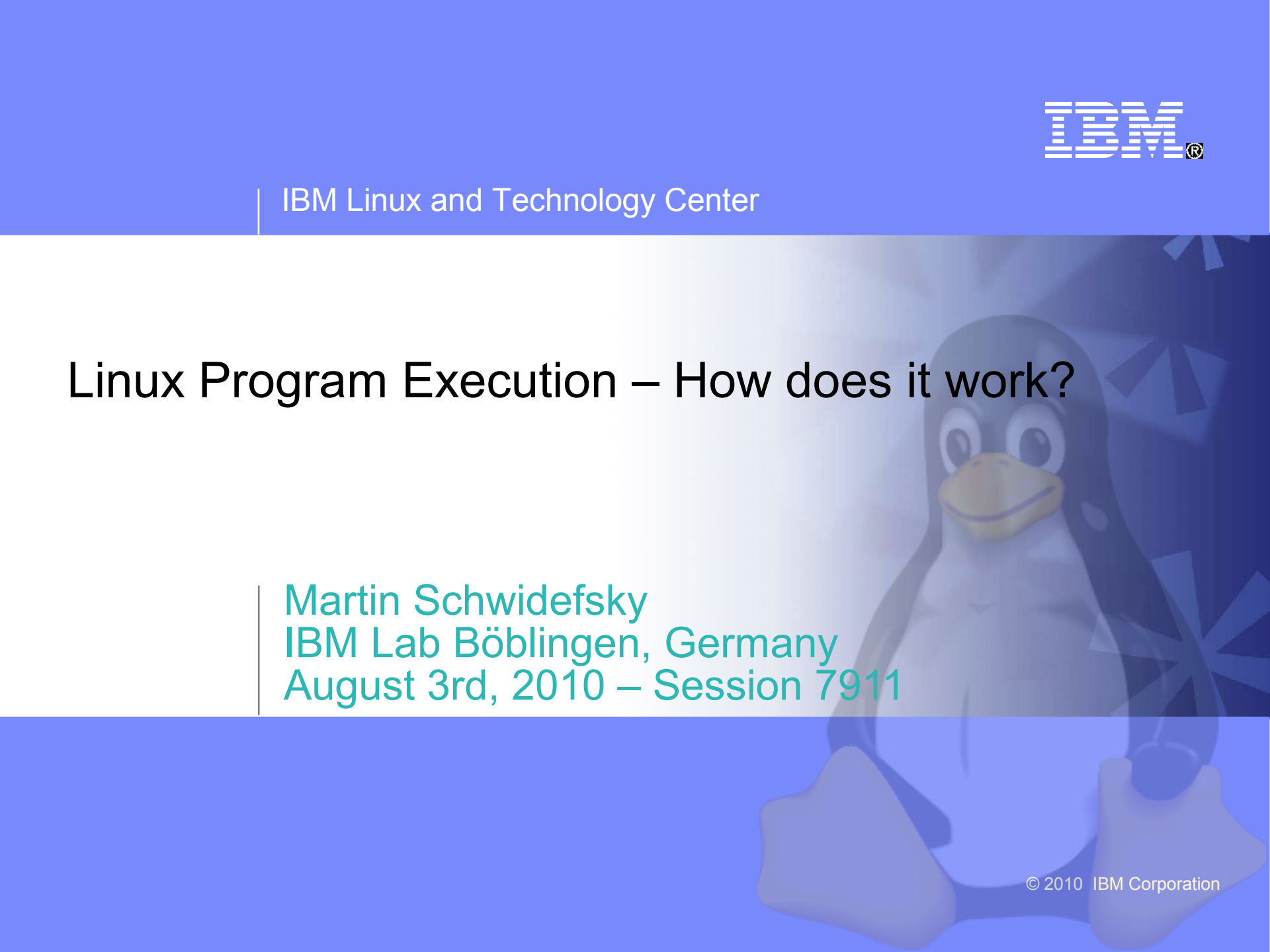

Linux Program Execution – How does it work?

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IBM Lab Böblingen, Germany
August 3rd, 2010 – Session 7911

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Example program

- The goal of this presentation is to give an idea what happens in Linux to execute this simple “Hello World” program:

```
#include <stdio.h>
#include <stdlib.h>

int main(void)
{
        char *p = malloc(1024);
        printf("Hello world %p\n", p);
        return 0;
}
```

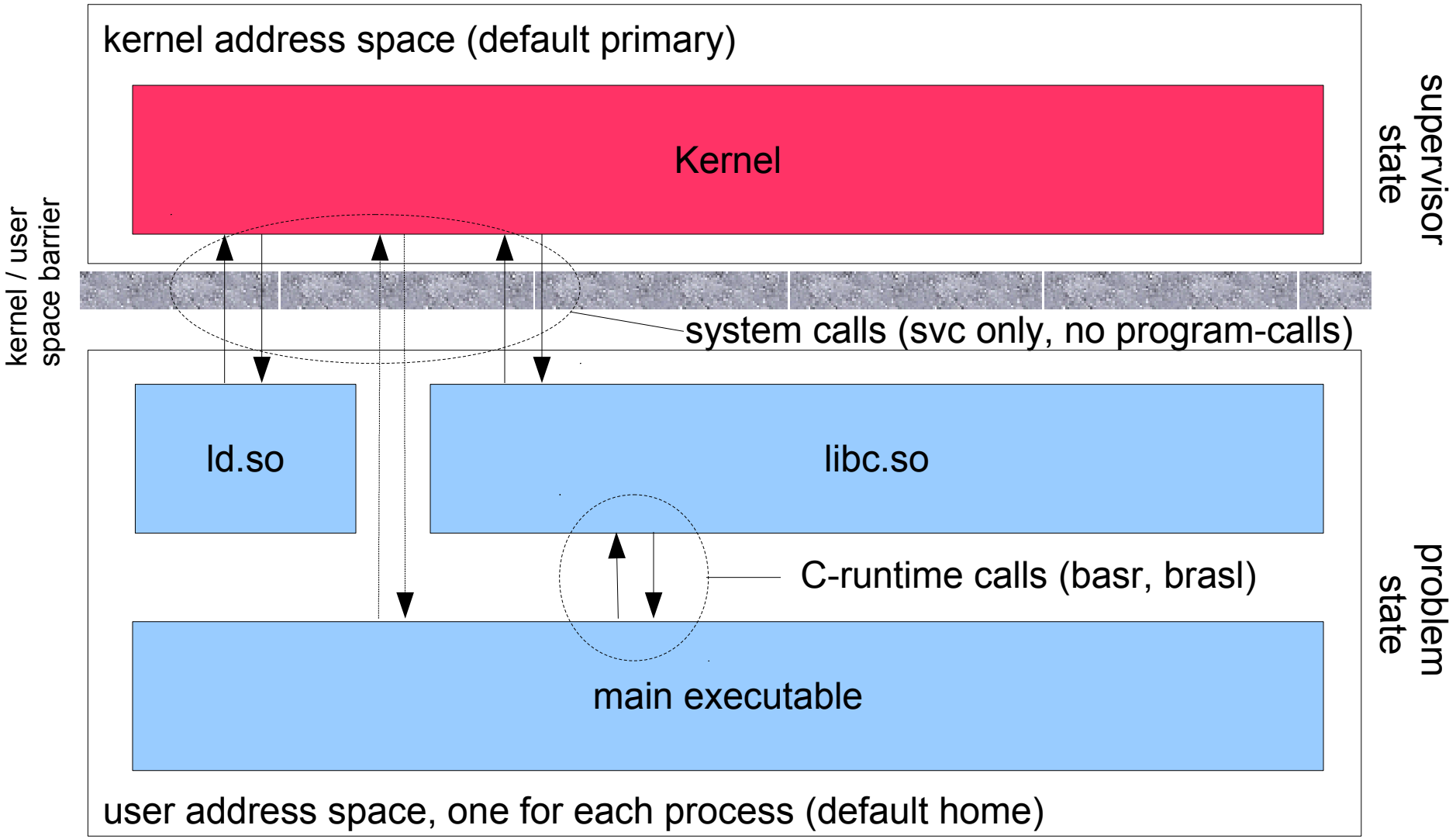
Unix design points

- Portable, multi-tasking and multi-user operating system
- Plain text for storing data
- “Everything is a stream of bytes”
- A hierarchical file system
  - Arbitrarily nested subdirectories
  - Devices are represented as special files
- Use of small programs that are connected through a command line interpreter and pipes
- Heavy use of the C programming language
- Division between user-space and kernel-space
- POSIX standard
  - Portable Operating System Interface [for Unix]

