NOVA introduction

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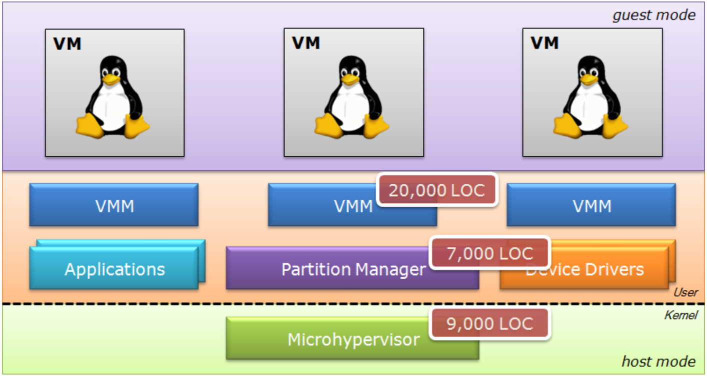
[1] Based on exercises by Benjamin Engel from TU Dresden.

NOVA microhypervisor



- Research project of TU Dresden (< 2012) and Intel Labs (≥ 2012).
- `http://hypervisor.org/`, x86, GPL.
- We will use a stripped down version (2 kLoC) of the microhypervisor (kernel).

Table of content

What you need to know?

- NOVA is implemented in C++ (and assembler).
- Each user "program" is represented by execution context data structure (`class Ec`).
- The first executed program is called root task (similar to `init` process in Unix).

Getting started

```
unzip nova.zip
cd nova
make # Compile everything
make run # Run it in Qemu emulator
```

Understanding qemu invocation

qemu-system-i386 -serial stdio -kernel kern/build/hypervisor -initrd user/hello

- Serial line of the emulated machine will go to stdout
- Address of `user/hello` binary will be passed to the kernel via *Multiboot info* data structure

Source code layout

- `user/` – user space code (hello world + other simple programs)
- `kern/` – stripped down NOVA kernel
  - you will need to modify `kern/src/ec.cc`

NOVA booting

1. CPU reset, BIOS executes
2. Bootloader loads the kernel binary and user application into memory
3. Bootloader starts executing the kernel (kern/src/start.S)
4. Kernel initializes CPU and paging (virtual memory) (start.S, init.cc)
5. Kernel allocates and maps one page for application stack (kern/src/ec.cc, Ec::root_invoke())
6. Kernel looks at ELF program header to see where the application wants to be loaded (Ec::root_invoke()).
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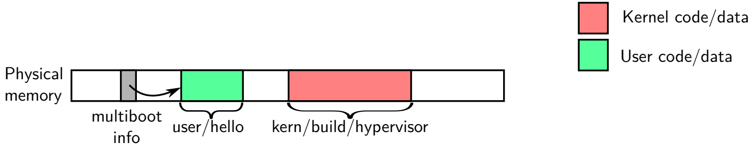

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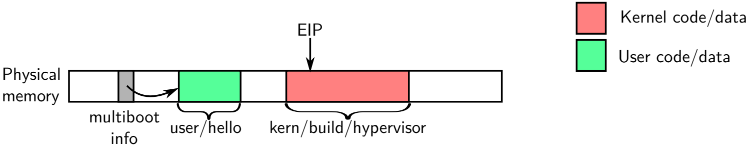

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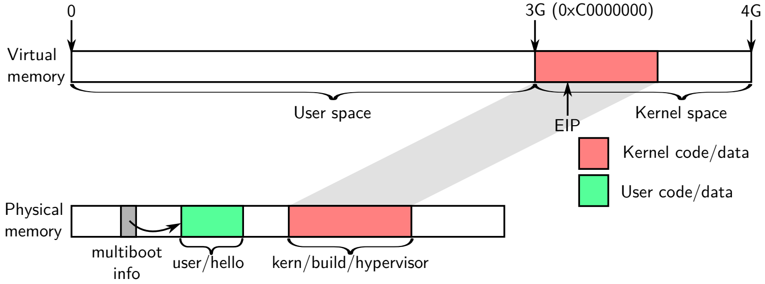

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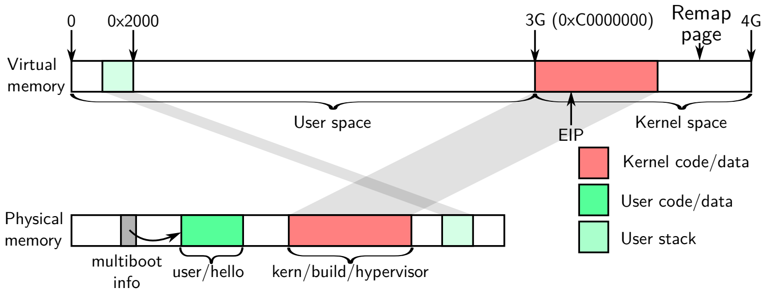

