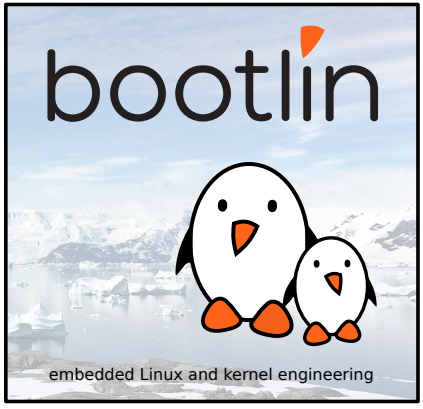
Inspecting and optimizing memory usage in Linux

João Marcos Costa
joaomarcos.costa@bootlin.com



João Marcos Costa

- Embedded Linux engineer and trainer at Bootlin since 2023
  - Embedded Linux experts
  - Engineering services: Linux BSP development, kernel porting and drivers, Yocto/Buildroot integration, real-time, boot-time, security, multimedia
  - Training services: Embedded Linux, Linux kernel drivers, Yocto, Buildroot, graphics stack, boot-time, real-time
- Open-source contributor
- Living in **Lyon**, France
- joaomarcos.costa@bootlin.com

https://bootlin.com/company/staff/joao-marcos-costa/

Background

- Project's requirements:
  - use as little memory as possible
  - furthermore, understand how the memory is being used
- iMX93 Evaluation Kit, with 2 GiB of LPDDR4X RAM
- a humble enthusiast, not a memory guru!

What is this talk about?

- Virtual memory
- Memory used by the kernel vs. by the programs
- Is it leaking?
- What if I don't have enough of it?

Introduction

Virtual memory: the basics

- Physical memory is not directly referred to. Virtual addresses are used instead
- The address translation is handled by the Memory Management Unit (MMU)
- The virtual address space is typically divided in 4KiB-long pages
- Other page sizes do exist (see Huge pages)
- Those pages are indexed in the MMU's Page Tables

Virtual memory: representing pages

include/linux/mm_types.h

```
struct page {
    unsigned long flags; /* Page status, see <include/linux/page-flags.h>*/
    struct list_head lru;
    struct address_space *mapping;
    pgoff_t index;
    atomic_t _refcount; /* Usage count */
    void *virtual;    /* Kernel virtual address */
};
```

- This struct represents physical page, not a virtual one
- Example: 2GiB of RAM $\equiv$ 524288 4KiB-long pages
  - *struct page* is $\approx$ 64-bytes long
  - $524288 \times 64 = 32MiB$ to represent physical memory pages

Virtual memory: representing pages

include/linux/mm_types.h

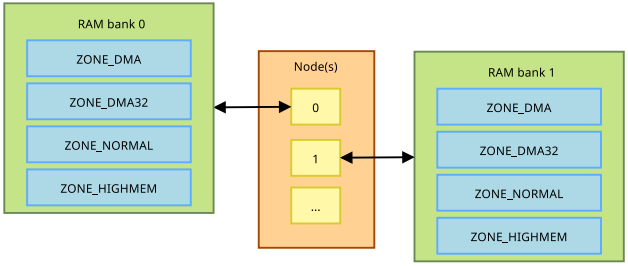
```
struct vm_area_struct {
    /* VMA covers [vm_start; vm_end) addresses within mm */
    unsigned long vm_start;
    unsigned long vm_end;
    struct mm_struct *vm_mm;    /* The address space we belong to. */
    const vm_flags_t vm_flags;
    struct list_head anon_vma_chain;
    struct anon_vma *anon_vma;
    /* Function pointers to deal with this struct. */
    const struct vm_operations_struct *vm_ops;
    struct file * vm_file;      /* File we map to (can be NULL). */
    void * vm_private_data;     /* was vm_pte (shared mem) */
};
```

- There is not a single struct to represent a virtual page
- Instead, Linux refers to a range of virtual addresses, or *Virtual Memory Area (VMA)*

