooks[i]);
        if (err)
            goto error;
    }
    return 0;

error:
    while (i != 0) {
        fh_remove_hook(&hooks[--i]);
    }
    return err;
}

void fh_remove_hooks(struct ftrace_hook *hooks, size_t count)
{
    size_t i;

    for (i = 0; i < count; i++)
        fh_remove_hook(&hooks[i]);
}
```

- Finally we implemented the main module `pageman.c` as follows. The code was well documented

```c
/** In pageman.c **/

#include "asm/page.h"
#include "asm/ptrace.h"
#include "linux/linkage.h"
#include "linux/panic.h"
```

```c
#include "linux/printk.h"
#include "linux/stddef.h"
#include <linux/module.h>
#include <linux/gfp.h>
#include <linux/ftrace.h>
#include "ftrace_helper.h"

/*
  * Every kernel module must present it self to the kernel. This is done using different MOD
*/
MODULE_LICENSE("GPL");
MODULE_AUTHOR("LADO SAHA");
MODULE_DESCRIPTION(
    "Another way mitigate the internal fragmentation of the Buddy Allocator.");
MODULE_VERSION("0.01");

#define MODULE_NAME "Pageman"
#define MOD_NAME_FIT MODULE_NAME "(Fit): "
#define MOD_NAME_FREE MODULE_NAME "(Free): "

/**
* The fit and free function is responsible for trimming down the number of allocated pages t
* then carefully frees the excess pages in such a way not to completely decompose higher ord
* When ever we intercept an allocation call with a size (x) KB, of order (n), and starting a
* 1) Ideal Case: x can be written as a 2^n times PAGE_SIZE e.g x=128KiB, x=1024KiB etc, we d
* 2) Worst Case: x cannot be written as 2^n times PAGE_SIZE e,g x=129KiB, x=1000KiB etc we t
*   2.0) We calculate the pages allocated by the buddy allocator by using the fact that it u
*   2.1) We calculate the minimum amount of pages which can fit the size (nr_pages_req) by f
*   2.1) We successively divide the address space orignally spanning from (virt to virt + 2
*       the size
*     2.1.1) In case the size can (not exactly) fit, we free right half to the required orde
*         In  case the size is exactly fit to the left half, we just free the right half and
*     2.1.2) In case the size cannot fit into the left half, we mark the left as allocated t
*         size required by subtracting from it the size of the left half allocated.
*     We decreement the order (n--) and restart the subdivision.
*
*   2.3) We finally stop, save the number of pages allocated in the pages_metadata array at
*     and return the initial address of the memory block and at this point we know that we h
*     required for the size.
* Complexity O(log2(n)) and in most computers, n = 11 thus O(1)
*
* @regs Eventhough this is unused, this the pointer to the registers of the hooked function
* returns address
*/
asmlinkage void *fit_and_free(const struct pt_regs *regs);
```

```
/**
 * This is a pointer to the make_alloc_exact function in the kernel. We do this to be able t
 * @pt_regs is the pointer to the registry entry which contains the information about the f
 */
asmlinkage void *(*orig_make_alloc_exact)(const struct pt_regs *);

/**
 * This is a pointer to the free_pages_exact function in the kernel which is hooked or inter
 */
asmlinkage void (*orig_free_pages_exact)(const struct pt_regs *);

/**
* The free and fit function is responsible for freeing the previously fitted pages.
* When ever we intercept a deallocation call on an address which was previously fitted(We kn
* If this is not the case, we do nothing else we execute this function.
* 1) We get the number of pages allocated from the array and calculate the size (x) KiB of t
* 2) We calculate the pages allocated which were to be allocated by the buddy allocator by t
*   2.1) We successively divide the address space orignally spanning from (virt to virt + 2
*       the allocated size
*     2.1.1) In case the size can (but not exactly) fit, we just consider the left half and
*         In  case the size can exactly fit to the left half, we just free the left half and
*     2.1.2) In case the size cannot fit into the left half, we free the left half to the re
*         from it the size of the left half freed and continue
*     We decreement the order (n--) and restart the subdivision.
*   2.2) We finally stop and reset the value of allocated pages in the array at index page f
* Complexity O(log2(n)) and in most computers, n = 11 thus O(1)
*
* @regs Eventhough this is unused, this the pointer to the registers of the hooked function
*/
asmlinkage void free_and_fit(const struct pt_regs *regs);

asmlinkage void *fit_and_free(const struct pt_regs *regs)
{
    unsigned long start_address = gb_start_address;

    if ((void *)start_address == NULL) {
        pr_err(MOD_NAME_FIT "Initial allocation failed\n");
        return NULL;
    }

    size_t size = gb_size;
    unsigned int nr_pages_req = DIV_ROUND_UP(size, PAGE_SIZE),
             init_order = gb_order, total_nr_pages = 1 << init_order;

    if (total_nr_pages == nr_pages_req) {
        pr_info(MOD_NAME_FIT
```

```
        "Nothing to fit with %zu KB and %u Pages\n",
        size / 1024, nr_pages_req);
    return (void *)start_address;
}

struct timespec64 start_time, end_time;
s64 elapsed_time;
unsigned long addr_start, addr_mid, addr_end, size_span, req_span;
struct page *page_head;
unsigned int order = init_order - 1;

// This is a log to benchmark the process
ktime_get_ts64(&start_time);
pr_info(MOD_NAME_FIT
    "Order From\t\t Mid\t\t To\t\t Fit_pages\t Fit_size\t Half_size\n");

addr_start = start_address;
addr_end = start_address + total_nr_pages * PAGE_SIZE;
req_span = PAGE_SIZE * nr_pages_req;

while (1) {
    addr_mid = (addr_start / 2 + addr_end / 2);
    size_span = addr_end - addr_mid;
    pr_info(MOD_NAME_FIT
        "%u   0x%lx 0x%lx 0x%lx \t%u \t%lu KB \t%lu KB\n",
        order, addr_start, addr_mid, addr_end, nr_pages_req,
        (req_span / 1024), (size_span / 1024));
    if (req_span > size_span) {
        req_span -= size_span;
        addr_start = addr_mid;
        order--;
    } else {
        page_head = virt_to_page((void *)(addr_mid + 1));
        __free_pages(page_head, order);
        if (req_span == size_span) {
            set_nr_pages_metadata(
                virt_to_page((void *)start_address),
                nr_pages_req);
            break;
        }
        addr_end = addr_mid;
        order--;
    }
}
// This is a log to benchmark the process
ktime_get_ts64(&end_time);
```

```
    elapsed_time = timespec64_sub(end_time, start_time).tv_nsec;
    pr_info(MOD_NAME_FIT
        "Stats| Fit_size=%lu KB \t Required_pages=%u \tOriginal_pages=%u \tElapse=%llu ns \r
        (size / 1024), nr_pages_req, total_nr_pages, elapsed_time);
    return (void *)start_address;
}

asmlinkage void (*orig_free_pages_exact)(const struct pt_regs *);

asmlinkage void free_and_fit(const struct pt_regs *regs)
{
    orig_free_pages_exact(regs);
    unsigned long start_address = gb_start_address;
    if ((void *)start_address == NULL) {
        pr_info(MOD_NAME_FREE "Invalid Address\n");
        return;
    };
    unsigned int fit_nr_pages =
        get_nr_pages_metadata(virt_to_page((void *)start_address));
    if (fit_nr_pages == 0) {
        pr_info(MOD_NAME_FREE "Not required\n");
        return;
    }

    struct page *page_head;
    unsigned long addr_start, addr_end, addr_mid, size_span, req_span;
    struct timespec64 start_time, end_time;
    s64 elapsed_time;
    // This is a log to benchmark the process
    ktime_get_ts64(&start_time);
    req_span = fit_nr_pages * PAGE_SIZE;
    unsigned short init_order = get_order(req_span);
    unsigned short order = init_order - 1;
    unsigned long total_nr_pages = 1 << init_order;

    if (fit_nr_pages == total_nr_pages) {
        pr_info(MOD_NAME_FREE "Nothing to Fit\n");
        return;
    }
    pr_info(MOD_NAME_FREE
        "Order From\t\t Mid\t\t To\t\t fit_pages\t left_size\t Half_size\n");

    addr_start = start_address;
    addr_end = start_address + (total_nr_pages * PAGE_SIZE);
    while (1) {
        addr_mid = addr_start / 2 + addr_end / 2;
```