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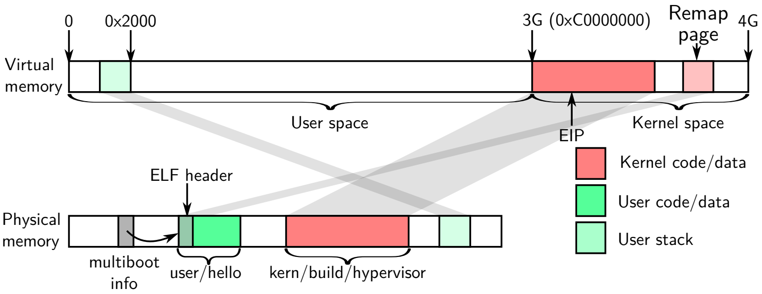

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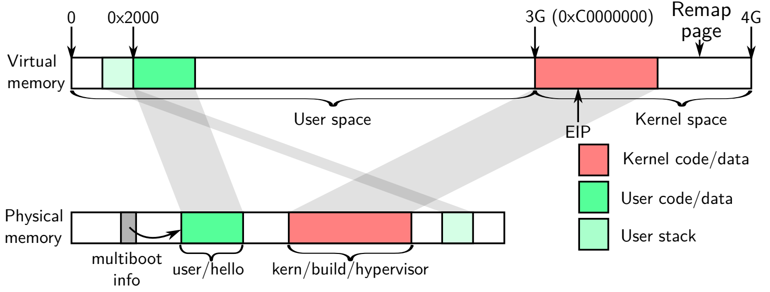

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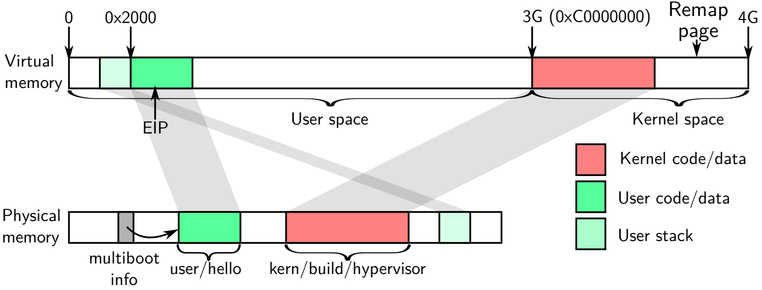
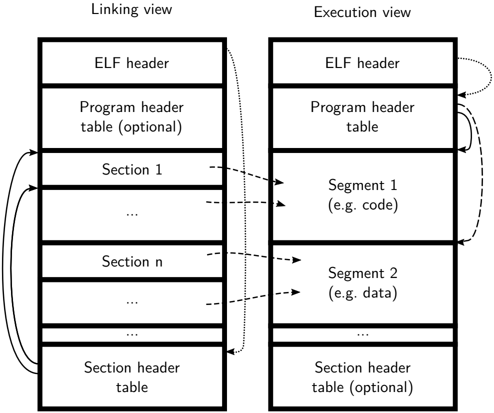


Program binaries

Executable and Linkable Format (ELF)
`http://www.sco.com/developers/devspecs/gabi41.pdf`, chapter 4



- Composed of headers, segments and sections
- One segment contains one or more sections
- A section may or may not belong to a segment
- All of this is controlled by “linker scripts” – they tell the linker how to link the program (more info later).

ELF header

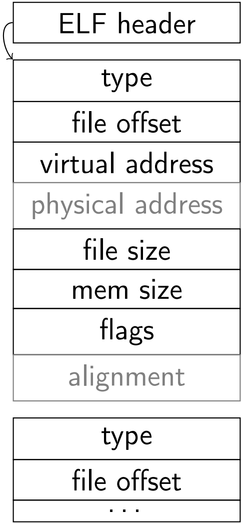
elf.h, class Eh

magic: 7f 'E' 'L' 'F'			
class	data	version	padd.
padding			
padding			
type		machine	
version			
entry			
ph_offset			
sh_offset			
flags			
eh_size		ph_size	
ph_count		sh_size	
sh_count		strtab	

- Each binary starts with this header
- Can be shown by `readelf -h`
- The code in `Ec::root_invoke`:
  - Checks magic, data == 1 and type == 2
  - Reads entry point, i.e. user EIP
  - Reads information about program headers
    - ph_count: number of program headers
    - ph_offset: where within the file the program header table starts