Memory zones

- Physical memory is divided in zones, rather than being an homogeneous pool of addresses
- **ZONE_DMA**: the lower 16 MiB, for Direct Memory Access (legacy?)
- **ZONE_DMA32**: between 16 MiB, and below 4 GiB (64-bit Linux only)
- **ZONE_NORMAL**:
  - For 32-bit machines, between 16 MiB and 896 MiB
  - For 64-bit machines, all memory above 4 GiB
- **ZONE_HIGHMEM**: the memory above 896 MiB, only in 32-bit machines

Zones and nodes



- Zones are attached to nodes, and nodes to CPUs
- One node per CPU
- Each node is aware of its zones and their available memory pages
- Non-Uniform Memory Access (NUMA)

Zones and nodes

512 MiB RAM, 32-bits machine

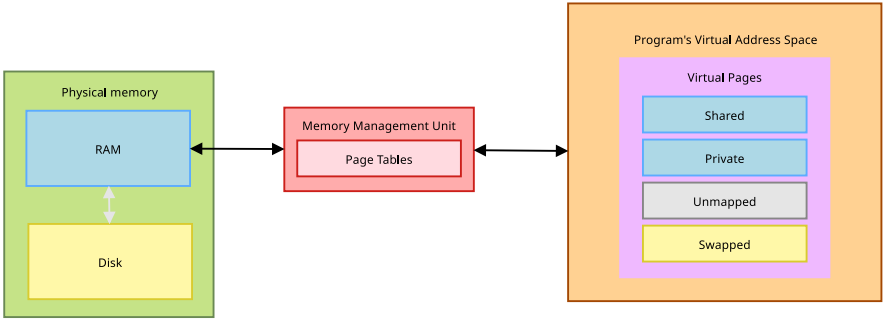
```
# cat /proc/buddyinfo
Node 0, zone   Normal     28     13      8      3      3      1      2      2      2      3      2     51
```

- Each column represents the number of available consecutive memory chunks of a certain size
- Every chunk's (i.e. column) size is defined by: $PAGESIZE \times K \times 2^n$
- e.g.: the first column ($K = 28, n = 0$) stands for 28 chunks of 4096 bytes

32 GiB RAM, 64-bits machine

```
# cat /proc/buddyinfo
Node 0, zone      DMA      0      0      0      0      0      0      0      0      1      1      2
Node 0, zone    DMA32   2241   1787   1400   1356    935    485    157     39      7      5      0
Node 0, zone   Normal  26143  18051  12270   8620   5536   3278   1564    620    206     40      3
```

Virtual memory: what does it provide?



- Memory is represented in a simpler way: as a uniform and continguous address space
- Each process will run in its own isolated addres space
- Primary and secondary memory (i.e., the disk) are abstracted as one
- Processes can share memory segments (e.g., shared libraries, and IPC)

Memory usage in kernel-space

Memory usage in kernel-space

- Memory allocations (*vmalloc()* and *kmalloc()*)
- Modules
- The kernel's binary itself
- Low level allocations (simply not tracked)

Examining the boot logs

- The starting point for our analysis
- `Memory: A/B available (...)`
- `B`: The total physical memory (minus *OPTEE*)
- `A`: `B` minus the memory reserved by/for the kernel (i.e., `reserved` field)

Kernel logs from early boot

```
[    0.000000] Memory: 2012000K/2064384K available (7936K kernel code, 572K rwdata, 1708K
rodata, 1280K init, 328K bss, 52384K reserved, 0K cma-reserved)
```

Examining the boot logs

- `kernel code`: `.text` section of the kernel binary
- `rwdata`: initialized (and writable) global and static variables
- `rodata`: read-only kernel data as constants and strings
- `init`: initialization code, reclaimed later
- `bss`: uninitialized data
- `reserved`: an overall metric for memory reserved by/for the kernel including code, data, and the physical pages (32 MiB, in this case)
- `cma-reserved`: Contiguous Memory Allocator