```
        size_span = addr_end - addr_mid;
        pr_info(MOD_NAME_FREE
            "%u   0x%lx 0x%lx 0x%lx \t%u \t%lu KB \t%lu KB\n",
            order, addr_start, addr_mid, addr_end, fit_nr_pages,
            (req_span / 1024), (size_span / 1024));
        if (req_span < size_span) {
            addr_end = addr_mid;
            order--;
        } else {
            page_head = virt_to_page((void *)(addr_start));
            __free_pages(page_head, order);
            if (req_span == size_span) {
                set_nr_pages_metadata(
                    virt_to_page((void *)start_address), 0);
                break;
            }
            req_span -= size_span;
            addr_start = addr_mid;
            order--;
        }
    }

    // This is a log to benchmark the process
    ktime_get_ts64(&end_time);
    elapsed_time = timespec64_sub(end_time, start_time).tv_nsec;
    pr_info(MOD_NAME_FREE
        "Stats| Free_size=%lu KB \t fit_pages=%u \tMax_pages=%lu \tElapse=%llu ns\n\n",
        (fit_nr_pages * PAGE_SIZE) / 1024, fit_nr_pages, total_nr_pages,
        elapsed_time);
}

/**
 * This array contains all the hooks to the functions.
 * We first write the name of the function to hook, followed by the function to be called i
*/
static struct ftrace_hook hooks[2] = {
    // Hook to the function make_alloc_exact by fit_and_free
    HOOK("make_alloc_exact", fit_and_free, &orig_make_alloc_exact),
    // Hook to the function free_pages_exact by free_and_fit
    HOOK("free_pages_exact", free_and_fit, &orig_free_pages_exact)
};

/**
 * We initialize the pageman module.
 * During the initialization, we insert the hooks into memory and await function calls to t
 * Then, we set @is_pageman_loaded to True meaning the hooks have been installed and pagema
```

```c
*/
static int __init pageman_init(void)
{
    int err;
    err = fh_install_hooks(hooks, ARRAY_SIZE(hooks));
    if (err)
        return err;

    is_pageman_loaded = true;
    pr_info(MODULE_NAME "Succesfully loaded\n");
    return 0;
}

/**
 * We destroy or uninstall our module including the hooks.
 * Then make sure we set @is_pageman_loaded to False
  */
static void __exit pageman_exit(void)
{
    fh_remove_hooks(hooks, ARRAY_SIZE(hooks));

    is_pageman_loaded = false;
    pr_info("Pageman(F&F): unloaded\n");
}

// This 2 calls are respectively called when we insert and remove our modules.
module_init(pageman_init);
module_exit(pageman_exit);
```

7. Insterting and running Pageman

Pageman could be inserted at boot time or later. The safer option was to insert it at runtime before finally inserting at boot time

- Inserting Pageman after boot

```bash
# In file ~/manager/linux-6.5.3/pageman/
# Compiling Pageman and generating the module file (pageman.ko)
make all

# Insertion of the module
sudo insmod pageman.ko

# Verifying the insertion was successfull was in one part done by querying the list of load
lsmod | grep pageman

# Seeing the actions of Pageman from its log messages
```

```
sudo dmesg

# Or to watch it live updates and exit with (Ctrl+C)
sudo dmesg -w

# Removing the module
sudo rmmod pageman
```

- Inserting Pageman during boot

To do this, we had proceeded as follows

```
# Navigate to the modules-load.d directory
cd /etc/modules-load.d

# Append our module name to the `module.conf` file
sudo cat pageman >> modules.conf

# Next, we navigate to a convinient location to copy our <module_name>.ko file
# We chose to add it to the /acpi directory but any other choice is valid
cd ~/manager/linux-6.5.3/pageman
make clean
make
sudo cp pageman.ko /lib/modules/6.5.3/drivers/acpi

# Finally, we rebuid the modules index
sudo depmod

# Then we can reboot the computer and test
sudo reboot

# To undo the chages, we just do the reverse
# i.e removing our module name and module.ko file then running `sudo depmod`
```

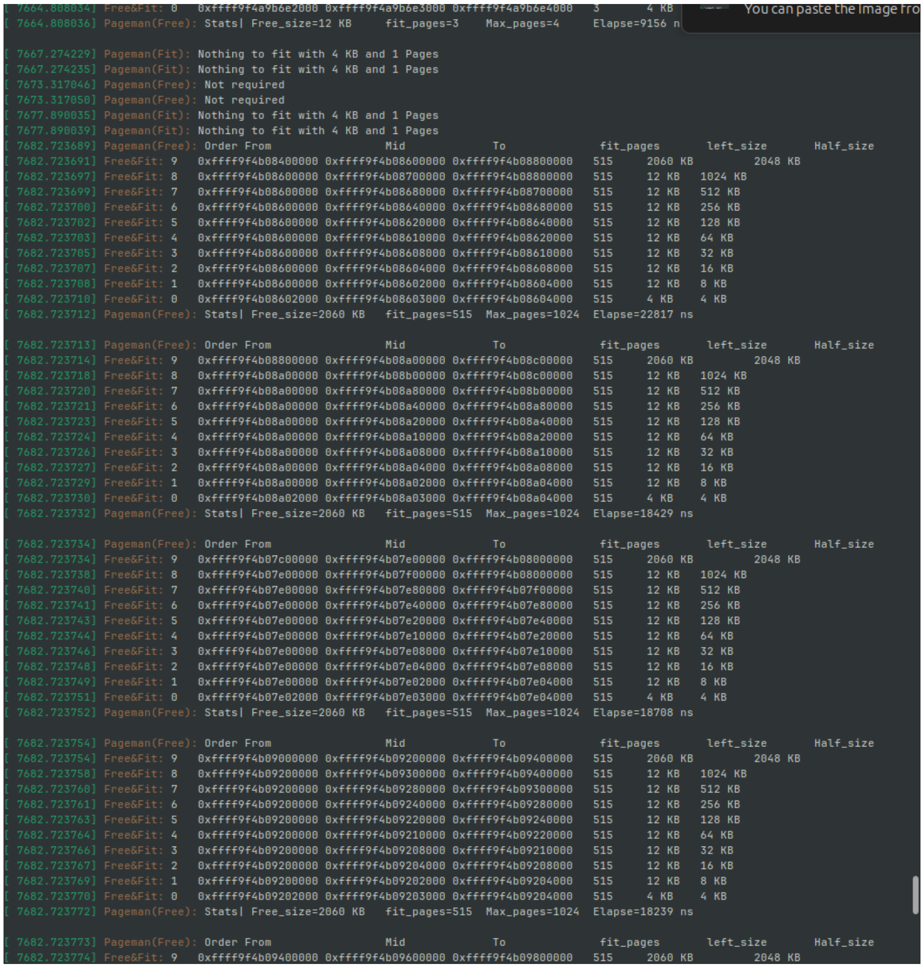
This wrapped up the implementation of pageman. After this, we noticed the following results

Results

After the implementation, we could admire the results of our pageman module hijacking the normal linux page allocator. By consulting kernel log messages we were able to get the following screenshots

```
Nov 23 01:36:06 sih-pc systemd-modules-load[236]: Inserted module 'pageman'
Nov 23 01:36:06 sih-pc kernel: PagemanSuccesfully loaded
```

