CS 318 Principles of Operating Systems

Fall 2021

Lecture 10: Virtual Memory

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Administrivia

Lab 2 is out

- Due Saturday 10/16 11:59 pm
- Review session this Friday 5-6 pm

Next Tuesday is project hacking day

- No class, work on lab 2
- I will hold office hours (Zoom + Malone 231) at 9:30 am and at the lecture time

Memory Management

Next few lectures are going to cover memory management

Goals of memory management

- To provide a convenient abstraction for programming
- To allocate scarce memory resources among competing processes to maximize performance with minimal overhead

Mechanisms

- Physical and virtual addressing (1)
- Techniques: partitioning, paging, segmentation (1)
- Page table management, TLBs, VM tricks (2)

Policies

- Page replacement algorithms (3)

Lecture Overview

Virtual memory warm-up

Survey techniques for implementing virtual memory

- Fixed and variable partitioning
- Paging
- Segmentation

Focus on hardware support and lookup procedure

Virtual Memory

The abstraction that the OS provides for managing memory

- VM enables a program to execute with less physical memory than it "needs"
- How? Many programs do not need all of their code and data at once (or ever)
- OS will adjust memory allocation to a process based upon its behavior
- VM requires hardware support and OS management algorithms to pull it off

Let's go back to the beginning…

In the beginning…

Rewind to the days of "second-generation" computers

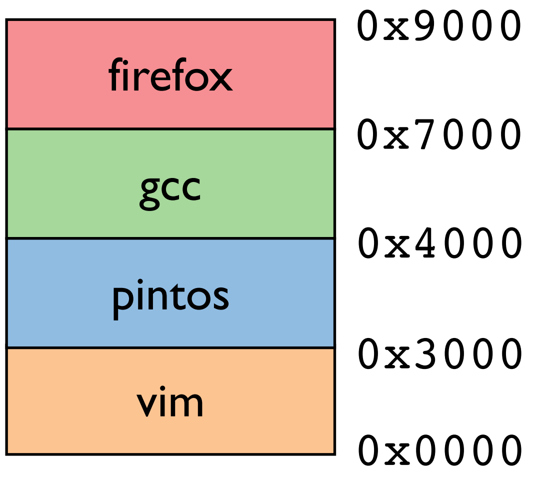
- Programs use physical addresses directly
- OS loads job, runs it, unloads it

Multiprogramming changes all of this

- Want multiple processes in memory at once

Consider multiprogramming on physical memory

- What happens if pintos needs to expand?
- If vim needs more memory than is on the machine?
- If pintos has an error and writes to address `0x7100`?
- When does gcc have to know it will run at `0x4000`?
- What if vim isn't using its memory?



Issues in Sharing Physical Memory

Protection

- A bug in one process can corrupt memory in another
- Must somehow prevent process *A* from trashing *B*'s memory
- Also prevent *A* from even observing B's memory (ssh-agent)