Program header table

elf.h, class Ph

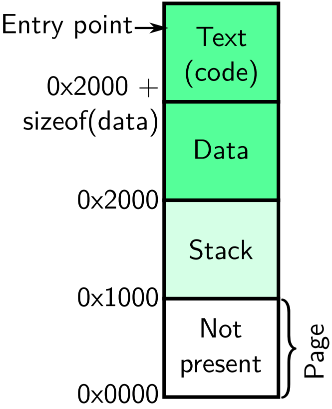


- Describes segments of the binary
- `Ec::root_invoke` does:
  - If type == PT_LOAD (1) ⇒ map this segment to memory
  - If flags has PF_W (2) set ⇒ make the page(s) writable
  - Read offset to know where this segment starts relative to the beginning of the file
  - Read virtual address to know where to map this segment to
  - Read file/mem size to know the segment size (in file and memory)

User space memory map

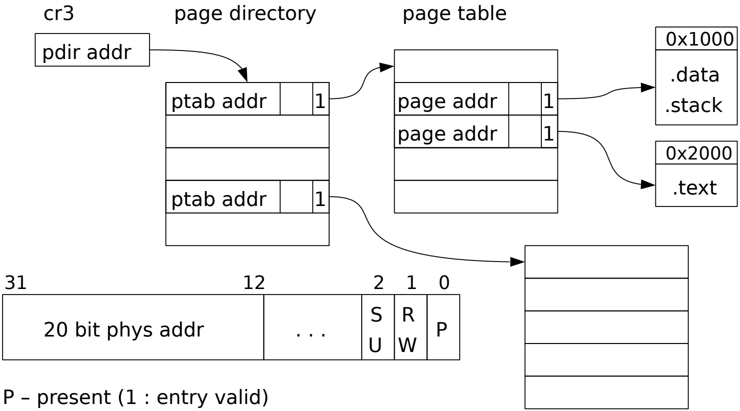
As defined by a so called "linker script" (user/linker.ld)

- Stack is expected to go from 0x2000 downwards.
- First page is left "not present" to catch NULL pointer deference errors.
- Entry point and sizes of text/data sections is stored in various headers in the program binary.



Understanding Ptab::insert_mapping – x86 page tables

See `kern/src/ptab.cc`



P – present (1 : entry valid)

R/W – 0 : read only, 1 : writable

S/U – 0 : kernel only, 1 : user

See also Intel System Programming Guide, sect. 4.3 "32-bit paging" (link)

Additional information

Linker script

Linker scripts tell the linker how to link the program, i.e.

- which sections go to which segment,
- at which address the segments should be loaded, etc.
- Documentation: run "`info ld Scripts`"

user/linker.ld

- Program entry point at symbol **_start**
- Two segments: **data** (6 ⇒ RW) and **text** (5 ⇒ RX)
- Put sections **.text** into segment **text** and sections **.data**, **.rodata** and **.bss** into segment **data**[2]
- **ALIGN** end of data (and start of text) to a page boundary (**0x1000**)

[2] **.text** sections contain executable code, **.data** initialized (global) variables, **.rodata** read-only data (e.g. declared with const qualifier) and **.bss** contains uninitialized (zeroed) data.

Program startup – user/src/start.S

Code that runs before main()

```
.text
.global _start
_start:
    mov $stack_top, %esp
    call main
    ud2
```

- Put this into the **.text** section
- Define global symbol **_start**
- Setup a stack by loading the address of **stack_top** into **esp** (`stack_top` is defined in `linker.ld`)
- Call function **main()**
- If main returns, execute "undefined" instruction. When this is executed, CPU generates an exception and the kernel tells us about that.

Building and inspecting the user program

- Goto the user directory and run `make` there
- Inspect the binary by `nm user/hello`

```
00003000 T main
00002000 D stack_top
00003029 T _start
```

- There are three symbols in the text section (T) and three in data section (D)
- Decode headers: **readelf -h -l user/hello** or **objdump -x user/hello**

Understanding kernel exceptions

- ```c
  void main() {
          *((int*)0x234) = 0x12; /* Write 0x12 to address 0x234 */
  }
  ```
- Address 0x234 is in the zeroth page (0x0 – 0x3ff), which is not present (i.e. the present flag in the page table entry is 0).
- Accessing this page generates a "Page fault" exception.
- The kernel "handles" the exception by printing useful information about it.
- You can try the above program (stored in user/pagefault.c) by running:

  ```
  make -C user pagefault
  qemu-system-i386 -serial stdio -kernel kern/build/hypervisor \
                                 -initrd user/pagefault
  ```

  It produces this output:

  ```
  NOVA Microhypervisor 0.3 (Cleetwood Cove)

  Ec::handle_exc Page Fault (eip=0x3000 cr2=0x234)
  eax=0xcffffdc ebx=0x1803000 ecx=0x5 edx==0xc0009000
  esi=0xdf001074 edi=0x5 ebp=0x1801000 esp==0x1ffc
  unhandled kernel exception
  ```
- eip – the instruction that caused the fault, cr2 – the faulty address
- Find the address 0x3000 (eip) in `objdump -S user/pagefault`
  ```