```
Nov 23 01:36:07 sih-pc kernel: Pageman(Free): Order From              Mid               To              fit_pages       left_size       Half_size
Nov 23 01:36:07 sih-pc kernel: Free&Fit: 1   0xffff9f49473b4000 0xffff9f49473b6000 0xffff9f49473b8000        3        12 KB       8 KB
Nov 23 01:36:07 sih-pc kernel: Free&Fit: 0   0xffff9f49473b6000 0xffff9f49473b7000 0xffff9f49473b8000        3        4 KB        4 KB
Nov 23 01:36:07 sih-pc kernel: Pageman(Free): Stats| Free_size=12 KB          fit_pages=3         Max_pages=4         Elapse=5655 ns
Nov 23 01:36:07 sih-pc kernel: Pageman(Fit): Order From              Mid               To              Fit_pages       Fit_size        Half_size
Nov 23 01:36:07 sih-pc kernel: Pageman(Fit): 1   0xffff9f49473b8000 0xffff9f49473ba000 0xffff9f49473bc000        3        12 KB       8 KB
Nov 23 01:36:07 sih-pc kernel: Pageman(Fit): 0   0xffff9f49473ba000 0xffff9f49473bb000 0xffff9f49473bc000        3        4 KB        4 KB
Nov 23 01:36:07 sih-pc kernel: Pageman(Fit): Stats| Fit_size=8 KB          Required_pages=3         Original_pages=4         Elapse=8742 ns
Nov 23 01:36:07 sih-pc kernel: Pageman(Free): Order From              Mid               To              fit_pages       left_size       Half_size
Nov 23 01:36:07 sih-pc kernel: Free&Fit: 1   0xffff9f49473b8000 0xffff9f49473ba000 0xffff9f49473bc000        3        12 KB       8 KB
Nov 23 01:36:07 sih-pc kernel: Free&Fit: 0   0xffff9f49473ba000 0xffff9f49473bb000 0xffff9f49473bc000        3        4 KB        4 KB
Nov 23 01:36:07 sih-pc kernel: Pageman(Free): Stats| Free_size=12 KB          fit_pages=3         Max_pages=4         Elapse=5842 ns
Nov 23 01:36:07 sih-pc kernel: Pageman(Fit): Order From              Mid               To              Fit_pages       Fit_size        Half_size
Nov 23 01:36:07 sih-pc kernel: Pageman(Fit): 1   0xffff9f49473bc000 0xffff9f49473be000 0xffff9f49473c0000        3        12 KB       8 KB
Nov 23 01:36:07 sih-pc kernel: Pageman(Fit): 0   0xffff9f49473be000 0xffff9f49473bf000 0xffff9f49473c0000        3        4 KB        4 KB
Nov 23 01:36:07 sih-pc kernel: Pageman(Fit): Stats| Fit_size=8 KB          Required_pages=3         Original_pages=4         Elapse=8212 ns
Nov 23 01:36:07 sih-pc kernel: Pageman(Free): Order From              Mid               To              fit_pages       left_size       Half_size
Nov 23 01:36:07 sih-pc kernel: Free&Fit: 1   0xffff9f49473bc000 0xffff9f49473be000 0xffff9f49473c0000        3        12 KB       8 KB
Nov 23 01:36:07 sih-pc kernel: Free&Fit: 0   0xffff9f49473be000 0xffff9f49473bf000 0xffff9f49473c0000        3        4 KB        4 KB
Nov 23 01:36:07 sih-pc kernel: Pageman(Free): Stats| Free_size=12 KB          fit_pages=3         Max_pages=4         Elapse=5515 ns
Nov 23 01:36:07 sih-pc kernel: Pageman(Fit): Order From              Mid               To              Fit_pages       Fit_size        Half_size
Nov 23 01:36:07 sih-pc kernel: Pageman(Fit): 1   0xffff9f4948450000 0xffff9f4948452000 0xffff9f4948454000        3        12 KB       8 KB
Nov 23 01:36:07 sih-pc kernel: Pageman(Fit): 0   0xffff9f4948452000 0xffff9f4948453000 0xffff9f4948454000        3        4 KB        4 KB
Nov 23 01:36:07 sih-pc kernel: Pageman(Fit): Stats| Fit_size=8 KB          Required_pages=3         Original_pages=4         Elapse=8291 ns
Nov 23 01:36:07 sih-pc kernel: Pageman(Free): Order From              Mid               To              fit_pages       left_size       Half_size
Nov 23 01:36:07 sih-pc kernel: Free&Fit: 1   0xffff9f4948450000 0xffff9f4948452000 0xffff9f4948454000        3        12 KB       8 KB
Nov 23 01:36:07 sih-pc kernel: Free&Fit: 0   0xffff9f4948452000 0xffff9f4948453000 0xffff9f4948454000        3        4 KB        4 KB
Nov 23 01:36:07 sih-pc kernel: Pageman(Free): Stats| Free_size=12 KB          fit_pages=3         Max_pages=4         Elapse=5946 ns
Nov 23 01:36:07 sih-pc kernel: Pageman(Fit): Order From              Mid               To              Fit_pages       Fit_size        Half_size
Nov 23 01:36:07 sih-pc kernel: Pageman(Fit): 1   0xffff9f4948454000 0xffff9f4948456000 0xffff9f4948458000        3        12 KB       8 KB
Nov 23 01:36:07 sih-pc kernel: Pageman(Fit): 0   0xffff9f4948456000 0xffff9f4948457000 0xffff9f4948458000        3        4 KB        4 KB
Nov 23 01:36:07 sih-pc kernel: Pageman(Fit): Stats| Fit_size=8 KB          Required_pages=3         Original_pages=4         Elapse=7164 ns
Nov 23 01:36:07 sih-pc kernel: Pageman(Free): Order From              Mid               To              fit_pages       left_size       Half_size
Nov 23 01:36:07 sih-pc kernel: Free&Fit: 1   0xffff9f4948454000 0xffff9f4948456000 0xffff9f4948458000        3        12 KB       8 KB
Nov 23 01:36:07 sih-pc kernel: Free&Fit: 0   0xffff9f4948456000 0xffff9f4948457000 0xffff9f4948458000        3        4 KB        4 KB
Nov 23 01:36:07 sih-pc kernel: Pageman(Free): Stats| Free_size=12 KB          fit_pages=3         Max_pages=4         Elapse=5555 ns
Nov 23 01:36:07 sih-pc kernel: Pageman(Fit): Order From              Mid               To              Fit_pages       Fit_size        Half_size
Nov 23 01:36:07 sih-pc kernel: Pageman(Fit): 1   0xffff9f4948458000 0xffff9f494845a000 0xffff9f494845c000        3        12 KB       8 KB
Nov 23 01:36:07 sih-pc kernel: Pageman(Fit): 0   0xffff9f494845a000 0xffff9f494845b000 0xffff9f494845c000        3        4 KB        4 KB
Nov 23 01:36:07 sih-pc kernel: Pageman(Fit): Stats| Fit_size=8 KB          Required_pages=3         Original_pages=4         Elapse=8919 ns
Nov 23 01:36:07 sih-pc kernel: Pageman(Free): Order From              Mid               To              fit_pages       left_size       Half_size
Nov 23 01:36:07 sih-pc kernel: Free&Fit: 1   0xffff9f4948458000 0xffff9f494845a000 0xffff9f494845c000        3        12 KB       8 KB
Nov 23 01:36:07 sih-pc kernel: Free&Fit: 0   0xffff9f494845a000 0xffff9f494845b000 0xffff9f494845c000        3        4 KB        4 KB
Nov 23 01:36:07 sih-pc kernel: Pageman(Free): Stats| Free_size=12 KB          fit_pages=3         Max_pages=4         Elapse=5985 ns
```



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[ 7664.808034] Free&Fit: 0   0xffff9f4a9b6e2000 0xffff9f4a9b6e3000 0xffff9f4a9b6e4000   3      4 KB