POSIX.1 – Core Services

- Process Creation and Control
  - Executable machine code (kernel threads vs. user space threads)
  - Virtual memory with code, data, a call stack
  - Resource descriptors allocated to the process
  - Security attributes: process owner, permissions
  - Processor state (context)
- Signals, Timers
  - Notifications sent to a process via an asynchronous function call
  - Timing events delivered as signals
- File and Directory Operations
- Pipes
- .. and some more

Simplistic system layout

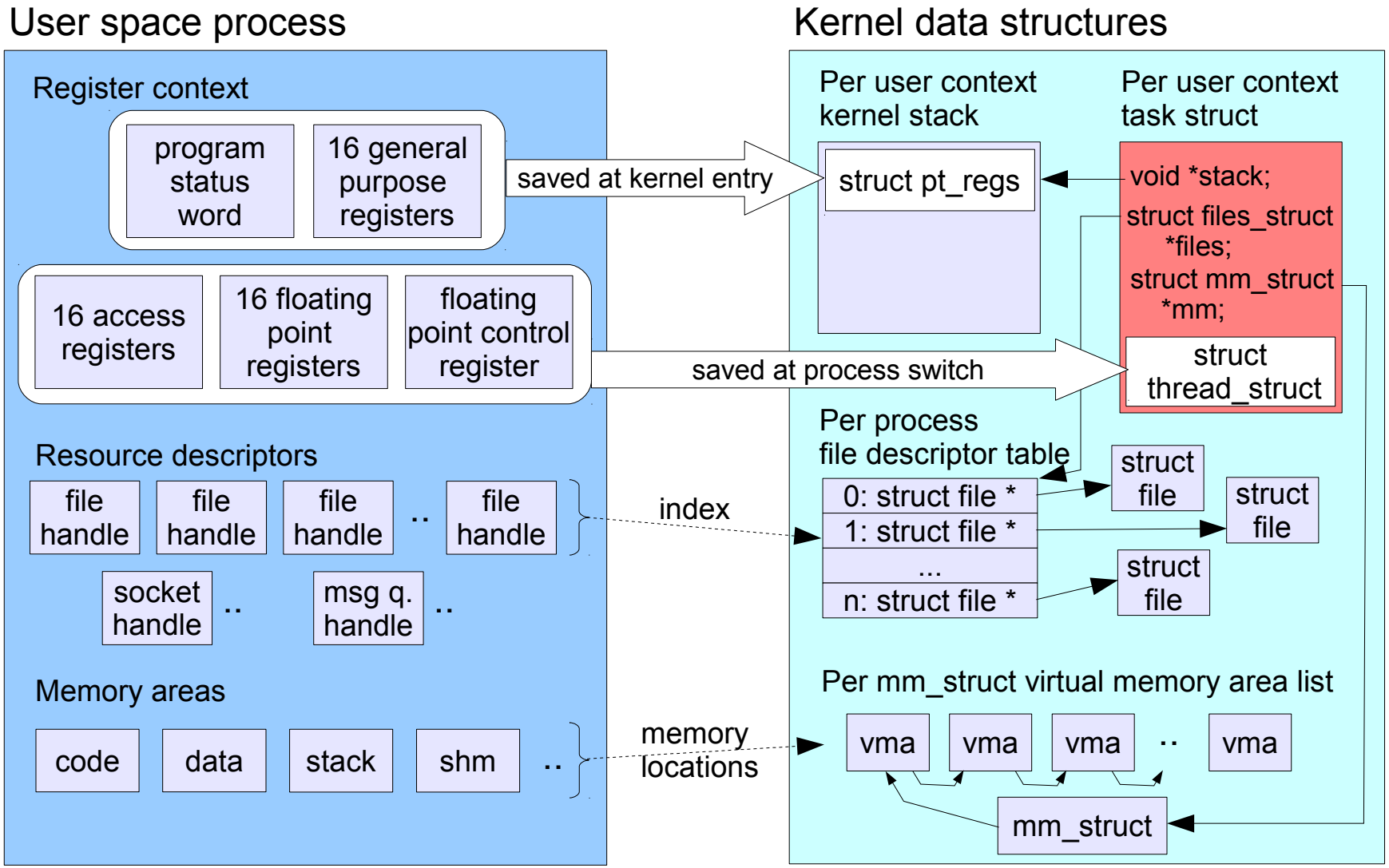


Kernel access to user data (uaccess)

- Strict separation between the kernel and user address space
  - Kernel address space uses a three level page table, max 4TB
  - User address space uses two, three or four level page table, max 8PT
- **No kernel data structures visible in user space**
  - In particular the lowcore pages are not mapped to user space
  - Usually there is nothing mapped at address zero
- The uaccess functions provide access to user data for kernel code

	copy to user	copy from user	futex
kernel in primary machine < z9	mvcs	mvcp	sacf to secondary + compare-and-swap
kernel in primary machine >= z9	mvcos	mvcos	sacf to secondary + compare-and-swap
kernel in home machine < z9	page table walk	page table walk	page table walk + compare-and-swap
kernel in home machine >= z9	mvcos	mvcos	page table walk + compare-and-swap

User space context & kernel data structures



Frequently used system calls

- Working with files
  - open, dup, read, write, lseek, close, stat, creat, truncate, ..
- Filesystem operations
  - link, unlink, rename, mkdir, rmdir, ..
- Virtual memory operations
  - brk, mmap, munmap, mprotect, mlock, munlock
- Process create, execution, termination
  - fork, clone, execve, exit, pause, wait4, pipe, chdir, ..
- Signals
  - kill, signal, sigaction, sigprocmask, sigreturn, ..
- .. and many more, currently there are 332 system calls for Linux on System z, some of them multiplexer e.g. ipc

strace of statically linked “Hello World”

```
> cat hello.c
#include <stdio.h>
#include <stdlib.h>
int main(void)
{
      char *p = malloc(1024);
      printf("Hello world %p\n", p);
      return 0;
}

> gcc -static -o hello -O2 hello.c

> strace -v ./hello
execve("./hello", ["./hello"], ["HOSTNAME=t6360015", "TERM=xterm",
       "SHELL=/bin/bash", "HISTSIZE=1000",
       "SSH_CLIENT=9.152.212.37 56750 22"...,
       "SSH_TTY=/dev/pts/0", "USER=root", "USERNAME=root",
       "PATH=/sbin:/bin:/usr/sbin:/bin"..., "PWD=/root", "SHLVL=1",
       "HOME=/root", "BASH_ENV=/root/.bashrc", "LOGNAME=root",
       "_=/usr/bin/strace"]) = 0
brk(0) = 0x8009d000
brk(0x8009df60) = 0x8009df60
brk(0x800bef60) = 0x800bef60
brk(0x800bf000) = 0x800bf000
fstat(1, {st_mode=S_IFCHR|0620, st_rdev=makedev(136, 0), ...}) = 0
mmap(NULL, 4096, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0)
     = 0x20000000000
write(1, "Hello world 0x8009e5e0\n"..., 23) = 23
exit_group(0) = ?
```

Binary formats

- Linux knows about different binary formats
  - aout: the oldest executable format for Linux, does not exists for System z
  - elf: Executable and Linkage Format, the standard executable format
  - em86: wrapper for /usr/bin/em86 to run x86 ELF binaries on Alpha machines
  - flat: uClinux FLAT format binaries
  - misc: used for wrapper-driven binary formats, e.g. interpreted languages like Java, Python, .net, etc.
  - som: HP/UX binary executable format
- Execve loads the first block of the executable and calls the available binary format handlers until one is found which can execute the binary

ELF ABI

- Executable and Linkage Format Application Binary Interface (ELF ABI)
  - Data representation: byte ordering, fundamental types, alignment
  - Function calling: register usage, stack frame layout, parameter passing,
  - OS interface: virtual address space, initial registers, environment, arguments, auxiliary vector
  - Object file format: header, sections, relocations, global offset table, procedure link table
- ELF binary format handler checks for ".ELF" in the first block

```
00000000: 7f45 4c46 0202 0100 0000 0000 0000 0000  .ELF............
00000010: 0002 0016 0000 0001 0000 0000 8000 2bfc  ..............+.
00000020: 0000 0000 0000 0040 0000 0000 0001 7ed0  .......@......~.
00000030: 0000 0000 0040 0038 0009 0040 001d 001c  .....@.8...@....
00000040: 0000 0006 0000 0005 0000 0000 0000 0040  ...............@
```

