Virtual Memory

2024 Fall ECE 344: Operating Systems

Lecture 11

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2.0.1

How Should We Implement Virtual Mapping?

What are your ideas for mapping a process's virtual memory to physical memory?

Virtual Memory Checklist

- ☐ Multiple processes must be able to co-exist
- ☐ Processes are not aware they are sharing physical memory
- ☐ Processes cannot access each others data (unless allowed explicitly)
- ☐ Performance close to using physical memory
- ☐ Limit the amount of fragmentation (wasted memory)

Remember That Memory is Byte Addressable

The smallest unit you can use to address memory is one byte

You can read or write one byte at a time at minimum

Each “addresss” is like an index of an array

Segmentation or Segments are Coarse Grained

Divide the virtual address space into segments for: code, data, stack, and heap

- Note: this looks like an ELF file, large sections of memory with permissions

Each segment is a variable size, and can be dynamically resized

- This is an old legacy technique that's no longer used

Segments can be large and very costly to relocate

- It also leads to fragmentation (gaps of unused memory)

No longer used in modern operating systems

Segmentation Details

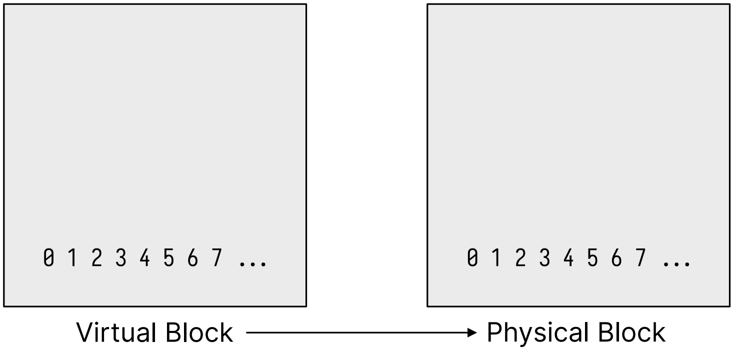
Each segment contains a: base, limit, and permissions
- You get a physical address by using: `segment selector:offset`

The MMU checks that your offset is within the limit (size)
- If it is, it calculates base + offset, and does permission checks
  - Otherwise, it's a segmentation fault

For example 0x1:0xFF with segment 0x1 base = 0x2000, limit = 0x1FF
- Translates to 0x20FF

Note: Linux sets every base to 0, and limit to the maximum amount

First Insight: Divide Memory into Fixed-Sized Chunks



Memory Management Unit (MMU)

Maps virtual address to physical address
- Also checks permissions

One technique is to divide memory up into fixed-size pages (typically 4096 bytes)
- A page in virtual memory is called a page
- A page in physical memory is called a frame

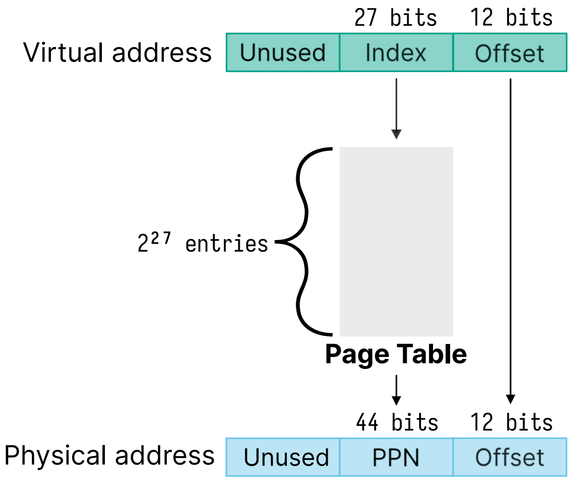
You Typically Do Not Use All 64 Virtual Address Bits

CPUs may have different levels of virtual addresses you can use
- Implementation ideas are the same

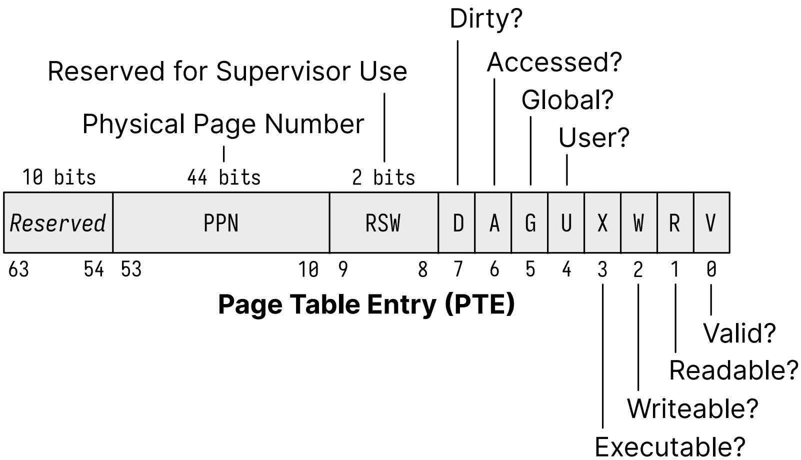
We'll assume a 39 bit virtual address space used by RISC-V and other architectures
- Allows for 512 GiB of addressable memory (called Sv39)

Implemented with a page table indexed by Virtual Page Number (VPN)
- Looks up the Physical Page Number (PPN)

The Page Table Translates Virtual to Physical Addresses



The Page Table Entry (PTE) Also Stores Flags in the Lower Bits



Page Table Entry (PTE)

The Kernel Handles Translating Virtual Addresses

Considering the following page table:

VPN	PPN
0x0	0x1
0x1	0x4
0x2	0x3
0x3	0x7

We would get the following virtual $\rightarrow$ physical address translations:

0x0AB0 $\rightarrow$ 0x1AB0
0x1FA0 $\rightarrow$ 0x4FA0
0x2884 $\rightarrow$ 0x3884
0x32D0 $\rightarrow$ 0x72D0

Page Translation Example Problem

Assume you have a 8-bit virtual address, 10-bit physical address and each page is 64 bytes

- How many virtual pages are there?
- How many physical pages are there?
- How many entries are in the page table?
- Given the page table is `[0x2, 0x5, 0x1, 0x8]` what's the physical address of `0xF1`?

Page Translation Example Problem

Assume you have a 8-bit virtual address, 10-bit physical address and each page is 64 bytes

- How many virtual pages are there? $\frac{2^8}{2^6} = 4$
- How many physical pages are there? $\frac{2^{10}}{2^6} = 16$
- How many entries are in the page table? 4
- Given the page table is `[0x2, 0x5, 0x1, 0x8]` what's the physical address of `0xF1`?
  `0x231`

Each Process Gets Its Own Page Table

- When you `fork` a process, it will copy the page table from the parent
  - Turn off the write permission so the kernel can implement copy-on-write
- The problem is there are 2^{27} entries in the page table, each one is 8 bytes
  - This means the page table would be 1 GiB
- Note that RISC-V translates a 39-bit virtual to a 56-bit physical address
  - It has 10 bits to spare in the PTE and could expand
  - Page size is 4096 bytes (size of offset field)

You May Be Thinking That Seems Like A Lot of Work

In the "Subprocess" lecture, we're doing a `fork` followed by `exec`
   why do we need to copy the page tables?

We don't! There's a system call for that — `vfork`

`vfork` shares all memory with the parent
   It's undefined behavior to modify anything

Only used in very performance sensitive programs

We Use Pages for Memory Translation

Divide memory into blocks, so we only have to translate once per block

Use page tables (array of PTEs) to access the PPN (and flags)

New problem: these page tables are always huge!