[ 7664.808036] Pageman(Free): Stats| Free_size=12 KB     fit_pages=3    Max_pages=4     Elapse=9156 n

[ 7667.274229] Pageman(Fit): Nothing to fit with 4 KB and 1 Pages
[ 7667.274235] Pageman(Fit): Nothing to fit with 4 KB and 1 Pages
[ 7673.317046] Pageman(Free): Not required
[ 7673.317050] Pageman(Free): Not required
[ 7677.890035] Pageman(Fit): Nothing to fit with 4 KB and 1 Pages
[ 7677.890039] Pageman(Fit): Nothing to fit with 4 KB and 1 Pages
[ 7682.723689] Pageman(Free): Order From                Mid               To                fit_pages       left_size       Half_size
[ 7682.723691] Free&Fit: 9   0xffff9f4b08400000 0xffff9f4b08600000 0xffff9f4b08800000   515     2060 KB         2048 KB
[ 7682.723697] Free&Fit: 8   0xffff9f4b08600000 0xffff9f4b08700000 0xffff9f4b08800000   515     12 KB   1024 KB
[ 7682.723699] Free&Fit: 7   0xffff9f4b08600000 0xffff9f4b08680000 0xffff9f4b08700000   515     12 KB   512 KB
[ 7682.723700] Free&Fit: 6   0xffff9f4b08600000 0xffff9f4b08640000 0xffff9f4b08680000   515     12 KB   256 KB
[ 7682.723702] Free&Fit: 5   0xffff9f4b08600000 0xffff9f4b08620000 0xffff9f4b08640000   515     12 KB   128 KB
[ 7682.723703] Free&Fit: 4   0xffff9f4b08600000 0xffff9f4b08610000 0xffff9f4b08620000   515     12 KB   64 KB
[ 7682.723705] Free&Fit: 3   0xffff9f4b08600000 0xffff9f4b08608000 0xffff9f4b08610000   515     12 KB   32 KB
[ 7682.723707] Free&Fit: 2   0xffff9f4b08600000 0xffff9f4b08604000 0xffff9f4b08608000   515     12 KB   16 KB
[ 7682.723708] Free&Fit: 1   0xffff9f4b08600000 0xffff9f4b08602000 0xffff9f4b08604000   515     12 KB   8 KB
[ 7682.723710] Free&Fit: 0   0xffff9f4b08602000 0xffff9f4b08603000 0xffff9f4b08604000   515     4 KB    4 KB
[ 7682.723712] Pageman(Free): Stats| Free_size=2060 KB   fit_pages=515  Max_pages=1024  Elapse=22817 ns

[ 7682.723713] Pageman(Free): Order From                Mid               To                fit_pages       left_size       Half_size
[ 7682.723714] Free&Fit: 9   0xffff9f4b08800000 0xffff9f4b08a00000 0xffff9f4b08c00000   515     2060 KB         2048 KB
[ 7682.723718] Free&Fit: 8   0xffff9f4b08a00000 0xffff9f4b08b00000 0xffff9f4b08c00000   515     12 KB   1024 KB
[ 7682.723720] Free&Fit: 7   0xffff9f4b08a00000 0xffff9f4b08a80000 0xffff9f4b08b00000   515     12 KB   512 KB
[ 7682.723721] Free&Fit: 6   0xffff9f4b08a00000 0xffff9f4b08a40000 0xffff9f4b08a80000   515     12 KB   256 KB
[ 7682.723723] Free&Fit: 5   0xffff9f4b08a00000 0xffff9f4b08a20000 0xffff9f4b08a40000   515     12 KB   128 KB
[ 7682.723724] Free&Fit: 4   0xffff9f4b08a00000 0xffff9f4b08a10000 0xffff9f4b08a20000   515     12 KB   64 KB
[ 7682.723726] Free&Fit: 3   0xffff9f4b08a00000 0xffff9f4b08a08000 0xffff9f4b08a10000   515     12 KB   32 KB
[ 7682.723727] Free&Fit: 2   0xffff9f4b08a00000 0xffff9f4b08a04000 0xffff9f4b08a08000   515     12 KB   16 KB
[ 7682.723729] Free&Fit: 1   0xffff9f4b08a00000 0xffff9f4b08a02000 0xffff9f4b08a04000   515     12 KB   8 KB
[ 7682.723730] Free&Fit: 0   0xffff9f4b08a02000 0xffff9f4b08a03000 0xffff9f4b08a04000   515     4 KB    4 KB
[ 7682.723732] Pageman(Free): Stats| Free_size=2060 KB   fit_pages=515  Max_pages=1024  Elapse=18429 ns

[ 7682.723734] Pageman(Free): Order From                Mid               To                fit_pages       left_size       Half_size
[ 7682.723734] Free&Fit: 9   0xffff9f4b07c00000 0xffff9f4b07e00000 0xffff9f4b08000000   515     2060 KB         2048 KB
[ 7682.723738] Free&Fit: 8   0xffff9f4b07e00000 0xffff9f4b07f00000 0xffff9f4b08000000   515     12 KB   1024 KB
[ 7682.723740] Free&Fit: 7   0xffff9f4b07e00000 0xffff9f4b07e80000 0xffff9f4b07f00000   515     12 KB   512 KB
[ 7682.723741] Free&Fit: 6   0xffff9f4b07e00000 0xffff9f4b07e40000 0xffff9f4b07e80000   515     12 KB   256 KB
[ 7682.723743] Free&Fit: 5   0xffff9f4b07e00000 0xffff9f4b07e20000 0xffff9f4b07e40000   515     12 KB   128 KB
[ 7682.723744] Free&Fit: 4   0xffff9f4b07e00000 0xffff9f4b07e10000 0xffff9f4b07e20000   515     12 KB   64 KB
[ 7682.723746] Free&Fit: 3   0xffff9f4b07e00000 0xffff9f4b07e08000 0xffff9f4b07e10000   515     12 KB   32 KB
[ 7682.723748] Free&Fit: 2   0xffff9f4b07e00000 0xffff9f4b07e04000 0xffff9f4b07e08000   515     12 KB   16 KB
[ 7682.723749] Free&Fit: 1   0xffff9f4b07e00000 0xffff9f4b07e02000 0xffff9f4b07e04000   515     12 KB   8 KB
[ 7682.723751] Free&Fit: 0   0xffff9f4b07e02000 0xffff9f4b07e03000 0xffff9f4b07e04000   515     4 KB    4 KB
[ 7682.723752] Pageman(Free): Stats| Free_size=2060 KB   fit_pages=515  Max_pages=1024  Elapse=18708 ns

[ 7682.723754] Pageman(Free): Order From                Mid               To                fit_pages       left_size       Half_size
[ 7682.723754] Free&Fit: 9   0xffff9f4b09000000 0xffff9f4b09200000 0xffff9f4b09400000   515     2060 KB         2048 KB
[ 7682.723758] Free&Fit: 8   0xffff9f4b09200000 0xffff9f4b09300000 0xffff9f4b09400000   515     12 KB   1024 KB
[ 7682.723760] Free&Fit: 7   0xffff9f4b09200000 0xffff9f4b09280000 0xffff9f4b09300000   515     12 KB   512 KB
[ 7682.723761] Free&Fit: 6   0xffff9f4b09200000 0xffff9f4b09240000 0xffff9f4b09280000   515     12 KB   256 KB
[ 7682.723763] Free&Fit: 5   0xffff9f4b09200000 0xffff9f4b09220000 0xffff9f4b09240000   515     12 KB   128 KB
[ 7682.723764] Free&Fit: 4   0xffff9f4b09200000 0xffff9f4b09210000 0xffff9f4b09220000   515     12 KB   64 KB
[ 7682.723766] Free&Fit: 3   0xffff9f4b09200000 0xffff9f4b09208000 0xffff9f4b09210000   515     12 KB   32 KB
[ 7682.723767] Free&Fit: 2   0xffff9f4b09200000 0xffff9f4b09204000 0xffff9f4b09208000   515     12 KB   16 KB
[ 7682.723769] Free&Fit: 1   0xffff9f4b09200000 0xffff9f4b09202000 0xffff9f4b09204000   515     12 KB   8 KB
[ 7682.723770] Free&Fit: 0   0xffff9f4b09202000 0xffff9f4b09203000 0xffff9f4b09204000   515     4 KB    4 KB
[ 7682.723772] Pageman(Free): Stats| Free_size=2060 KB   fit_pages=515  Max_pages=1024  Elapse=18239 ns

[ 7682.723773] Pageman(Free): Order From                Mid               To                fit_pages       left_size       Half_size
[ 7682.723774] Free&Fit: 9   0xffff9f4b09400000 0xffff9f4b09600000 0xffff9f4b09800000   515     2060 KB         2048 KB
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[ 7682.724094] Free&Fit: 8   0xffff9f4b0ce00000 0xffff9f4b0cf00000 0xffff9f4b0d000000   515     12 KB   1024 KB
[ 7682.724096] Free&Fit: 7   0xffff9f4b0ce00000 0xffff9f4b0ce80000 0xffff9f4b0cf00000   515     12 KB   512 KB