- System z supplement to the ELF ABI
  www.linuxfoundation.org/spec/ELF/zSeries/lzsabi0_s390.html

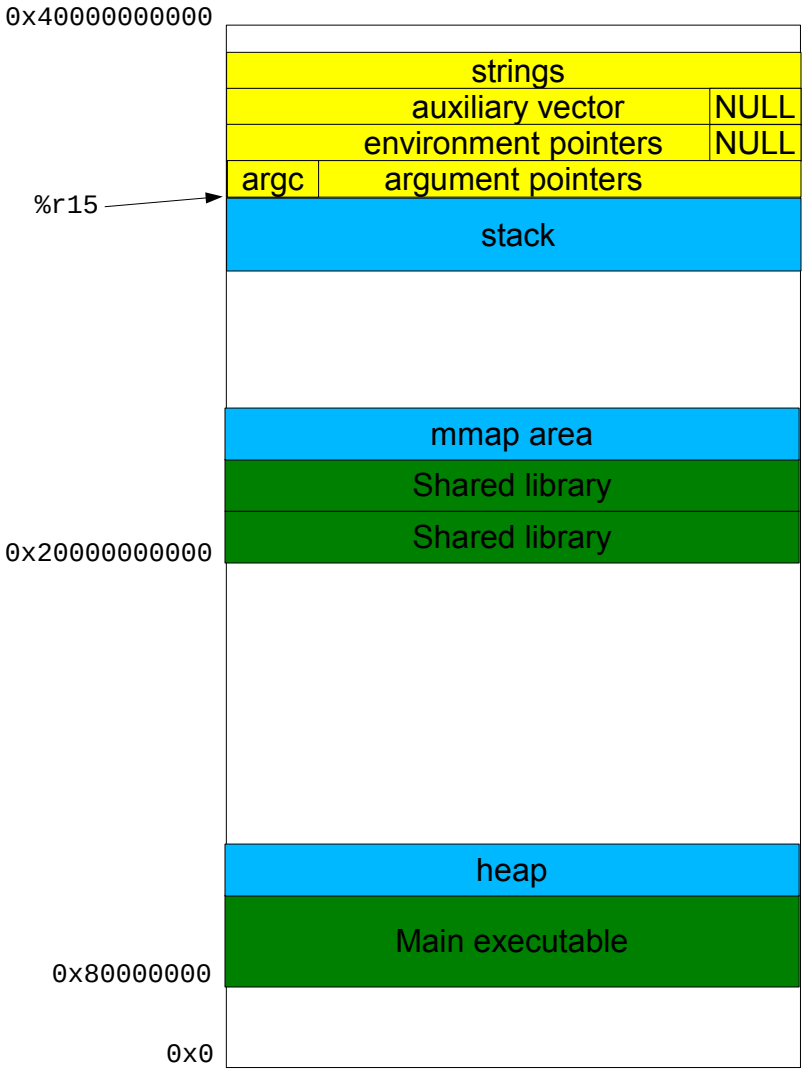
ELF ABI: registers

Register name	Usage	Call effect
%r0,%r1	General purpose	Volatile
%r2	Parameter passing and return value	Volatile
%r3, %r4, %r5	Parameter passing	Volatile
%r6	Parameter passing	Volatile
%r7 - %r11	Local variables	Saved
%r12	Local variable, GOT pointer	Saved
%r13	Local variable, literal pool pointer	Saved
%r14	Return address	Volatile
%r15	Stack pointer	Saved
%f0, %f2, %f4, %f6	Parameter passing and return values	Volatile
%f1, %r3, %f5, %f7	General purpose	Saved
%f8 - %f15	General purpose	Volatile
%a0 - %a1	Reserved for system use (TLS pointer)	Reserved
%a2 - %a15	General purpose	Volatile

ELF ABI: entries in the auxiliary vector

AT_EXECFD/AT_EXECFN	File descriptor and filename of the executable
AT_PHDR/AT_PHNUM	Program headers address and size for program
AT_PAGESZ	System page size
AT_BASE	Base address of interpreter (dynamic linking)
AT_FLAGS	Flags
AT_ENTRY	Entry point of the program
AT_UID/AT_EUID	Real and effective user id
AT_GID/AT_EGID	Real and effective group id
AT_PLATFORM	String identifying platform
AT_HWCAP	Machine dependent hints about processor capabilities
AT_FPUCW	Used FPU control word
.. and some more	

ELF ABI: System z standard virtual memory layout

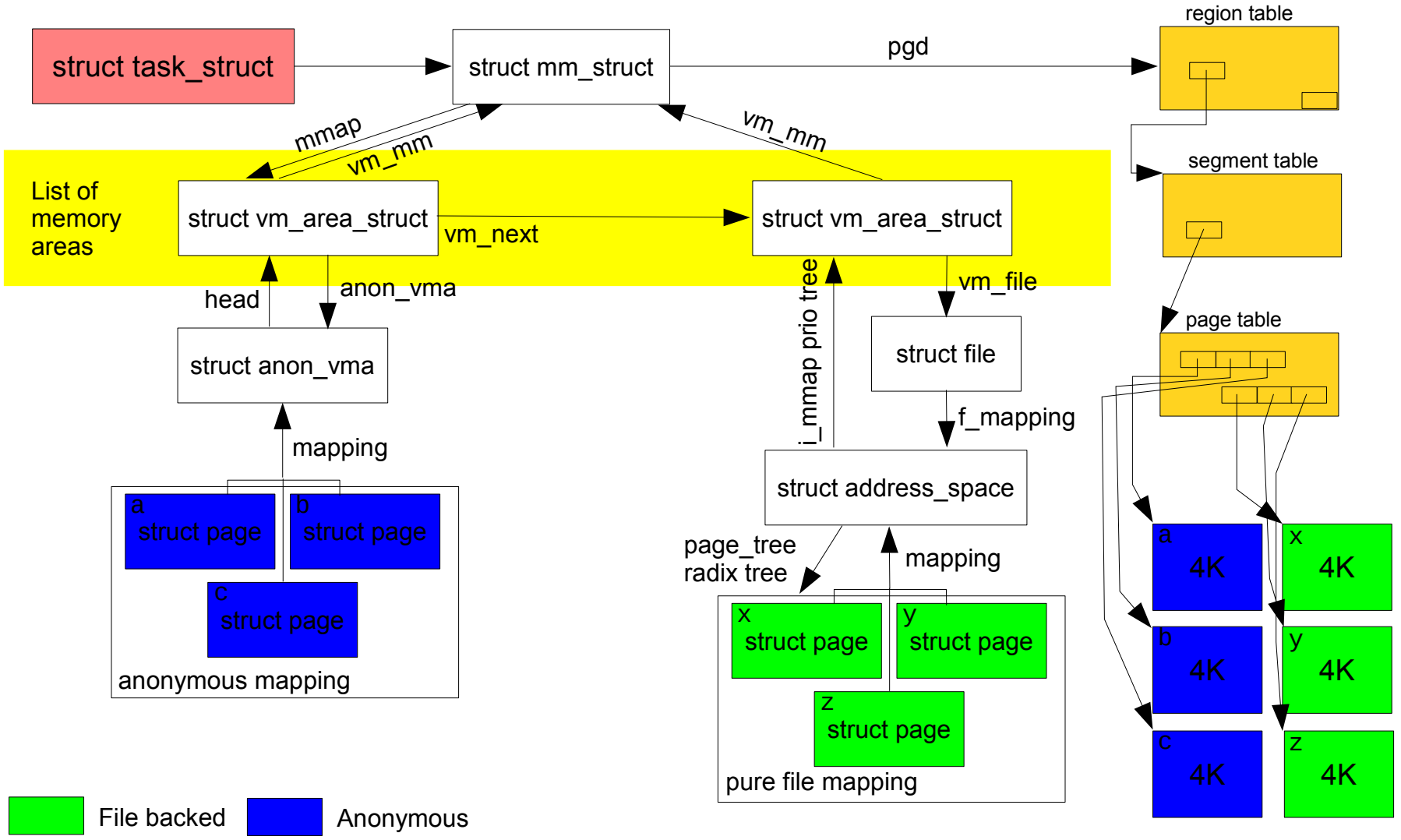


- Main executable usually at 2GB
  - Standard linker script uses 2GB as starting point
- Heap is located right after the main executable
- Libraries usually at 2TB
  - Prelink pre-allocates libraries and binaries
- Stack allocated near the end of the address space
  - Stack grows down
- Argument count: the number of argument pointers
- Argument pointers refer to a set of positional strings passed to the application. Example: `"cp" "file-a" "file-b"`
- Environment pointers refer to a set of dynamic named string values, each process has its own private set. Example: `"PWD=/home/user"`
- The auxiliary vector conveys information from the OS to the application.