Examining the boot logs

mm/mm_init.c

```
static void __init mem_init_print_info(void)
{
    [...]

        pr_info("Memory: %luK/%luK available (%luK kernel code, %luK rwdata, %luK rodata, %luK init, %luK bss, %luK reserved, %luK cma-reserved"
#ifdef  CONFIG_HIGHMEM
        ", %luK highmem"
#endif
        ")\n",
        K(nr_free_pages()), K(physpages),
        codesize / SZ_1K, datasize / SZ_1K, rosize / SZ_1K,
        (init_data_size + init_code_size) / SZ_1K, bss_size / SZ_1K,
        K(physpages - totalram_pages() - totalcma_pages),
        K(totalcma_pages)
#ifdef  CONFIG_HIGHMEM
        , K(totalhigh_pages())
#endif
        );

    [...]
```

Kernel memory usage, but from user-space

Kernel logs from early boot

```
[    0.000000] Memory: 2012000K/2064384K available (...1280K init...
```

/proc/meminfo

```
root@xxxx-imx93:~# grep MemTotal /proc/meminfo
MemTotal:        2013280 kB
```

- Total memory slightly increased after `init` segment was retrieved
- `/proc/meminfo`: significant information about the kernel's memory usage

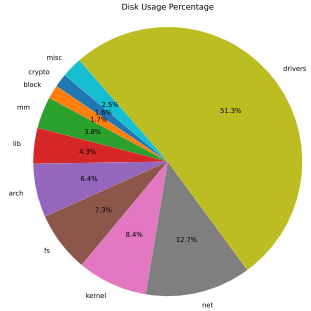
Examining /proc/meminfo

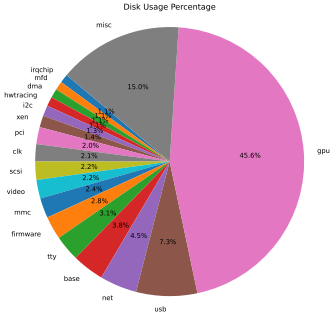
- Slab: total memory utilized for caching in-kernel data structures, managed by the Slab allocator
- KernelStack: memory allocated to kernel stacks
- PageTables: lowest level arrays of pages for address translation
- VmallocUsed: the used portion of vmalloc memory area

/proc/meminfo

```
# cat /proc/meminfo
Slab:                9440 kB
KernelStack:          752 kB
PageTables:           628 kB
VmallocUsed:        15204 kB
[...]
```

The kernel binary





- How much space each component takes in the final binary
- Rough numbers, based on the disk usage in the build directory
- The less code, the better!

Memory usage in user-space

First approach: using ps command

```
# ps aux
USER         PID %CPU %MEM    VSZ   RSS TTY      STAT START   TIME COMMAND
root           1  0.0  0.6  22452  3080 ?        Ss   Jan05   0:17 /sbin/init
root         161  0.0  0.3   5440  1728 ?        Ss   Jan05   0:02 /lib/systemd/systemd-udevd
root         169  0.0  1.1  13120  6024 ?        Ss   Jan05   1:19 /lib/systemd/systemd-journald
root         214  0.0  0.1   2776   844 ?        Ss   Jan05   0:00 /sbin/klogd -n
```

- Virtual Set Size and Resident Set Size
- VSZ: total virtual memory size, as listed in /proc/<PID>/maps
- RSS: the memory that is actually mapped to physical pages
- Equivalent to VIRT and RES in top command
- RSS repeatedly accounts for shared memory areas ⚠