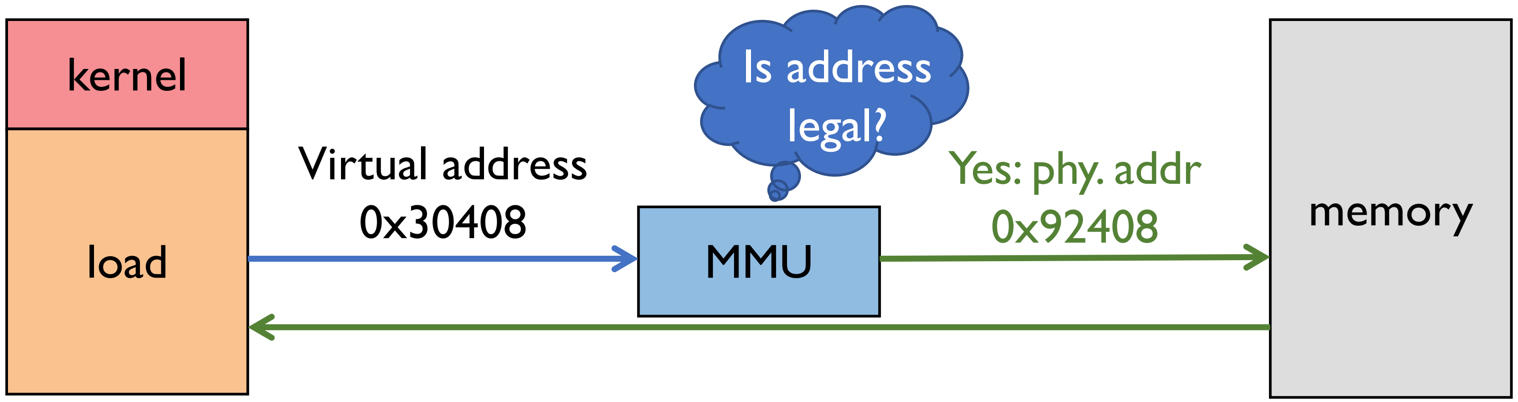
Transparency

- A process shouldn't require particular physical memory bits
- Yet processes often require large amounts of contiguous memory (for stack, large data structures, etc.)

Resource exhaustion

- Programmers typically assume machine has "enough" memory
- Sum of sizes of all processes often greater than physical memory

Virtual Memory Goals



Give each program its own virtual address space

- At runtime, *Memory-Management Unit* (MMU) relocates each load/store
- Application doesn't see physical memory addresses