[ 7682.724097] Free&Fit: 6   0xffff9f4b0ce00000 0xffff9f4b0ce40000 0xffff9f4b0ce80000   515     12 KB   256 KB
[ 7682.724099] Free&Fit: 5   0xffff9f4b0ce00000 0xffff9f4b0ce20000 0xffff9f4b0ce40000   515     12 KB   128 KB
[ 7682.724100] Free&Fit: 4   0xffff9f4b0ce00000 0xffff9f4b0ce10000 0xffff9f4b0ce20000   515     12 KB   64 KB
[ 7682.724102] Free&Fit: 3   0xffff9f4b0ce00000 0xffff9f4b0ce08000 0xffff9f4b0ce10000   515     12 KB   32 KB
[ 7682.724103] Free&Fit: 2   0xffff9f4b0ce00000 0xffff9f4b0ce04000 0xffff9f4b0ce08000   515     12 KB   16 KB
[ 7682.724105] Free&Fit: 1   0xffff9f4b0ce00000 0xffff9f4b0ce02000 0xffff9f4b0ce04000   515     12 KB   8 KB
[ 7682.724106] Free&Fit: 0   0xffff9f4b0ce02000 0xffff9f4b0ce03000 0xffff9f4b0ce04000   515     4 KB    4 KB
[ 7682.724108] Pageman(Free): Stats| Free_size=2060 KB   fit_pages=515  Max_pages=1024  Elapse=18314 ns

[ 7682.724109] Pageman(Free): Order From               Mid              To               fit_pages      left_size      Half_size
[ 7682.724110] Free&Fit: 9   0xffff9f4b0d000000 0xffff9f4b0d200000 0xffff9f4b0d400000   515     2060 KB        2048 KB
[ 7682.724114] Free&Fit: 8   0xffff9f4b0d200000 0xffff9f4b0d300000 0xffff9f4b0d400000   515     12 KB   1024 KB
[ 7682.724115] Free&Fit: 7   0xffff9f4b0d200000 0xffff9f4b0d280000 0xffff9f4b0d300000   515     12 KB   512 KB
[ 7682.724117] Free&Fit: 6   0xffff9f4b0d200000 0xffff9f4b0d240000 0xffff9f4b0d280000   515     12 KB   256 KB
[ 7682.724118] Free&Fit: 5   0xffff9f4b0d200000 0xffff9f4b0d220000 0xffff9f4b0d240000   515     12 KB   128 KB
[ 7682.724120] Free&Fit: 4   0xffff9f4b0d200000 0xffff9f4b0d210000 0xffff9f4b0d220000   515     12 KB   64 KB
[ 7682.724121] Free&Fit: 3   0xffff9f4b0d200000 0xffff9f4b0d208000 0xffff9f4b0d210000   515     12 KB   32 KB
[ 7682.724123] Free&Fit: 2   0xffff9f4b0d200000 0xffff9f4b0d204000 0xffff9f4b0d208000   515     12 KB   16 KB
[ 7682.724124] Free&Fit: 1   0xffff9f4b0d200000 0xffff9f4b0d202000 0xffff9f4b0d204000   515     12 KB   8 KB
[ 7682.724126] Free&Fit: 0   0xffff9f4b0d202000 0xffff9f4b0d203000 0xffff9f4b0d204000   515     4 KB    4 KB
[ 7682.724127] Pageman(Free): Stats| Free_size=2060 KB   fit_pages=515  Max_pages=1024  Elapse=18193 ns

[ 7682.724129] Pageman(Free): Order From               Mid              To               fit_pages      left_size      Half_size
[ 7682.724129] Free&Fit: 9   0xffff9f4b0d400000 0xffff9f4b0d600000 0xffff9f4b0d800000   515     2060 KB        2048 KB
[ 7682.724134] Free&Fit: 8   0xffff9f4b0d600000 0xffff9f4b0d700000 0xffff9f4b0d800000   515     12 KB   1024 KB
[ 7682.724135] Free&Fit: 7   0xffff9f4b0d600000 0xffff9f4b0d680000 0xffff9f4b0d700000   515     12 KB   512 KB
[ 7682.724137] Free&Fit: 6   0xffff9f4b0d600000 0xffff9f4b0d640000 0xffff9f4b0d680000   515     12 KB   256 KB
[ 7682.724138] Free&Fit: 5   0xffff9f4b0d600000 0xffff9f4b0d620000 0xffff9f4b0d640000   515     12 KB   128 KB
[ 7682.724140] Free&Fit: 4   0xffff9f4b0d600000 0xffff9f4b0d610000 0xffff9f4b0d620000   515     12 KB   64 KB
[ 7682.724141] Free&Fit: 3   0xffff9f4b0d600000 0xffff9f4b0d608000 0xffff9f4b0d610000   515     12 KB   32 KB
[ 7682.724143] Free&Fit: 2   0xffff9f4b0d600000 0xffff9f4b0d604000 0xffff9f4b0d608000   515     12 KB   16 KB
[ 7682.724144] Free&Fit: 1   0xffff9f4b0d600000 0xffff9f4b0d602000 0xffff9f4b0d604000   515     12 KB   8 KB
[ 7682.724146] Free&Fit: 0   0xffff9f4b0d602000 0xffff9f4b0d603000 0xffff9f4b0d604000   515     4 KB    4 KB
[ 7682.724147] Pageman(Free): Stats| Free_size=2060 KB   fit_pages=515  Max_pages=1024  Elapse=18517 ns

[ 7682.724149] Pageman(Free): Order From               Mid              To               fit_pages      left_size      Half_size
[ 7682.724149] Free&Fit: 9   0xffff9f4b0d800000 0xffff9f4b0da00000 0xffff9f4b0dc00000   515     2060 KB        2048 KB
[ 7682.724153] Free&Fit: 8   0xffff9f4b0da00000 0xffff9f4b0db00000 0xffff9f4b0dc00000   515     12 KB   1024 KB
[ 7682.724155] Free&Fit: 7   0xffff9f4b0da00000 0xffff9f4b0da80000 0xffff9f4b0db00000   515     12 KB   512 KB
[ 7682.724156] Free&Fit: 6   0xffff9f4b0da00000 0xffff9f4b0da40000 0xffff9f4b0da80000   515     12 KB   256 KB
[ 7682.724158] Free&Fit: 5   0xffff9f4b0da00000 0xffff9f4b0da20000 0xffff9f4b0da40000   515     12 KB   128 KB
[ 7682.724159] Free&Fit: 4   0xffff9f4b0da00000 0xffff9f4b0da10000 0xffff9f4b0da20000   515     12 KB   64 KB
[ 7682.724161] Free&Fit: 3   0xffff9f4b0da00000 0xffff9f4b0da08000 0xffff9f4b0da10000   515     12 KB   32 KB
[ 7682.724162] Free&Fit: 2   0xffff9f4b0da00000 0xffff9f4b0da04000 0xffff9f4b0da08000   515     12 KB   16 KB
[ 7682.724164] Free&Fit: 1   0xffff9f4b0da00000 0xffff9f4b0da02000 0xffff9f4b0da04000   515     12 KB   8 KB
[ 7682.724165] Free&Fit: 0   0xffff9f4b0da02000 0xffff9f4b0da03000 0xffff9f4b0da04000   515     4 KB    4 KB
[ 7682.724167] Pageman(Free): Stats| Free_size=2060 KB   fit_pages=515  Max_pages=1024  Elapse=18138 ns

[ 7682.724168] Pageman(Free): Order From               Mid              To               fit_pages      left_size      Half_size
[ 7682.724169] Free&Fit: 9   0xffff9f4b0dc00000 0xffff9f4b0de00000 0xffff9f4b0e000000   515     2060 KB        2048 KB
[ 7682.724173] Free&Fit: 8   0xffff9f4b0de00000 0xffff9f4b0df00000 0xffff9f4b0e000000   515     12 KB   1024 KB
[ 7682.724175] Free&Fit: 7   0xffff9f4b0de00000 0xffff9f4b0de80000 0xffff9f4b0df00000   515     12 KB   512 KB
[ 7682.724176] Free&Fit: 6   0xffff9f4b0de00000 0xffff9f4b0de40000 0xffff9f4b0de80000   515     12 KB   256 KB
[ 7682.724178] Free&Fit: 5   0xffff9f4b0de00000 0xffff9f4b0de20000 0xffff9f4b0de40000   515     12 KB   128 KB
[ 7682.724179] Free&Fit: 4   0xffff9f4b0de00000 0xffff9f4b0de10000 0xffff9f4b0de20000   515     12 KB   64 KB
[ 7682.724181] Free&Fit: 3   0xffff9f4b0de00000 0xffff9f4b0de08000 0xffff9f4b0de10000   515     12 KB   32 KB
[ 7682.724182] Free&Fit: 2   0xffff9f4b0de00000 0xffff9f4b0de04000 0xffff9f4b0de08000   515     12 KB   16 KB
[ 7682.724184] Free&Fit: 1   0xffff9f4b0de00000 0xffff9f4b0de02000 0xffff9f4b0de04000   515     12 KB   8 KB
[ 7682.724185] Free&Fit: 0   0xffff9f4b0de02000 0xffff9f4b0de03000 0xffff9f4b0de04000   515     4 KB    4 KB
[ 7682.724187] Pageman(Free): Stats| Free_size=2060 KB   fit_pages=515  Max_pages=1024  Elapse=18729 ns