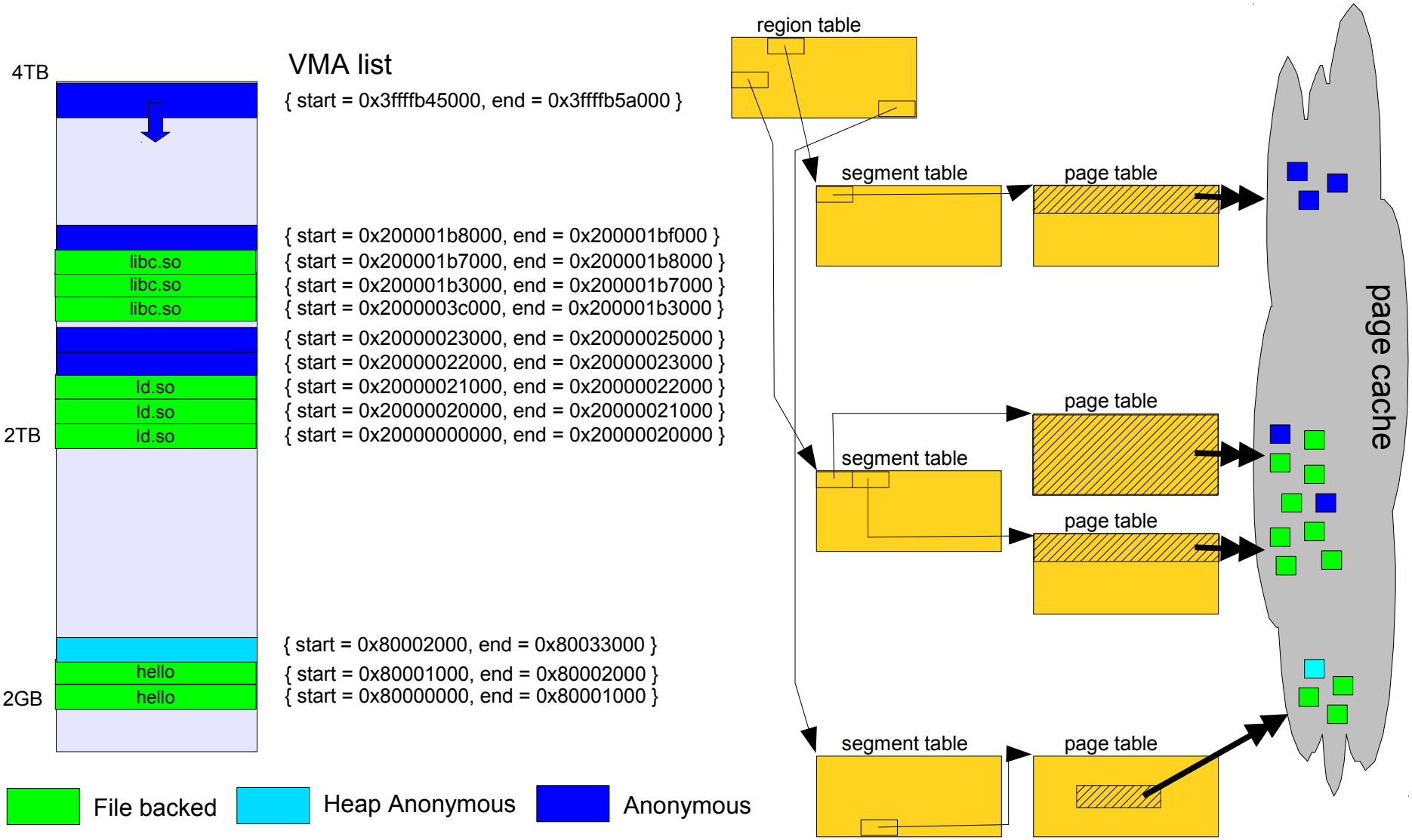
Memory management data structures

- **Virtual address space (struct mm_struct)**
  - Describes the virtual address space of a process
  - Contains the head of a list of memory areas
  - Contains counters and other information about the virtual address space
- **Memory areas (struct vm_area_struct)**
  - Defines an area in the mm_struct with start and end address
  - Either a “window” into a file starting at an offset or an anonymous area (or both)
- **Anonymous memory area (struct anon_vma)**
  - The mapping of an anonymous page points to a struct anon_vma
  - The anon_vma contains the head of a list of related memory areas
  - vmas on the list will be related by forking and vma splitting / merging
- **Page descriptor (struct page)**
  - Each physical page in the system has a struct page associated with it
  - Used to keep track of whatever the page is used for