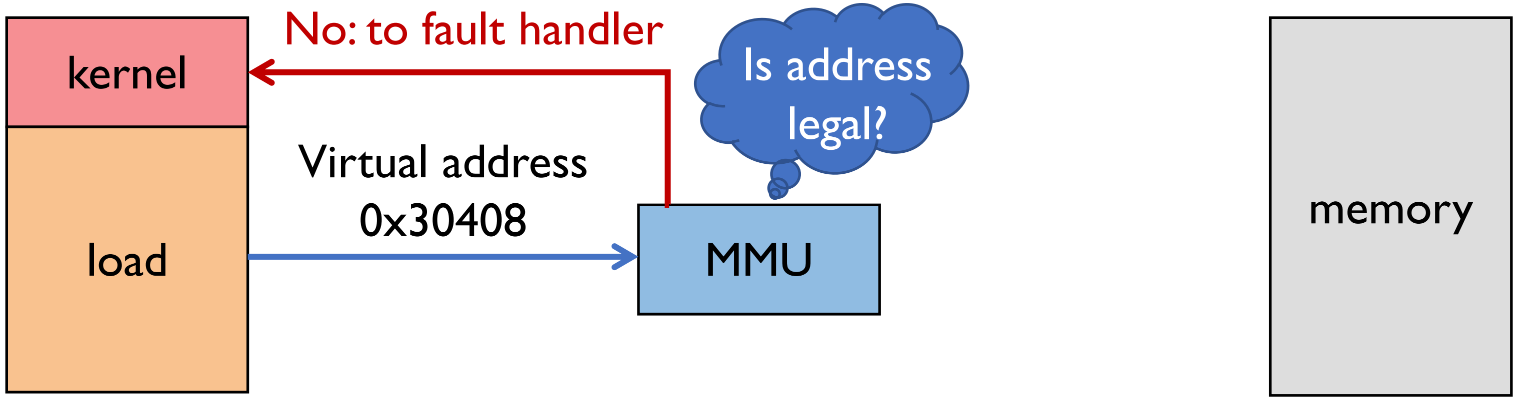
Enforce protection

- Prevent one app from messing with another's memory

And allow programs to see more memory than exists

- Somehow relocate some memory accesses to disk

Virtual Memory Goals



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Virtual Memory Advantages

Can re-locate program while running

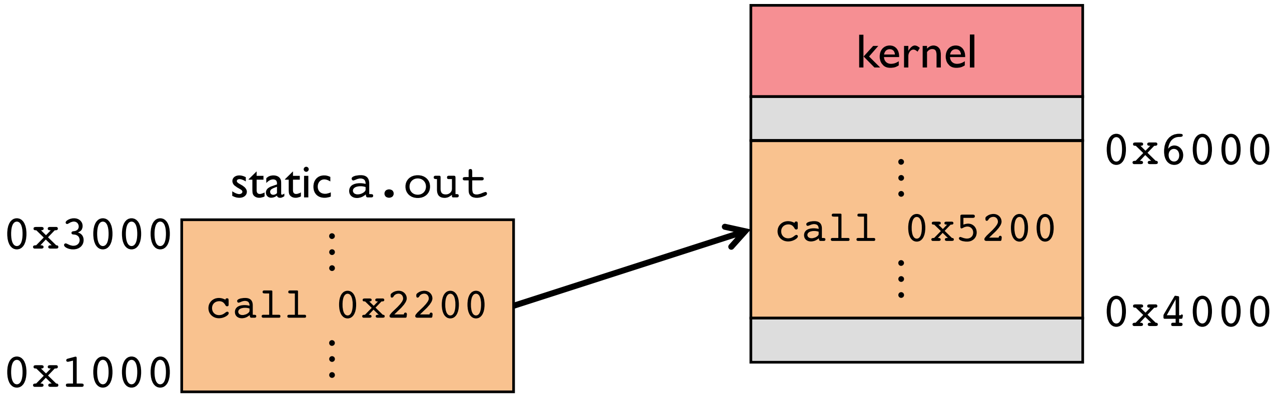
- Run partially in memory, partially on disk

Most of a process's memory may be idle (80/20 rule)

- Write idle parts to disk until needed
- Let other processes use memory of idle part
- Like CPU virtualization: when process not using CPU, switch (Not using a memory region? switch it to another process)

Challenge: VM = extra layer, could be slow

Idea 1: Load-time Linking



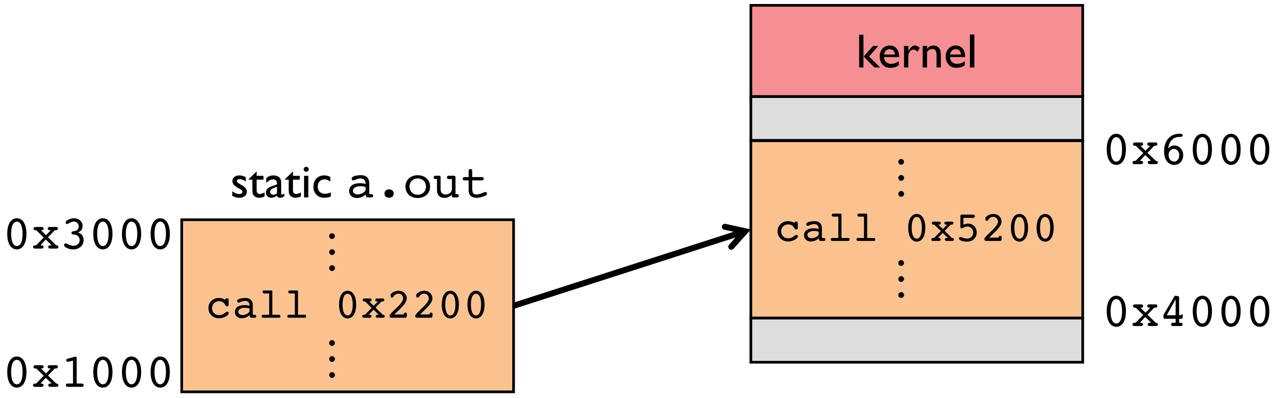
Linker patches addresses of symbols like `printf`

Idea: link when process executed, not at compile time

- Determine where process will reside in memory
- Adjust all references within program (using addition)

Problems?