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[ 7594.469489] Pageman(Fit): 9   0xffff9f4b0d800000 0xffff9f4b0da00000 0xffff9f4b0dc00000      515     2060 KB        2048 KB
[ 7594.469492] Pageman(Fit): 8   0xffff9f4b0da00000 0xffff9f4b0db00000 0xffff9f4b0dc00000      515     12 KB   1024 KB
[ 7594.469498] Pageman(Fit): 7   0xffff9f4b0da00000 0xffff9f4b0da80000 0xffff9f4b0db00000      515     12 KB   512 KB
[ 7594.469503] Pageman(Fit): 6   0xffff9f4b0da00000 0xffff9f4b0da40000 0xffff9f4b0da80000      515     12 KB   256 KB
[ 7594.469507] Pageman(Fit): 5   0xffff9f4b0da00000 0xffff9f4b0da20000 0xffff9f4b0da40000      515     12 KB   128 KB
[ 7594.469514] Pageman(Fit): 4   0xffff9f4b0da00000 0xffff9f4b0da10000 0xffff9f4b0da20000      515     12 KB   64 KB
[ 7594.469720] Pageman(Fit): 3   0xffff9f4b0da00000 0xffff9f4b0da08000 0xffff9f4b0da10000      515     12 KB   32 KB
[ 7594.469725] Pageman(Fit): 2   0xffff9f4b0da00000 0xffff9f4b0da04000 0xffff9f4b0da08000      515     12 KB   16 KB
[ 7594.469728] Pageman(Fit): 1   0xffff9f4b0da00000 0xffff9f4b0da02000 0xffff9f4b0da04000      515     12 KB   8 KB
[ 7594.469730] Pageman(Fit): 0   0xffff9f4b0da02000 0xffff9f4b0da03000 0xffff9f4b0da04000      515     4 KB    4 KB
[ 7594.469733] Pageman(Fit): Stats| Fit_size=2060 KB     Required_pages=515     Original_pages=1024     Elapse=247284 ns

[ 7594.469736] page_exact_loop:18: alloc_pages_exact() alloc'ed 2109440 bytes memory (515 pages + rem 0 bytes) from the BSA @ ffff9f4b0
d800000 (actual=ffff9f4b0d800000)
[ 7594.470331] Pageman(Fit): Order From          Mid             To              Fit_pages       Fit_size        Half_size
[ 7594.470333] Pageman(Fit): 9   0xffff9f4b0dc00000 0xffff9f4b0de00000 0xffff9f4b0e000000      515     2060 KB        2048 KB
[ 7594.470336] Pageman(Fit): 8   0xffff9f4b0de00000 0xffff9f4b0df00000 0xffff9f4b0e000000      515     12 KB   1024 KB
[ 7594.470343] Pageman(Fit): 7   0xffff9f4b0de00000 0xffff9f4b0de80000 0xffff9f4b0df00000      515     12 KB   512 KB
[ 7594.470348] Pageman(Fit): 6   0xffff9f4b0de00000 0xffff9f4b0de40000 0xffff9f4b0de80000      515     12 KB   256 KB
[ 7594.470352] Pageman(Fit): 5   0xffff9f4b0de00000 0xffff9f4b0de20000 0xffff9f4b0de40000      515     12 KB   128 KB
[ 7594.470356] Pageman(Fit): 4   0xffff9f4b0de00000 0xffff9f4b0de10000 0xffff9f4b0de20000      515     12 KB   64 KB
[ 7594.470360] Pageman(Fit): 3   0xffff9f4b0de00000 0xffff9f4b0de08000 0xffff9f4b0de10000      515     12 KB   32 KB
[ 7594.470363] Pageman(Fit): 2   0xffff9f4b0de00000 0xffff9f4b0de04000 0xffff9f4b0de08000      515     12 KB   16 KB
[ 7594.470366] Pageman(Fit): 1   0xffff9f4b0de00000 0xffff9f4b0de02000 0xffff9f4b0de04000      515     12 KB   8 KB
[ 7594.470369] Pageman(Fit): 0   0xffff9f4b0de02000 0xffff9f4b0de03000 0xffff9f4b0de04000      515     4 KB    4 KB
[ 7594.470372] Pageman(Fit): Stats| Fit_size=2060 KB     Required_pages=515     Original_pages=1024     Elapse=41602 ns

[ 7594.470375] page_exact_loop:19: alloc_pages_exact() alloc'ed 2109440 bytes memory (515 pages + rem 0 bytes) from the BSA @ ffff9f4b0
dc00000 (actual=ffff9f4b0dc00000)
[ 7628.271408] Pageman(Fit): Order From          Mid             To              Fit_pages       Fit_size        Half_size
[ 7628.271412] Pageman(Fit): 1   0xffff9f4aa09c0000 0xffff9f4aa09c2000 0xffff9f4aa09c4000      3       12 KB   8 KB
[ 7628.271415] Pageman(Fit): 0   0xffff9f4aa09c2000 0xffff9f4aa09c3000 0xffff9f4aa09c4000      3       4 KB    4 KB
[ 7628.271417] Pageman(Fit): Stats| Fit_size=9 KB        Required_pages=3       Original_pages=4        Elapse=8751 ns

[ 7628.272141] Pageman(Free): Order From                 Mid             To              fit_pages       left_size       Half_size
[ 7628.272143] Free&Fit: 1   0xffff9f4aa09c0000 0xffff9f4aa09c2000 0xffff9f4aa09c4000   3       12 KB   8 KB
[ 7628.272145] Free&Fit: 0   0xffff9f4aa09c2000 0xffff9f4aa09c3000 0xffff9f4aa09c4000   3       4 KB    4 KB
[ 7628.272147] Pageman(Free): Stats| Free_size=12 KB     fit_pages=3    Max_pages=4     Elapse=6206 ns

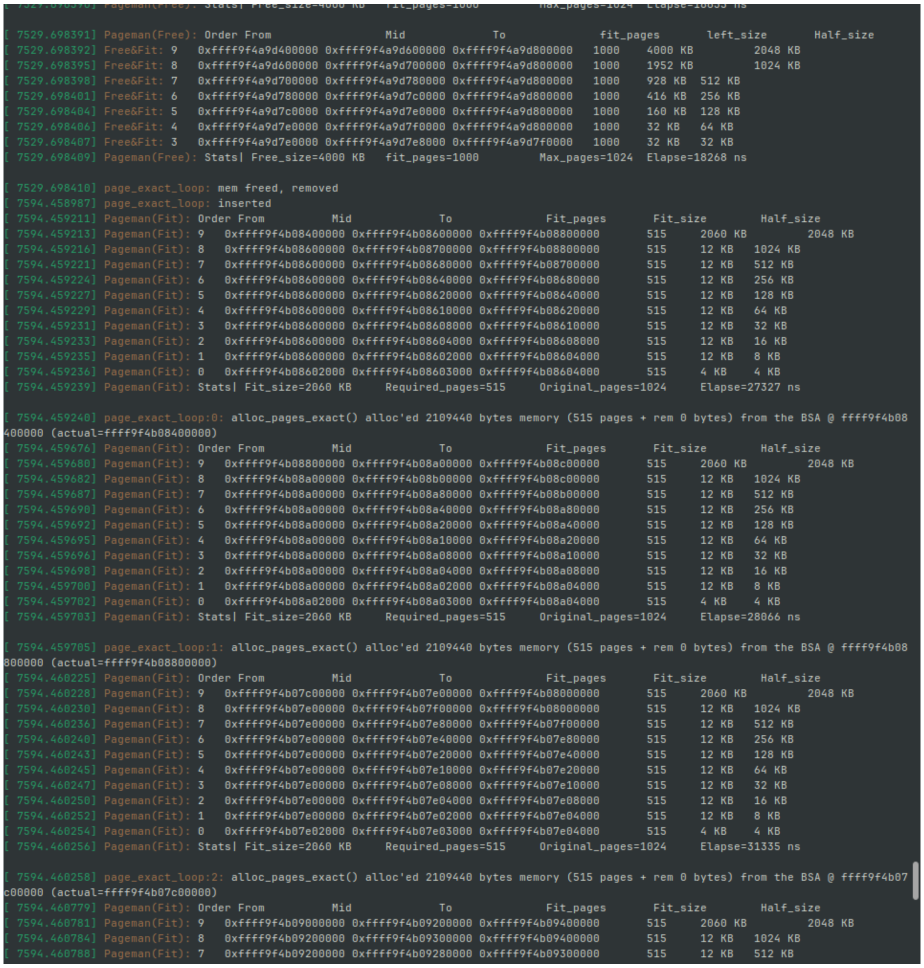
[ 7628.473708] Pageman(Fit): Order From          Mid             To              Fit_pages       Fit_size        Half_size
[ 7628.473713] Pageman(Fit): 1   0xffff9f4a664c0000 0xffff9f4a664c2000 0xffff9f4a664c4000      3       12 KB   8 KB
[ 7628.473717] Pageman(Fit): 0   0xffff9f4a664c2000 0xffff9f4a664c3000 0xffff9f4a664c4000      3       4 KB    4 KB
[ 7628.473720] Pageman(Fit): Stats| Fit_size=9 KB        Required_pages=3       Original_pages=4        Elapse=12364 ns

[ 7628.473841] Pageman(Free): Order From                 Mid             To              fit_pages       left_size       Half_size
[ 7628.473843] Free&Fit: 1   0xffff9f4a664c0000 0xffff9f4a664c2000 0xffff9f4a664c4000   3       12 KB   8 KB
[ 7628.473845] Free&Fit: 0   0xffff9f4a664c2000 0xffff9f4a664c3000 0xffff9f4a664c4000   3       4 KB    4 KB
[ 7628.473848] Pageman(Free): Stats| Free_size=12 KB     fit_pages=3    Max_pages=4     Elapse=6929 ns

[ 7637.210649] Pageman(Fit): Order From          Mid             To              Fit_pages       Fit_size        Half_size
[ 7637.210652] Pageman(Fit): 1   0xffff9f4a6b778000 0xffff9f4a6b77a000 0xffff9f4a6b77c000      3       12 KB   8 KB
[ 7637.210655] Pageman(Fit): 0   0xffff9f4a6b77a000 0xffff9f4a6b77b000 0xffff9f4a6b77c000      3       4 KB    4 KB
[ 7637.210658] Pageman(Fit): Stats| Fit_size=9 KB        Required_pages=3       Original_pages=4        Elapse=9612 ns

[ 7637.211290] Pageman(Free): Order From                 Mid             To              fit_pages       left_size       Half_size
[ 7637.211292] Free&Fit: 1   0xffff9f4a6b778000 0xffff9f4a6b77a000 0xffff9f4a6b77c000   3       12 KB   8 KB
[ 7637.211295] Free&Fit: 0   0xffff9f4a6b77a000 0xffff9f4a6b77b000 0xffff9f4a6b77c000   3       4 KB    4 KB
[ 7637.211297] Pageman(Free): Stats| Free_size=12 KB     fit_pages=3    Max_pages=4     Elapse=7025 ns

[ 7655.524163] Pageman(Fit): Nothing to fit with 4 KB and 1 Pages
[ 7655.524169] Pageman(Fit): Nothing to fit with 4 KB and 1 Pages
[ 7661.568757] Pageman(Free): Not required
[ 7661.568761] Pageman(Free): Not required
```


```
[ 7529.698391] Pageman(Free): Order From               Mid             To              fit_pages      left_size      Half_size