Virtual memory areas kernel data structures

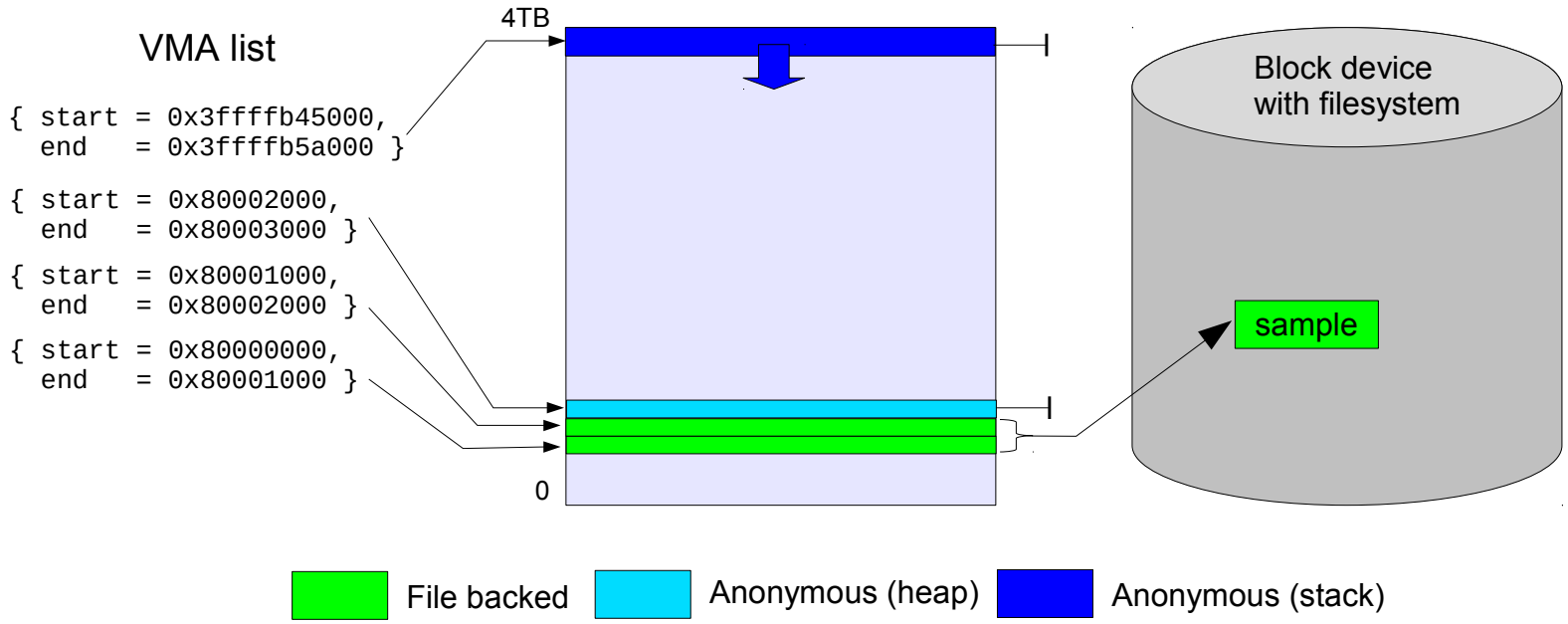


Virtual memory areas and page tables



/proc/<pid>/maps of a simple static ELF executable

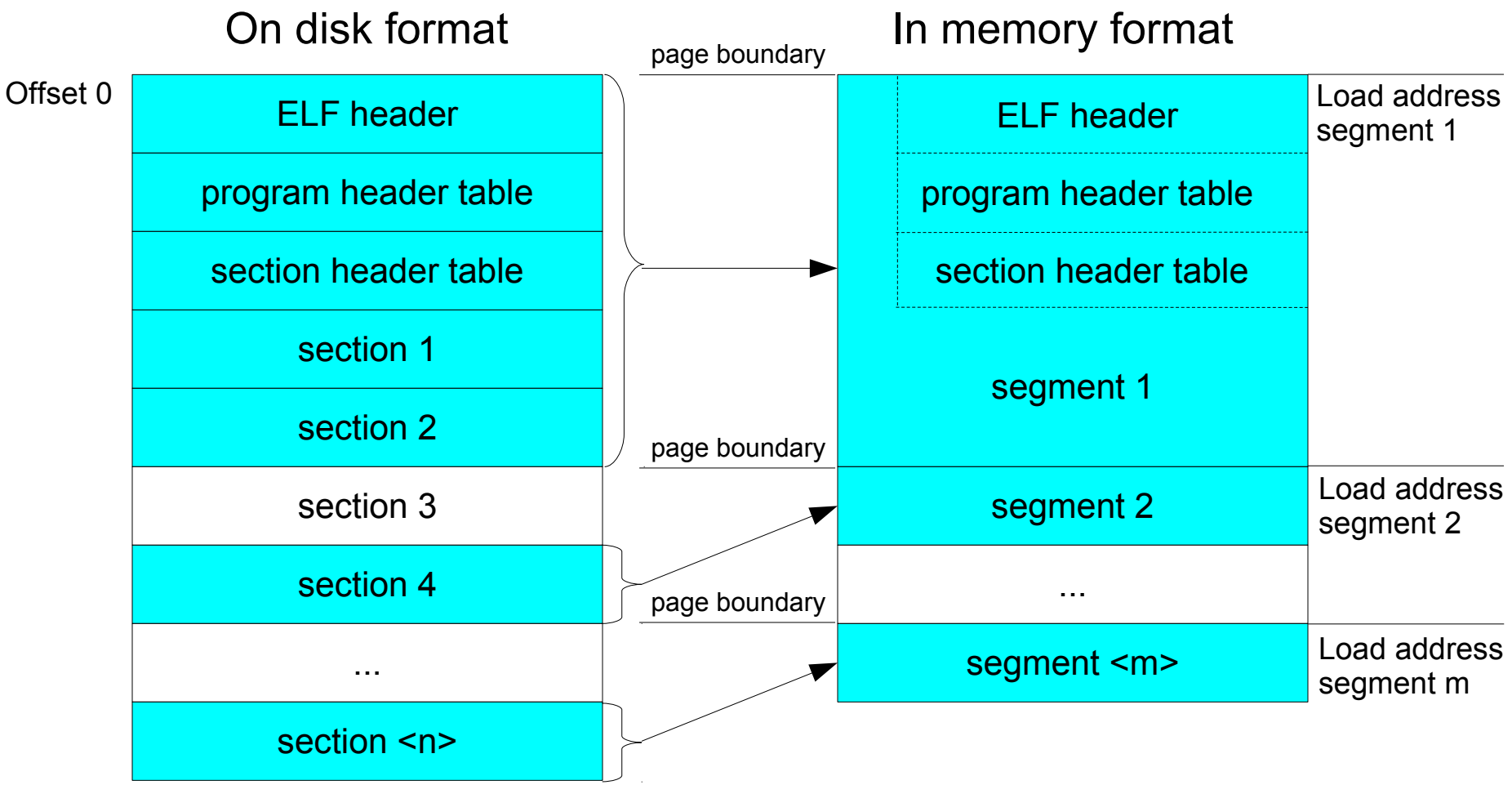
```
Start            End              Acc  Offset   Bdev  Ino     File
=============================================================================
   80000000-   80001000 r-xp 00000000 5e:12 32275   /root/sample
   80001000-   80002000 rwxp 00000000 5e:12 32275   /root/sample
   80002000-   80003000 rw-p 00000000 00:00 0       [heap]
3ffffb5f000-3ffffb74000 rw-p 00000000 00:00 0       [stack]
```



ELF object file format – header (readelf -h)

```
ELF Header:
  Magic:   7f 45 4c 46 02 02 01 00 00 00 00 00 00 00 00 00
  Class:                             ELF64
  Data:                              2's complement, big endian
  Version:                           1 (current)
  OS/ABI:                            UNIX - System V
  ABI Version:                       0
  Type:                              EXEC (Executable file)
  Machine:                           IBM S/390
  Version:                           0x1
  Entry point address:               0x800000e8
  Start of program headers:          64 (bytes into file)
  Start of section headers:          448 (bytes into file)
  Flags:                             0x0
  Size of this header:               64 (bytes)
  Size of program headers:           56 (bytes)
  Number of program headers:         3
  Size of section headers:           64 (bytes)
  Number of section headers:         8
  Section header string table index: 7
```

ELF object file format



ELF object file format – program headers (readelf -l)

```
Elf file type is EXEC (Executable file)
Entry point 0x800000e8
There are 3 program headers, starting at offset 64

Program Headers:
  Type           Offset             VirtAddr           PhysAddr
                 FileSiz            MemSiz              Flags  Align
  LOAD           0x0000000000000000 0x0000000080000000 0x0000000080000000
                 0x0000000000000150 0x0000000000000150  R E    1000
  LOAD           0x0000000000000150 0x0000000080001150 0x0000000080001150
                 0x0000000000000010 0x0000000000000020  RW     1000
  GNU_STACK      0x0000000000000000 0x0000000000000000 0x0000000000000000
                 0x0000000000000000 0x0000000000000000  RW     8

 Section to Segment mapping:
  Segment Sections...
   00     .text .rodata .eh_frame
   01     .data .bss
   02
```

ELF object file format – section headers (readelf -S)