Idea 1: Load-time Linking



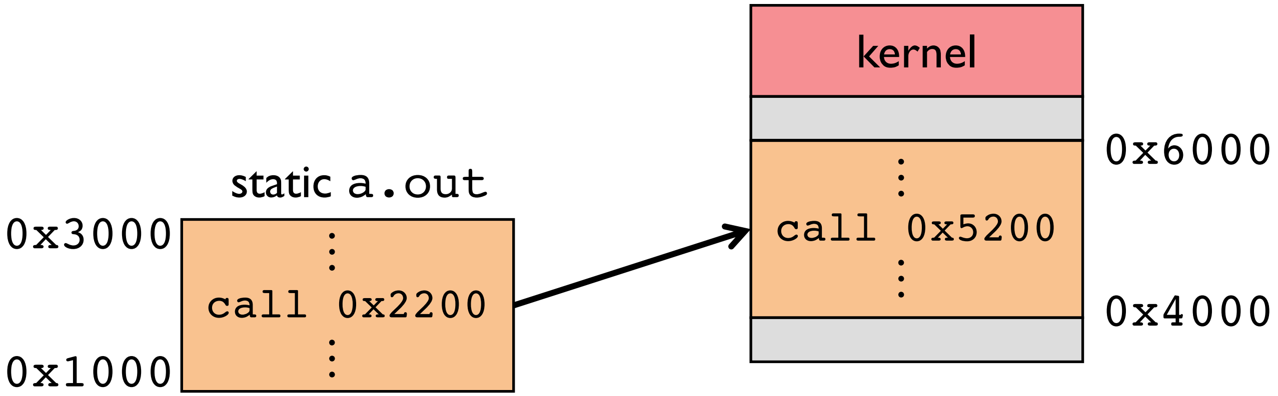
Linker patches addresses of symbols like `printf`

Idea: link when process executed, not at compile time

Problems?

- Patching required for each run, time-consuming
- How to move once already in memory? (consider data pointers)
- What if no contiguous free region fits program?

Idea 2: Base + Bound Register



Two special privileged registers: base and bound

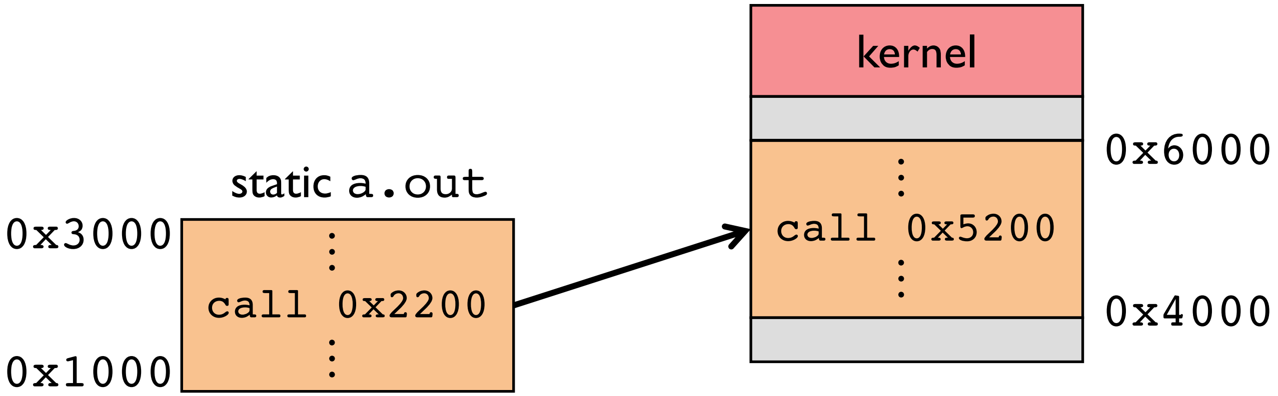
On each load/store/jump:

- Physical address = virtual address + base
- Check 0 ≤ virtual address < bound, else trap to kernel

How to move process in memory?

What happens on context switch?

Idea 2: Base + Bound Register



Two special privileged registers: base and bound

On each load/store/jump:

How to move process in memory?

- Change base register

What happens on context switch?