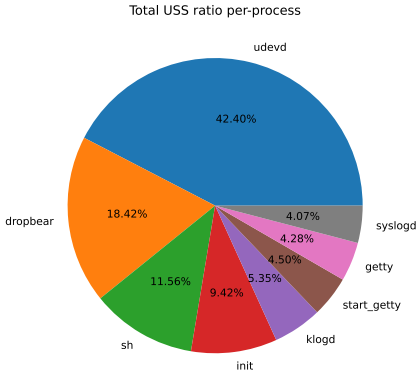
Second approach: using smem command

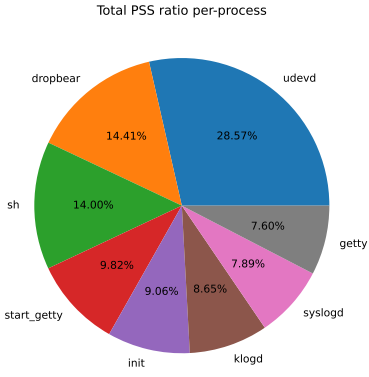
```
# smem -t
  PID User     Command                         Swap      USS      PSS      RSS
  290 0        /sbin/getty 38400 tty1             0       80      240     1380
  281 0        /sbin/syslogd -n -O /var/lo        0       76      249     1440
  284 0        /sbin/klogd -n                     0      100      273     1464
    1 0        init [5]                           0      176      286     1172
  289 0        /bin/sh /bin/start_getty 11        0       84      310     1576
  325 0        smemcap                            0      164      350     1528
  292 0        -sh                                0      216      442     1708
  273 0        /usr/sbin/dropbear -r /etc/        0      344      455     1340
  162 0        /sbin/udevd -d                     0      792      902     1784
--------------------------------------------------------------------------------
    9 1                                           0     2032     3507    13392
```

- Unique Set Size and Proportional Set Size
- USS: unique (private) memory per process
- PSS: proportional fraction of a shared memory zone
- if a 120Kb memory zone is shared among 3 proccesses, the PSS will be of 40Kb for each
- more details in /proc/<PID>/smaps

Plotting the memory usage with `smem`

- Record the data on the target: `smemcap > smemcap_imx93.tar`
- Plot it on the host: `smem --pie name -S smemcap_imx93.tar -s [uss|pss]`





free command

```
# free -h
               total        used        free      shared  buff/cache   available
Mem:            31Gi        18Gi       652Mi       3.5Gi        16Gi        12Gi
```

- used: unavailable memory
- available: used, but can be reclaimed
- free: not used for anything (wasted?)
- shared and buff/cache: tmpfs, kernel buffers, page cache, etc.
- check linuxatemyram.com

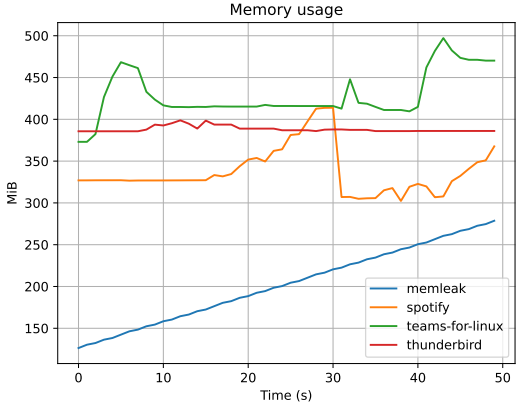
Optimization

Smaller code

- Thinking about features in a wider perspective (graphics, networking, filesystems, buses, virtualization, etc) then disabling the corresponding configs
- Compiler optimization level (size, rather than performance)
- Disable debugging (`CONFIG_DEBUG_KERNEL`)
- In iMX93: went from a 32MiB kernel to 11 MiB

Catching memory leaks

- Monitoring *procfs*
  - *free* command, for a global view
  - per-process *USS* and/or *RSS*, to find the leak source
  - `/proc/meminfo`, and `/proc/<PID>/smaps` respectively



Catching memory leaks

- Valgrind
  - Detects memory management errors: leaks, invalid accesses, bad freeing of heap blocks, etc.
  - No need to rebuild your program, but it works better with `-g`

```c
#include <stdlib.h>

int main() {
    char *string_a, *string_b;

    string_a = malloc(10); /* 10 bytes leaking */
    free(string_b); /* Invalid free */

    return 0;
}
```