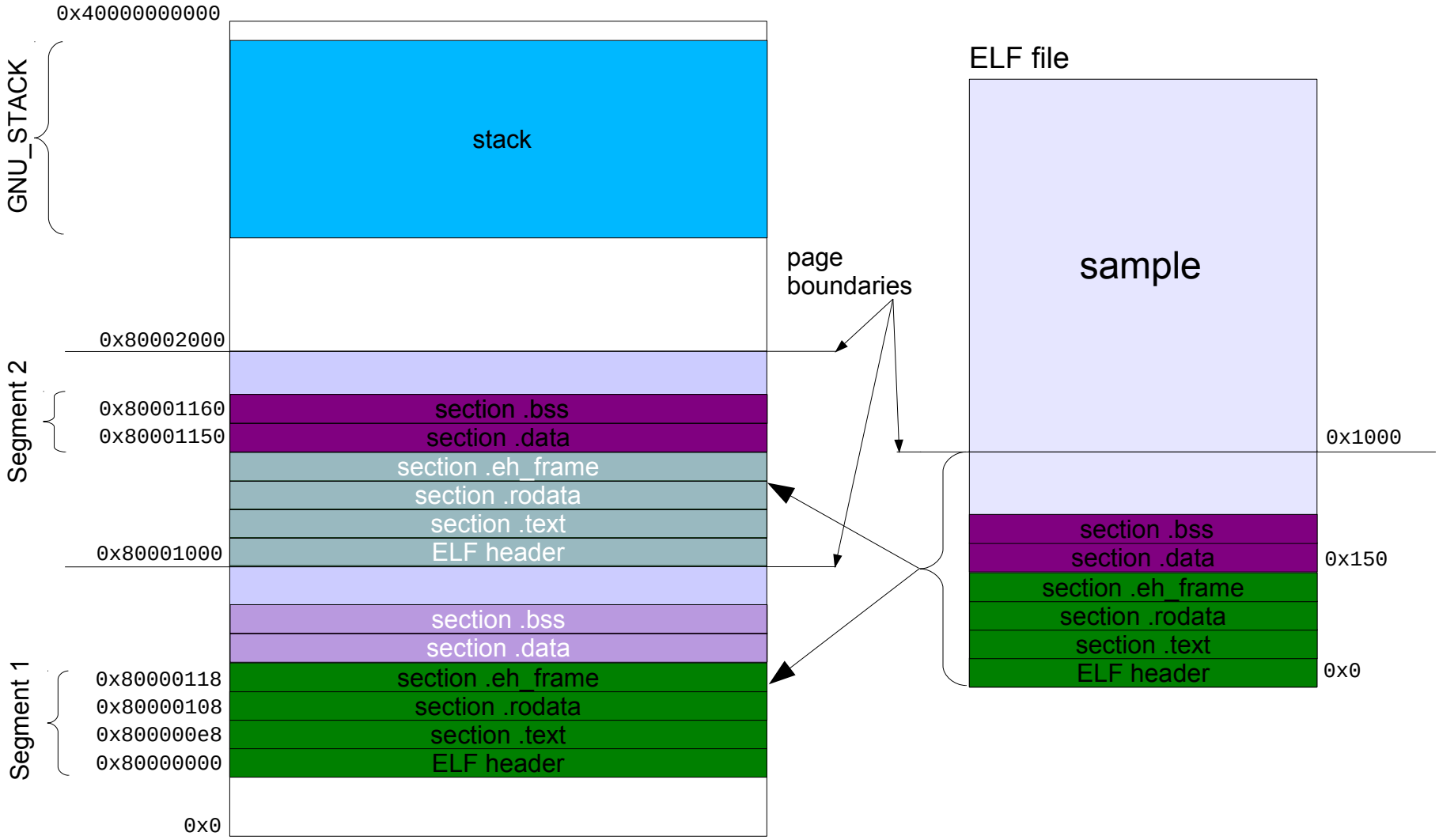
```
There are 8 section headers, starting at offset 0x1c0:

Section Headers:
  [Nr] Name              Type            Address          Offset
       Size              EntSize         Flags  Link  Info  Align
  [ 0]                   NULL            0000000000000000 00000000
       0000000000000000  0000000000000000           0     0     0
  [ 1] .text             PROGBITS        00000000800000e8 000000e8
       0000000000000020  0000000000000000  AX       0     0     4
  [ 2] .rodata           PROGBITS        0000000080000108 00000108
       0000000000000010  0000000000000000   A       0     0     4
  [ 3] .eh_frame         PROGBITS        0000000080000118 00000118
       0000000000000038  0000000000000000   A       0     0     8
  [ 4] .data             PROGBITS        0000000080001150 00000150
       0000000000000010  0000000000000000  WA       0     0     4
  [ 5] .bss              NOBITS          0000000080001160 00000160
       0000000000000010  0000000000000000  WA       0     0     4
  [ 6] .comment          PROGBITS        0000000000000000 00000160
       0000000000000028  0000000000000000           0     0     1
  [ 7] .shstrtab         STRTAB          0000000000000000 00000188
       0000000000000037  0000000000000000           0     0     1
Key to Flags:
  W (write), A (alloc), X (execute), M (merge), S (strings)
  I (info), L (link order), G (group), x (unknown)
  O (extra OS processing required) o (OS specific), p (processor specific)
```

Segment 1

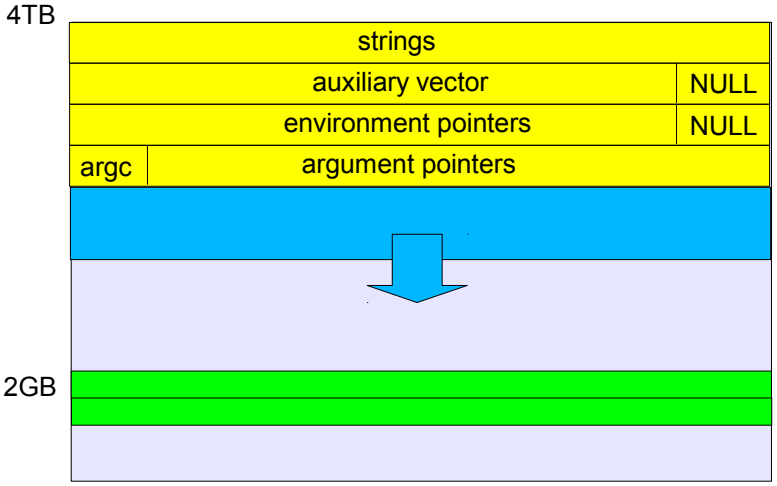
Segment 2

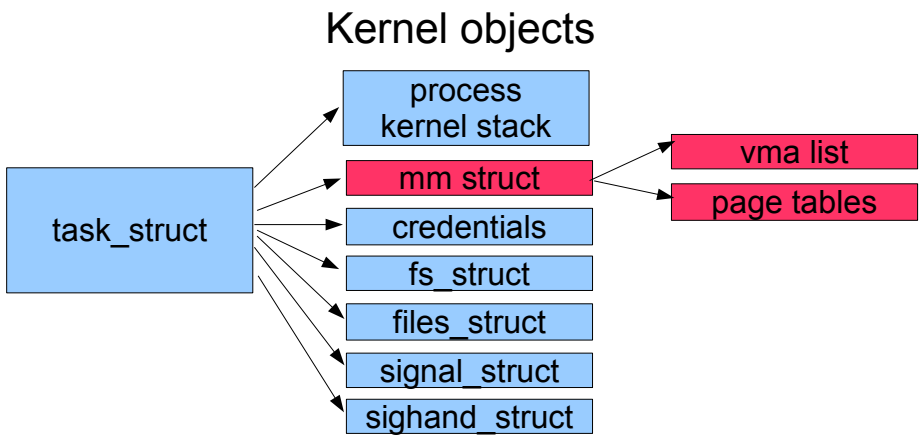
Mapping of file pages to the user address space



What happens on execve() ?

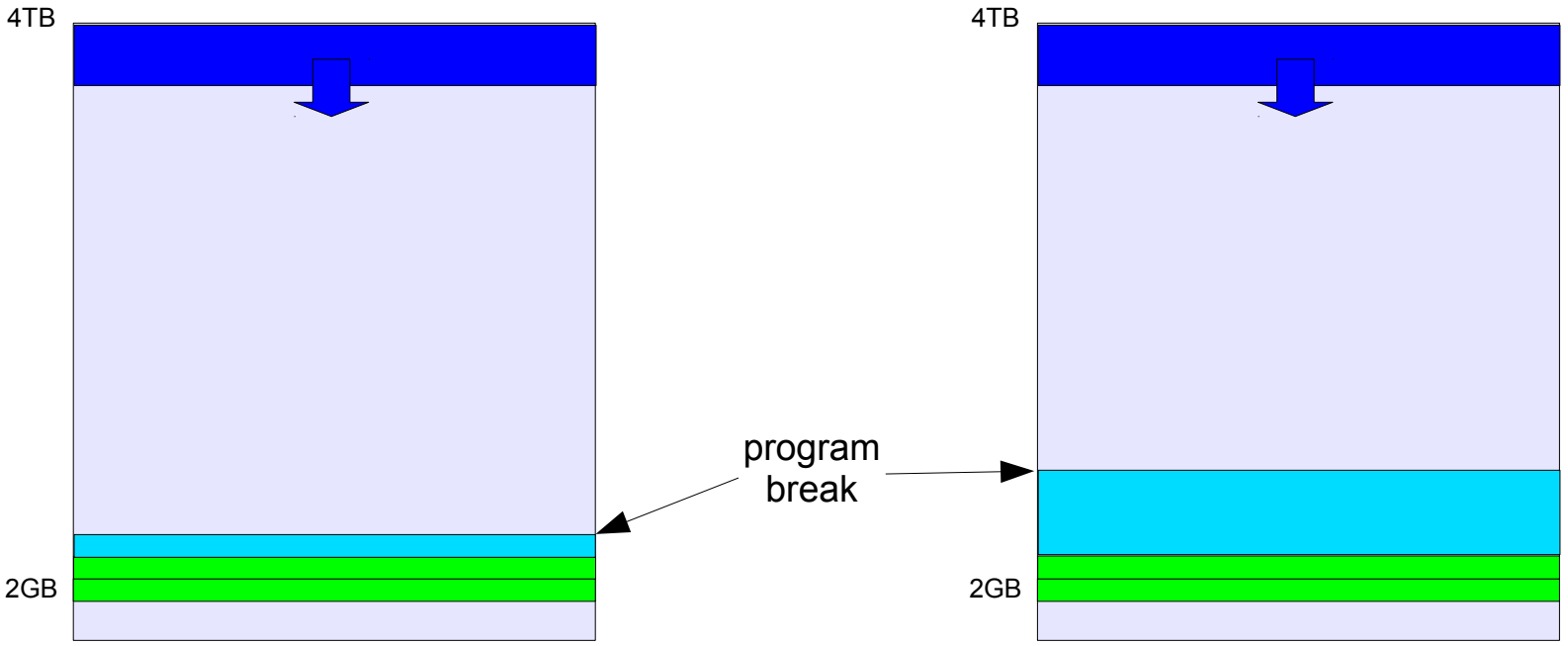
- Kernel copies environment & arguments from the current process
  - Number of internal pages used to be limited: argument list too long errors
- Kernel clears existing mappings and maps the PT_LOAD segments of the executable
  - Only the vma is created and the top level page directory is allocated
- Kernel creates auxiliary vector, environment & arguments
  - User copy causes page faults → stack page tables are created
  - Clearing of .bss section causes faults for writable segment of executable
- Kernel initializes processor state, including stack pointer & initial PSW