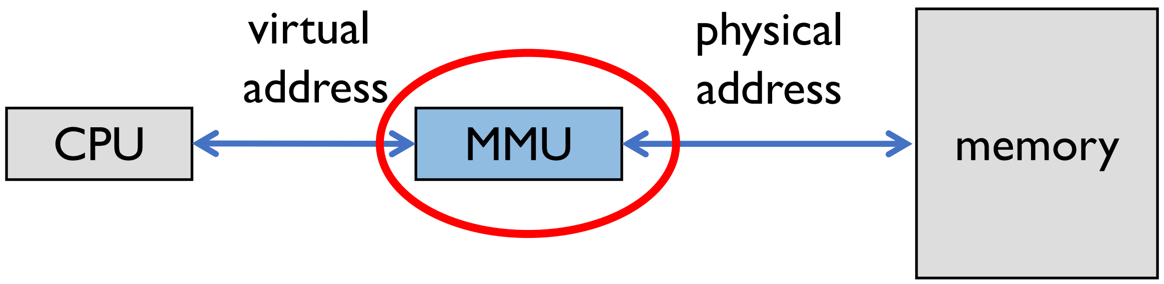
- OS must re-load base and bound register

Definitions

Programs load/store to virtual addresses

Actual memory uses physical addresses

VM Hardware is Memory Management Unit (MMU)



- Usually part of CPU
  - Configured through privileged instructions (e.g., load bound reg)
- Translates from virtual to physical addresses
- Gives per-process view of memory called address space

Base + Bound Trade-offs

Advantages

- Cheap in terms of hardware: only two registers
- Cheap in terms of cycles: do add and compare in parallel
- Examples: Cray-1 used this scheme

Disadvantages

Base + Bound Trade-offs

Advantages

- Cheap in terms of hardware: only two registers
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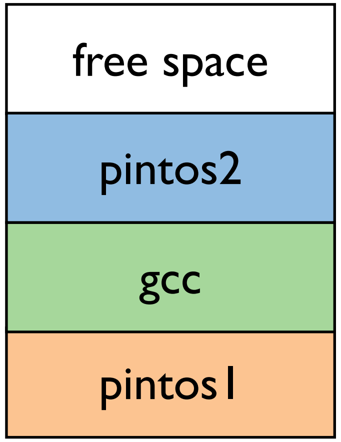
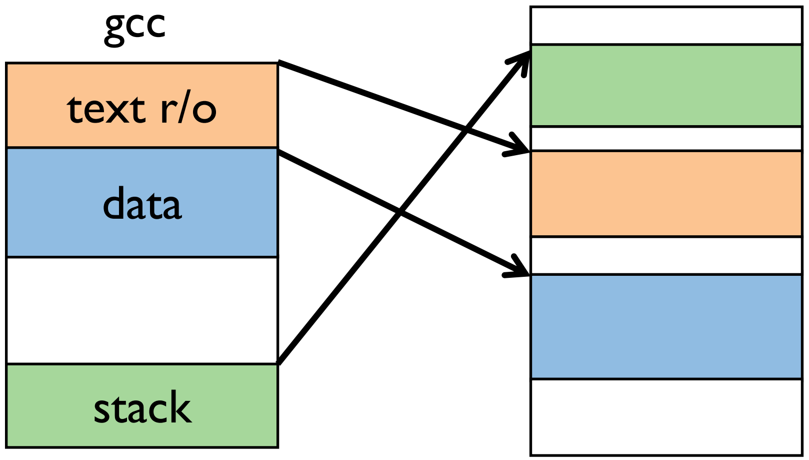
- Examples: Cray-1 used this scheme

Disadvantages

- Growing a process is expensive or impossible
- No way to share code or data (E.g., two copies of bochs, both running pintos)