[ 7529.698392] Free&Fit: 9   0xffff9f4a9d400000 0xffff9f4a9d600000 0xffff9f4a9d800000   1000    4000 KB        2048 KB
[ 7529.698395] Free&Fit: 8   0xffff9f4a9d600000 0xffff9f4a9d700000 0xffff9f4a9d800000   1000    1952 KB        1024 KB
[ 7529.698398] Free&Fit: 7   0xffff9f4a9d700000 0xffff9f4a9d780000 0xffff9f4a9d800000   1000    928 KB  512 KB
[ 7529.698401] Free&Fit: 6   0xffff9f4a9d780000 0xffff9f4a9d7c0000 0xffff9f4a9d800000   1000    416 KB  256 KB
[ 7529.698404] Free&Fit: 5   0xffff9f4a9d7c0000 0xffff9f4a9d7e0000 0xffff9f4a9d800000   1000    160 KB  128 KB
[ 7529.698406] Free&Fit: 4   0xffff9f4a9d7e0000 0xffff9f4a9d7f0000 0xffff9f4a9d800000   1000    32 KB   64 KB
[ 7529.698407] Free&Fit: 3   0xffff9f4a9d7e0000 0xffff9f4a9d7e8000 0xffff9f4a9d7f0000   1000    32 KB   32 KB
[ 7529.698409] Pageman(Free): Stats| Free_size=4000 KB   fit_pages=1000         Max_pages=1024  Elapse=18268 ns

[ 7529.698410] page_exact_loop: mem freed, removed
[ 7594.458987] page_exact_loop: inserted
[ 7594.459211] Pageman(Fit): Order From          Mid             To              Fit_pages      Fit_size       Half_size
[ 7594.459213] Pageman(Fit): 9   0xffff9f4b08400000 0xffff9f4b08600000 0xffff9f4b08800000       515     2060 KB        2048 KB
[ 7594.459216] Pageman(Fit): 8   0xffff9f4b08600000 0xffff9f4b08700000 0xffff9f4b08800000       515     12 KB   1024 KB
[ 7594.459221] Pageman(Fit): 7   0xffff9f4b08600000 0xffff9f4b08680000 0xffff9f4b08700000       515     12 KB   512 KB
[ 7594.459224] Pageman(Fit): 6   0xffff9f4b08600000 0xffff9f4b08640000 0xffff9f4b08680000       515     12 KB   256 KB
[ 7594.459227] Pageman(Fit): 5   0xffff9f4b08600000 0xffff9f4b08620000 0xffff9f4b08640000       515     12 KB   128 KB
[ 7594.459229] Pageman(Fit): 4   0xffff9f4b08600000 0xffff9f4b08610000 0xffff9f4b08620000       515     12 KB   64 KB
[ 7594.459231] Pageman(Fit): 3   0xffff9f4b08600000 0xffff9f4b08608000 0xffff9f4b08610000       515     12 KB   32 KB
[ 7594.459233] Pageman(Fit): 2   0xffff9f4b08600000 0xffff9f4b08604000 0xffff9f4b08608000       515     12 KB   16 KB
[ 7594.459235] Pageman(Fit): 1   0xffff9f4b08600000 0xffff9f4b08602000 0xffff9f4b08604000       515     12 KB   8 KB
[ 7594.459236] Pageman(Fit): 0   0xffff9f4b08602000 0xffff9f4b08603000 0xffff9f4b08604000       515     4 KB    4 KB
[ 7594.459239] Pageman(Fit): Stats| Fit_size=2060 KB     Required_pages=515     Original_pages=1024     Elapse=27327 ns

[ 7594.459240] page_exact_loop:0: alloc_pages_exact() alloc'ed 2109440 bytes memory (515 pages + rem 0 bytes) from the BSA @ ffff9f4b08
400000 (actual=ffff9f4b08400000)
[ 7594.459676] Pageman(Fit): Order From          Mid             To              Fit_pages      Fit_size       Half_size
[ 7594.459680] Pageman(Fit): 9   0xffff9f4b08800000 0xffff9f4b08a00000 0xffff9f4b08c00000       515     2060 KB        2048 KB
[ 7594.459682] Pageman(Fit): 8   0xffff9f4b08a00000 0xffff9f4b08b00000 0xffff9f4b08c00000       515     12 KB   1024 KB
[ 7594.459687] Pageman(Fit): 7   0xffff9f4b08a00000 0xffff9f4b08a80000 0xffff9f4b08b00000       515     12 KB   512 KB
[ 7594.459690] Pageman(Fit): 6   0xffff9f4b08a00000 0xffff9f4b08a40000 0xffff9f4b08a80000       515     12 KB   256 KB
[ 7594.459692] Pageman(Fit): 5   0xffff9f4b08a00000 0xffff9f4b08a20000 0xffff9f4b08a40000       515     12 KB   128 KB
[ 7594.459695] Pageman(Fit): 4   0xffff9f4b08a00000 0xffff9f4b08a10000 0xffff9f4b08a20000       515     12 KB   64 KB
[ 7594.459696] Pageman(Fit): 3   0xffff9f4b08a00000 0xffff9f4b08a08000 0xffff9f4b08a10000       515     12 KB   32 KB
[ 7594.459698] Pageman(Fit): 2   0xffff9f4b08a00000 0xffff9f4b08a04000 0xffff9f4b08a08000       515     12 KB   16 KB
[ 7594.459700] Pageman(Fit): 1   0xffff9f4b08a00000 0xffff9f4b08a02000 0xffff9f4b08a04000       515     12 KB   8 KB
[ 7594.459702] Pageman(Fit): 0   0xffff9f4b08a02000 0xffff9f4b08a03000 0xffff9f4b08a04000       515     4 KB    4 KB
[ 7594.459703] Pageman(Fit): Stats| Fit_size=2060 KB     Required_pages=515     Original_pages=1024     Elapse=28066 ns

[ 7594.459705] page_exact_loop:1: alloc_pages_exact() alloc'ed 2109440 bytes memory (515 pages + rem 0 bytes) from the BSA @ ffff9f4b08
800000 (actual=ffff9f4b08800000)
[ 7594.460225] Pageman(Fit): Order From          Mid             To              Fit_pages      Fit_size       Half_size
[ 7594.460228] Pageman(Fit): 9   0xffff9f4b07c00000 0xffff9f4b07e00000 0xffff9f4b08000000       515     2060 KB        2048 KB
[ 7594.460230] Pageman(Fit): 8   0xffff9f4b07e00000 0xffff9f4b07f00000 0xffff9f4b08000000       515     12 KB   1024 KB
[ 7594.460236] Pageman(Fit): 7   0xffff9f4b07e00000 0xffff9f4b07e80000 0xffff9f4b07f00000       515     12 KB   512 KB
[ 7594.460240] Pageman(Fit): 6   0xffff9f4b07e00000 0xffff9f4b07e40000 0xffff9f4b07e80000       515     12 KB   256 KB
[ 7594.460243] Pageman(Fit): 5   0xffff9f4b07e00000 0xffff9f4b07e20000 0xffff9f4b07e40000       515     12 KB   128 KB
[ 7594.460245] Pageman(Fit): 4   0xffff9f4b07e00000 0xffff9f4b07e10000 0xffff9f4b07e20000       515     12 KB   64 KB
[ 7594.460247] Pageman(Fit): 3   0xffff9f4b07e00000 0xffff9f4b07e08000 0xffff9f4b07e10000       515     12 KB   32 KB
[ 7594.460250] Pageman(Fit): 2   0xffff9f4b07e00000 0xffff9f4b07e04000 0xffff9f4b07e08000       515     12 KB   16 KB
[ 7594.460252] Pageman(Fit): 1   0xffff9f4b07e00000 0xffff9f4b07e02000 0xffff9f4b07e04000       515     12 KB   8 KB
[ 7594.460254] Pageman(Fit): 0   0xffff9f4b07e02000 0xffff9f4b07e03000 0xffff9f4b07e04000       515     4 KB    4 KB
[ 7594.460256] Pageman(Fit): Stats| Fit_size=2060 KB     Required_pages=515     Original_pages=1024     Elapse=31335 ns

[ 7594.460258] page_exact_loop:2: alloc_pages_exact() alloc'ed 2109440 bytes memory (515 pages + rem 0 bytes) from the BSA @ ffff9f4b07
c00000 (actual=ffff9f4b07c00000)
[ 7594.460779] Pageman(Fit): Order From          Mid             To              Fit_pages      Fit_size       Half_size
[ 7594.460781] Pageman(Fit): 9   0xffff9f4b09000000 0xffff9f4b09200000 0xffff9f4b09400000       515     2060 KB        2048 KB
[ 7594.460784] Pageman(Fit): 8   0xffff9f4b09200000 0xffff9f4b09300000 0xffff9f4b09400000       515     12 KB   1024 KB
[ 7594.460788] Pageman(Fit): 7   0xffff9f4b09200000 0xffff9f4b09280000 0xffff9f4b09300000       515     12 KB   512 KB
```