What happens on brk() ?

- brk/sbrk system calls change the location of the program break
- brk sets the end address of the heap, sbrk increases the size of the heap
- The new memory space is not backed with real memory right away, pages are allocated on first access



What happens on exit() / exit_group() ?

- **Almost all kernel structures for the process are freed**
  - For shared structures the reference counter is decremented
  - Examples: mm_struct, fs_struct, files_struct, signal_struct, sighand_struct ...
- **The address space (mm_struct) is cleared before it is freed**
  - munmap from address 0 to address -1
- **The task_struct is not (yet) freed**
  - The task state is set to TASK_DEAD
  - The parent is notified that the child has exited
  - The parent needs to call wait4()/waitid() to collect the exit status
  - A dead child process with wait4()/waitid() pending is a “Zombie”

Sequence of system calls for bash executing “hello”

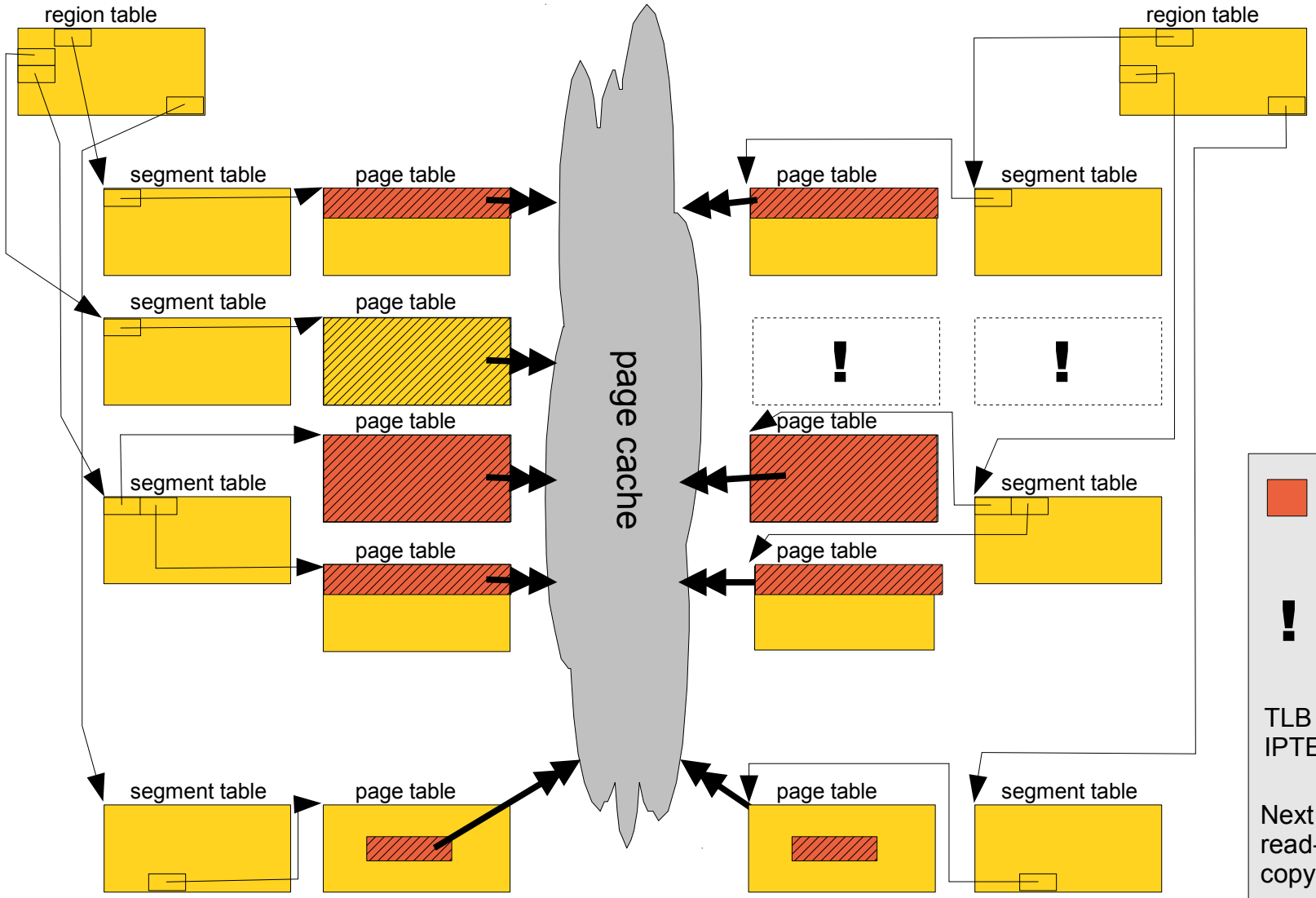
Parent	Child
`bash: clone()`	`<child process created by clone>`
`bash: wait4() <unfinished ...>`	`bash: execve(“./hello”, ...)`
	`hello: brk(0) = 0x8009d000`
	`hello: brk(0x8009df60) = 0x8009df60)`
	`hello: brk(0x800bef60) = 0x800bef60)`
	`hello: brk(0x800bf000) = 0x800bf000)`
	`hello: fstat(1, …) = 0`
	`hello: mmap(NULL, …) = 0x20000000000`
	`hello: write(1, “Hello World\n”, 12) = 12`
	`hello: exit_group(0)`
`bash: <... wait4 resumed>`	

- No “open” for file descriptor 1
  - Child inherits all open file descriptors of the parent process
  - execve closes all of them but the first 3: stdin, stdout, stderr
- No “close”, no “munmap”; exit_group takes care of that

What happens on clone() / fork() ?

- Execve() replaces the current context, fork() duplicates a context
- Allocate a new task_struct (dup_task_struct)
  - Copies almost all fields from the parent task_struct
- Create copies of various task related kernel data structures
  - Credentials, same rights for the child
  - File descriptor table, same files for the child
  - Filesystem info, same working directory, same umask
  - Copies the current set of signal handlers, empty set of pending signals
  - Duplicate virtual memory address space, only mlocks()s are not inherited
- Initialize per task information
  - Scheduler initialize per task fields and selects a run queue
  - Child gets a new pid / tpid
  - Resource utilization is reset, timers are reset
- Add new task to process tree

What happens on fork() / copy_mm() ?