Idea 3: Segmentation

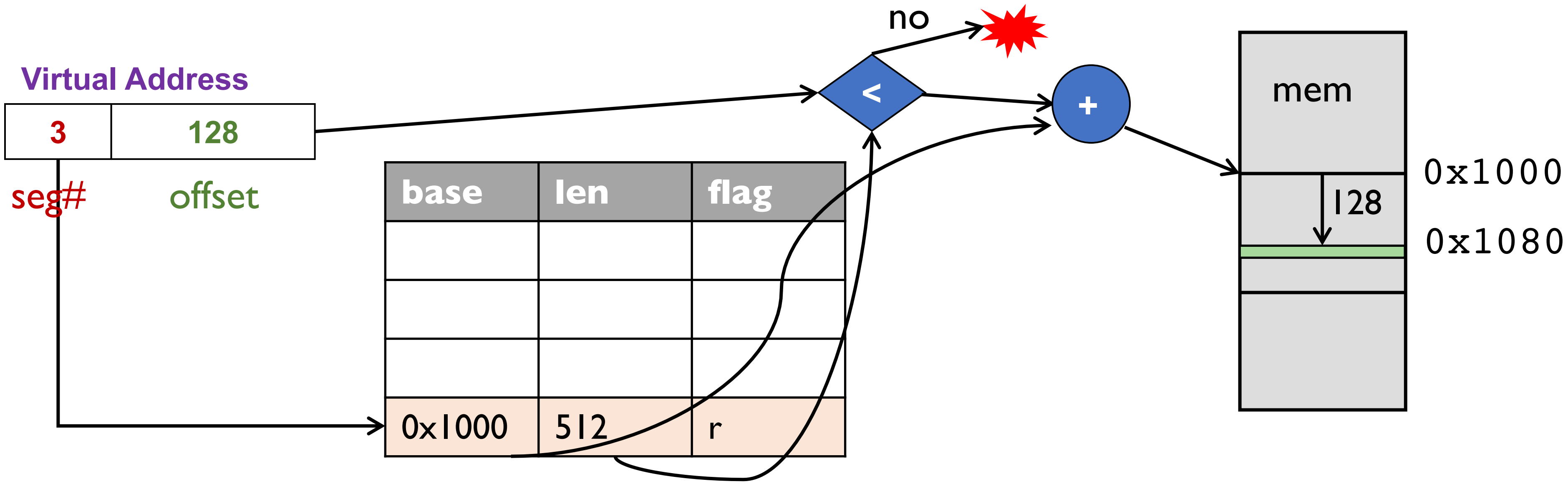


Let processes have many base/bound regs

- Address space built from many segments
- Can share/protect memory at segment granularity