Evaluation

To evaluate our algorithm, we created a small python script `statman` aimed at calculating the total amount of pages saved and the time taken to do so.

- Implementation of statman

```
"""
Pageman Profiler Documentation
By LADO SAHA


The Pageman Profiler is a tool that analyzes the performance of the Pageman algorithm using

Statistics Calculated
```

```
----------------------
The Pageman Profiler calculates:
- Fit Interception Count: Number of fit interceptions in logs.
- Free Interception Count: Number of free interceptions in logs.
- Required Pages: Pages required for each fit interception.
- Original Pages: Original number of pages before fit interception.
- Elapsed Time: Time elapsed during each fit interception.
- Elapsed Time: Time elapsed during each free interception.
- Overall Percentage Saved: Percentage of memory saved by Pageman.
- Total Number of Pages Saved: Total number of pages saved.
- Total Memory Saved: Total memory saved in megabytes.
- Total Time Elapsed at Allocation: Total time elapsed during fit interceptions.
- Total Time Elapsed at Free: Total time elapsed during free interceptions.

"""


import re
import subprocess

def evaluate_algorithm(log_file_path):
    saved_pages = []                 # List to store the number of saved pages for each fit
    original_pages = []              # List to store the number of original pages for each f
    time_elapsed = []                # List to store the time elapsed for each fit intercept
    time_elapsed_on_free = []        # List to store the time elapsed for each free intercep

    command = ['journalctl', '-b']   # Command to retrieve the system logs
    process = subprocess.Popen(command, stdout=subprocess.PIPE, stderr=subprocess.PIPE)
    output, error = process.communicate()

    # Decode the output as a string
    logs = output.decode('utf-8')

    for line in logs.split("\n"):
        match_fit = re.search(r"Stats\|\s*Fit_size=(\d+)\s+KB\s+Required_pages=(\d+)\s+Origi
        match_free = re.search(r"Stats\|\s*Free_size=(\d+)\s+KB\s+fit_pages=(\d+)\s+Max_page

        if match_fit:
            required_pages = int(match_fit.group(2))
            original = int(match_fit.group(3))
            time_ns = int(match_fit.group(4))
            saved_pages.append(original - required_pages)
            original_pages.append(original)
            time_elapsed.append(time_ns / (1e9))  # Convert nanoseconds to seconds

        elif match_free:
```

```
            time_ns = int(match_free.group(4))
            time_elapsed_on_free.append(time_ns / 1e9)

    # Calculate overall statistics
    total_saved_pages = sum(saved_pages)
    total_original_pages = sum(original_pages)
    total_time_elapsed = sum(time_elapsed)
    total_time_elapsed_free = sum(time_elapsed_on_free)

    percentage_saved = ((total_original_pages - total_saved_pages) / total_original_pages) *
    memory_saved_kb = total_saved_pages * 4  # Assuming 4 KB per page

    # Run uptime command to get system uptime
    command = ['uptime', '-p']
    process = subprocess.Popen(command, stdout=subprocess.PIPE, stderr=subprocess.PIPE)
    output, error = process.communicate()

    # Decode the output as a string
    uptime_info = output.decode('utf-8').strip()

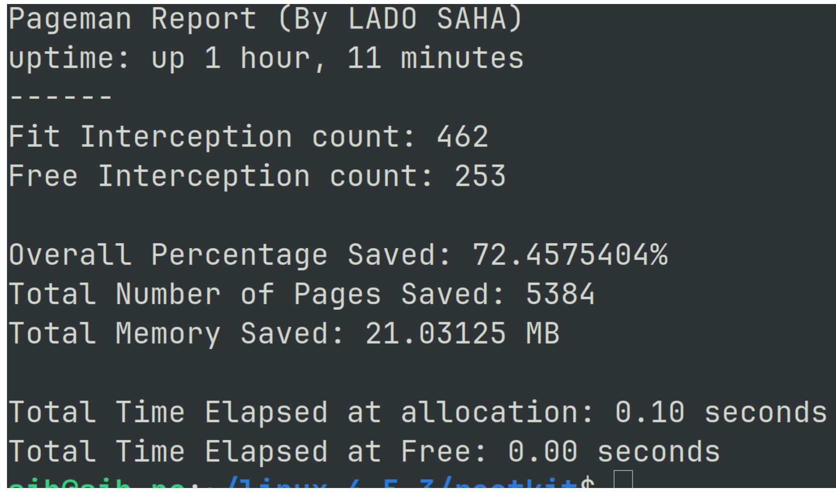
    # Print report
    print("Pageman Report (By LADO SAHA)")
    print(f"uptime: {uptime_info}")
    print("------")
    print(f"Fit Interception count: {len(saved_pages)}")
    print(f"Free Interception count: {len(time_elapsed_on_free)}\n")
    print(f"Overall Percentage Saved: {percentage_saved:.7f}%")
    print(f"Total Number of Pages Saved: {total_saved_pages}")
    print(f"Total Memory Saved: {memory_saved_kb / 1024} MB\n")
    print(f"Total Time Elapsed at allocation: {total_time_elapsed:.2f} seconds")
    print(f"Total Time Elapsed at Free: {total_time_elapsed_free:.2f} seconds")

# Example usage
log_file_path = "/var/log/kern.log"  # Path to the kernel log file, adjust as needed
evaluate_algorithm(log_file_path)
```

- Statman can be ran as follows from the terminal

```
cd ~/manager/linux-6.5.3/pageman/
python3 statman.py
```

- It is worth noting that it in order to appreciate the effect of Pageman, we need to run it after having the PC on for a long time.
- As an example, executing this simple evaluator on a machine with an uptime

of 1hr yields the following results 

```
Pageman Report (By LADO SAHA)
uptime: up 1 hour, 11 minutes
------
Fit Interception count: 462
Free Interception count: 253

Overall Percentage Saved: 72.4575404%
Total Number of Pages Saved: 5384
Total Memory Saved: 21.03125 MB

Total Time Elapsed at allocation: 0.10 seconds
Total Time Elapsed at Free: 0.00 seconds
```

Conclusion

The main difficulty faced during this project was the scarce resource about the exact project topic but this led us to go out of scope and gather more fundamental knowledge.

This project was indeed a great opportunity to get a solid foundation of the linux internals. Eventhough the solution we proposed has been lightly tested, we am certain that it has potentials and could be expanded upon to concieve a better memory management system equiped in all systems .

Thank

Aritcles & Resources

1. Billimoria, K. N. (2020). Linux Kernel Programming. Apress.
2. TheXcellerator. (2020, August 26). Linux Rootkits Part 2: Ftrace and Function Hooking. Retrieved from https://xcellerator.github.io/posts/linux_rootkits_02/
3. Bing AI
4. Poe.com
5. Reducing fragmentation through better allocation
6. Linux Kernel vs. Memory Fragmentation (Part I)
7. Difference between Internal and External fragmentation
8. Active memory defragmentation
9. Kernel memory management: where do I begin?
10. Memory management articles Here