Catching memory leaks

```
valgrind --leak-check=full --show-leak-kinds=all ./memleak
==941479== Memcheck, a memory error detector
==941479== Copyright (C) 2002-2022, and GNU GPL'd, by Julian Seward et al.
==941479== Using Valgrind-3.22.0 and LibVEX; rerun with -h for copyright info
==941479== Command: ./memleak
==941479==
==941479== Conditional jump or move depends on uninitialised value(s)
==941479==    at 0x4845ADF: free (vg_replace_malloc.c:985)
==941479==    by 0x401157: main (memleak.c:7)
==941479==
==941479==
==941479== HEAP SUMMARY:
==941479==     in use at exit: 10 bytes in 1 blocks
==941479==   total heap usage: 1 allocs, 0 frees, 10 bytes allocated
==941479==
==941479== 10 bytes in 1 blocks are definitely lost in loss record 1 of 1
==941479==    at 0x484280F: malloc (vg_replace_malloc.c:442)
==941479==    by 0x401147: main (memleak.c:6)
==941479==
==941479== LEAK SUMMARY:
==941479==    definitely lost: 10 bytes in 1 blocks
==941479==    indirectly lost: 0 bytes in 0 blocks
==941479==      possibly lost: 0 bytes in 0 blocks
==941479==    still reachable: 0 bytes in 0 blocks
==941479==         suppressed: 0 bytes in 0 blocks
==941479==
==941479== Use --track-origins=yes to see where uninitialised values come from
==941479== For lists of detected and suppressed errors, rerun with: -s
==941479== ERROR SUMMARY: 2 errors from 2 contexts (suppressed: 0 from 0)
```

Swap

- Freeing memory by moving pages to the disk
- Not quite suited for embedded systems: wearing out flash disks, unresponsiveness (*thrashing*), etc.
- Can be tuned with `/proc/sys/vm/swappiness`, ranging from 0 to 200
- Use it to balance swapping and filesystem paging (e.g., 100 means equal IO cost)
- Setting it to 0...
  - Disables it in a memory control group context
  - Does *not* disable it in a system-wide context

`Documentation/admin-guide/cgroup-v1/memory.rst`

```
Please note that unlike during the global reclaim, limit reclaim enforces that 0 swappiness really prevents from
any swapping even if there is a swap storage available. This might lead to memcg OOM killer if there are no file
pages to reclaim.
```

ZRAM: like swap, but better

- Pages are compressed then stored into a RAM-based block device
- Faster than disk-based swap

```
Device Drivers  --->
    [*] Block devices  --->
        <M> Compressed RAM block device support
        [*] Write back incompressible or idle page to backing device
        [*] Track zRam block status
```

Out of memory killer

- Last resource: a process is killed to reclaim memory
- Heuristic choice: the more memory the process takes, the higher its *badness*

mm/oom_kill.c

```
long oom_badness(struct task_struct *p, unsigned long totalpages)
{

    /* (...) */

    /*
     * The baseline for the badness score is the proportion of RAM that each
     * task's rss, pagetable and swap space use.
     */
    points = get_mm_rss(p->mm) + get_mm_counter(p->mm, MM_SWAPENTS) +
        mm_pgtables_bytes(p->mm) / PAGE_SIZE;

    /* Normalize to oom_score_adj units */
    adj *= totalpages / 1000;
    points += adj;

    return points;
}
```

Out of memory killer

- Tuning OOM Killer: `/proc/<PID>/oom_score_adj`
- This adjustment parameter ranges from -1000 to 1000

include/uapi/linux/oom.h

```
/*
 * /proc/<pid>/oom_score_adj set to OOM_SCORE_ADJ_MIN disables oom killing for
 * pid.
 */
#define OOM_SCORE_ADJ_MIN   (-1000)
#define OOM_SCORE_ADJ_MAX   1000
```

- Example: `echo -1000 > /proc/`pgrep myapp`/oom_score_adj`

```
# cat /proc/`pgrep firefox`/oom_score
738
# echo -1000 > /proc/`pgrep firefox`/oom_score_adj
# cat /proc/`pgrep firefox`/oom_score
0
```

- Firefox is now immune to the OOM Killer!

Questions? Suggestions? Comments?

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