Must specify segment as part of virtual address

Segmentation Mechanics



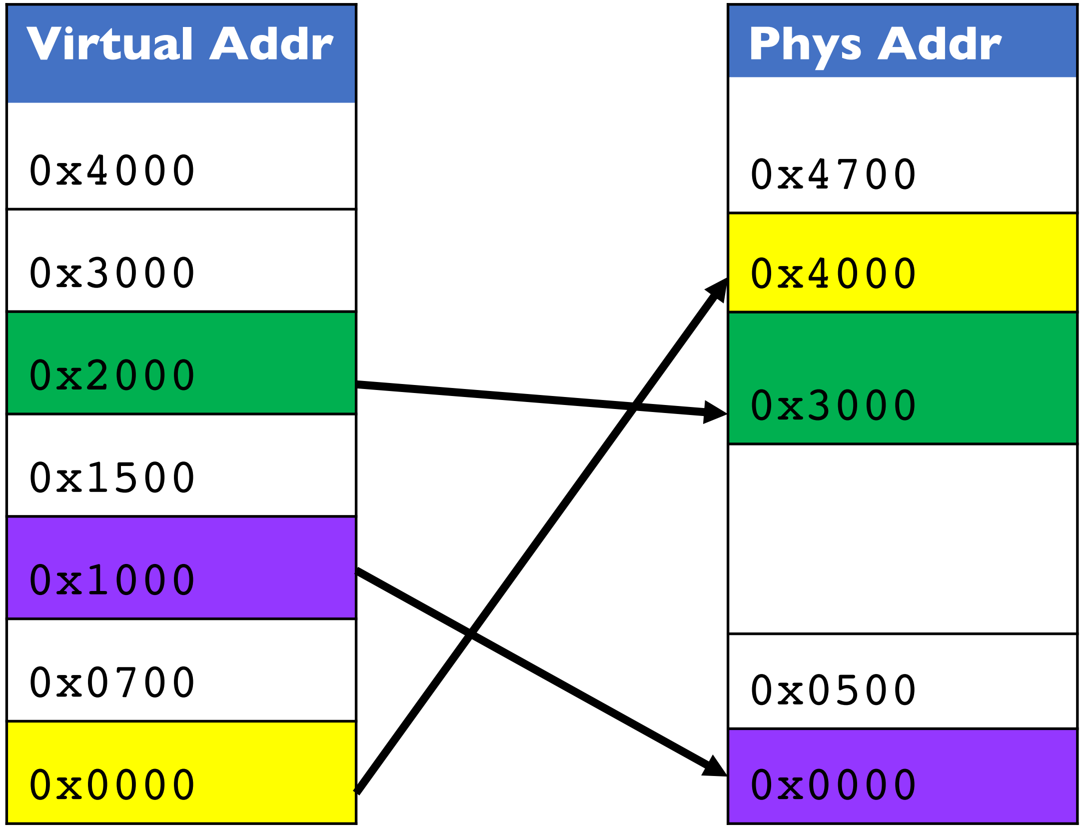
Each process has a segment table

Each VA indicates a segment and offset:

- Top bits of addr select segment, low bits select offset
- x86 stores segment #s in registers (CS, DS, SS, ES, FS, GS)

Segmentation Example

Segmen t	Base	Bound	RW
0	`0x4000`	`0x6ff`	`10`
1	`0x0000`	`0x4ff`	`11`
2	`0x3000`	`0xfff`	`11`
3			`00`



- **2-bit segment number (1st digit), 12 bit offset (last 3)**
  - Where is `0x0240`? `0x1108`? `0x265c`? `0x3002`? `0x1600`?

Segmentation Trade-offs

Advantages

- Multiple segments per process
- Can easily share memory! (how?)
- Don’t need entire process in memory

Disadvantages

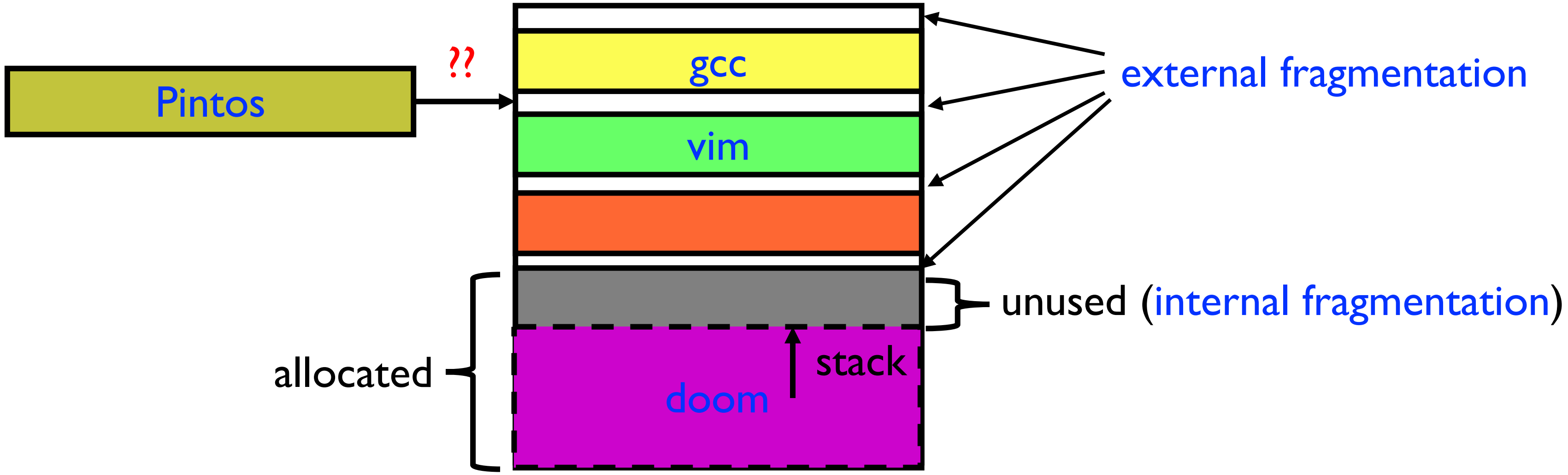
- Requires translation hardware, which could limit performance
- Segments not completely transparent to program (e.g., default segment faster or uses shorter instruction)
- *n* byte segment needs *n contiguous* bytes of physical memory
- Makes *fragmentation* a real problem.