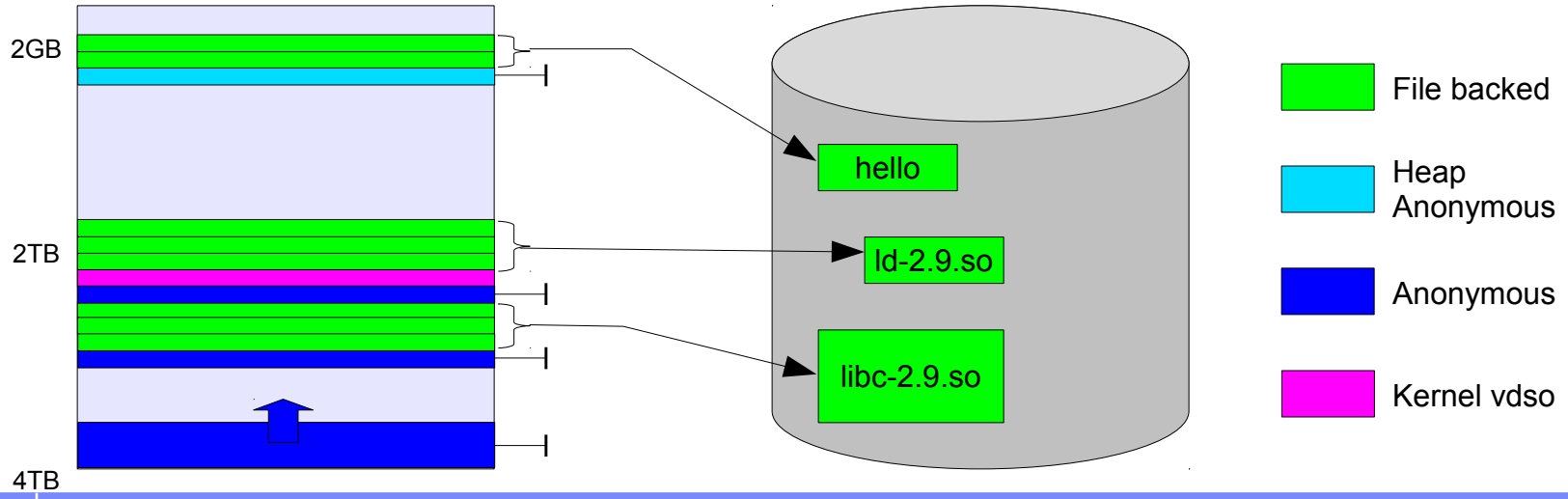


Dynamic linking of ELF objects

- **User space program can be statically or dynamically linked**
  - Dynamic ELF exec is mapped just like a statically linked exec
  - ELF .interp section gives the name of the “interpreter” = ld.so
  - ld.so is mapped and started instead of the main executable
  - ld.so loads and links the missing pieces for the dynamic executable
  - ld.so resolves the relocations between the different ELF objects
- **Usually a user space program has multiple ELF objects**
  - Main executable at 2GB (default)
  - Dynamic linker ld.so at 2TB
  - C-runtime libc.so at 2TB + sizeof ld.so object
  - More shared libraries
  - Kernel virtual dynamic shared object (vdso)
- **Shared libraries can by dynamically loaded / unloaded**
  - dlopen() / dlsym() / dlclose() calls to ld.so

/proc/<pid>/maps for dynamic “Hello World”

```
Start            End              Acc  Offset   Bdev  Ino     File
=============================================================================
   80000000-   80001000 r-xp 00000000 5e:01 11875   /root/hello
   80001000-   80002000 rwxp 00000000 5e:01 11875   /root/hello
   80002000-   80023000 rw-p 00000000 00:00 0       [heap]
20000000000-20000020000 r-xp 00000000 5e:01 272257  /lib/ld64.so.1
20000020000-20000021000 r-xp 0001f000 5e:01 272257  /lib/ld64.so.1
20000021000-20000022000 rwxp 00020000 5e:01 272257  /lib/ld64.so.1
20000022000-20000023000 rw-p 00000000 00:00 0
20000023000-20000025000 r-xp 00000000 00:00 0       [vdso]
20000025000-20000029000 rwxp 00000000 00:00 0
2000003f000-200001b6000 r-xp 00000000 5e:01 268320  /lib64/libc-2.11.90.so
200001b6000-200001ba000 r-xp 0018e000 5e:01 268320  /lib64/libc-2.11.90.so
200001ba000-200001bb000 rwxp 00192000 5e:01 268320  /lib64/libc-2.11.90.so
200001bb000-200001c1000 rwxp 00000000 00:00 0
3ffffb45000-3ffffb5a000 rw-p 00000000 00:00 0       [stack]
```



Sytem call trace of “Hello World”

bash (strace)

```
# strace -v ./hello
execve("./hello", ["./hello"], ["HOSTNAME=t6360015", "TERM=xterm", "SHELL=/bin/bash",
      "HISTSIZE=1000", "SSH_CLIENT=9.152.212.37 56750 22"..., "SSH_TTY=/dev/pts/0",
      "USER=root", "USERNAME=root", "PATH=/sbin:/bin:/usr/sbin:/bin"..., "PWD=/root",
      "SHLVL=1", "HOME=/root", "BASH_ENV=/root/.bashrc", "LOGNAME=root",
      "_=/usr/bin/strace"]) = 0
```

ld.so.1

```
brk(0) = 0x80002000
mmap(NULL, 4096, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0) =0x20000002000
mmap(NULL, 8192, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0) =0x20000003000
access("/etc/ld.so.preload", R_OK) = -1 ENOENT (No such file or directory)
open("/etc/ld.so.cache", O_RDONLY) = 3
fstat(3, {st_mode=S_IFREG|0644, st_size=93073, ...}) = 0
mmap(NULL, 93073, PROT_READ, MAP_PRIVATE, 3, 0) = 0x20000005000
close(3) = 0
open("/lib64/libc.so.6", O_RDONLY) = 3
read(3, "\177ELF\2\2\1\0\0\0\0\0\0\0\0\0"..., 832) = 832
fstat(3, {st_mode=S_IFREG|0755, st_size=10086079, ...}) = 0
mmap(NULL, 1574256, PROT_READ|PROT_EXEC, MAP_PRIVATE|MAP_DENYWRITE, 3, 0) =
     0x2000001c000
mmap(0x20000193000, 20480, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_FIXED|MAP_DENYWRITE,
     3, 0x176000) = 0x20000193000
mmap(0x20000198000, 17776, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_FIXED|MAP_ANONYMOUS,
     -1, 0) = 0x20000198000
close(3)                                = 0
mmap(NULL, 4096, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0) =
     0x2000019d000
mprotect(0x20000193000, 16384, PROT_READ) = 0
mprotect(0x20000020000, 4096, PROT_READ) = 0
munmap(0x20000028000, 93073) = 0
```

hello

```
fstat(1, {st_mode=S_IFCHR|0620, st_rdev=makedev(136, 0), ...}) = 0
mmap(NULL, 4096, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0) =
     0x20000028000
write(1, "Hello world 0x80002410\n"..., 12) = 12
exit_group(0)                           = ?
```

ELF object file format – relocations (readelf -r)

```
Relocation section '.rela.dyn' at offset 0x380 contains 1 entries:
  Offset          Info           Type           Sym. Value    Sym. Name + Addend
0000800019d8  00010000000a R_390_GLOB_DAT    0000000000000000 __gmon_start__ + 0

Relocation section '.rela.plt' at offset 0x398 contains 3 entries:
  Offset          Info           Type           Sym. Value    Sym. Name + Addend
0000800019c0  00020000000b R_390_JMP_SLOT    000000008000044c malloc + 0
0000800019c8  00030000000b R_390_JMP_SLOT    000000008000046c printf + 0
0000800019d0  00040000000b R_390_JMP_SLOT    000000008000048c __libc_start_main + 0
```

ELF object file format – typical relocations

R_390_64/R_390_32	Direct address of the symbol 64 bit / 32 bit
R_390_GLOB_DAT	Create global offset table (GOT) entry.
R_390_JMP_SLOT	Create procedure link table (PLT) entry.
R_390_RELATIVE	Adjust by program base.
R_390_TLS_TPOFF	Negated offset in static thread local storage (TLS) block.
R_390_TLS_DTPMOD	ID of module containing symbol.

Links for further reading

- ELF and ABI standards
  http://refspecs.freestandards.org/elf/
- System z supplement to the ELF ABI
  http://www.linuxfoundation.org/spec/ELF/zSeries/lzsabi0_s390.html
- Native POSIX thread library support
  http://people.redhat.com/~drepper/nptl-design.pdf
- Thread local storage support
  http://people.redhat.com/drepper/tls.pdf
- Understanding the Linux virtual memory manager
  http://ptgmedia.pearsoncmg.com/
  images/0131453483/downloads/gorman_book.pdf

Questions?

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