Fragmentation

Fragmentation ⇒ Inability to use free memory

Over time:

- Variable-sized pieces = many small holes (external fragmentation)
- Fixed-sized pieces = no external holes, but force internal waste (internal fragmentation)



Idea 4: Paging

Divide memory up into fixed-size *pages*

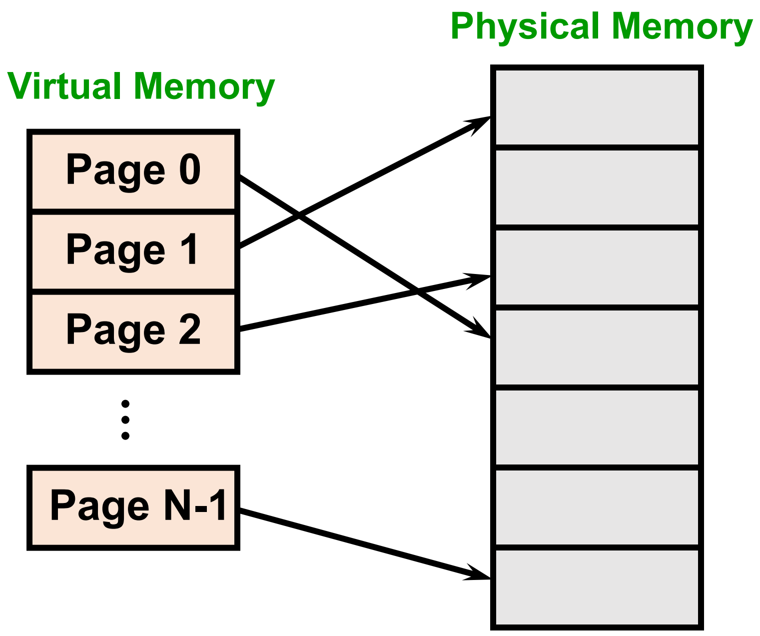
- Eliminates external fragmentation

Map virtual pages to physical pages

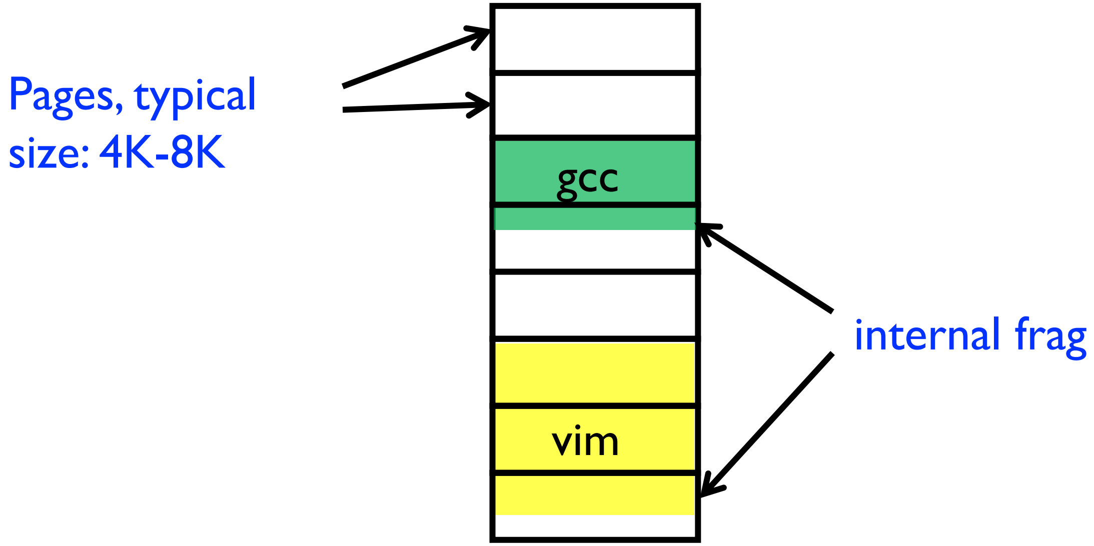
- Each process has separate mapping

Allow OS to gain control on certain operations

- Read-only pages trap to OS on write
- Invalid pages trap to OS on read or write
- OS can change mapping and resume application



Paging Trade-offs

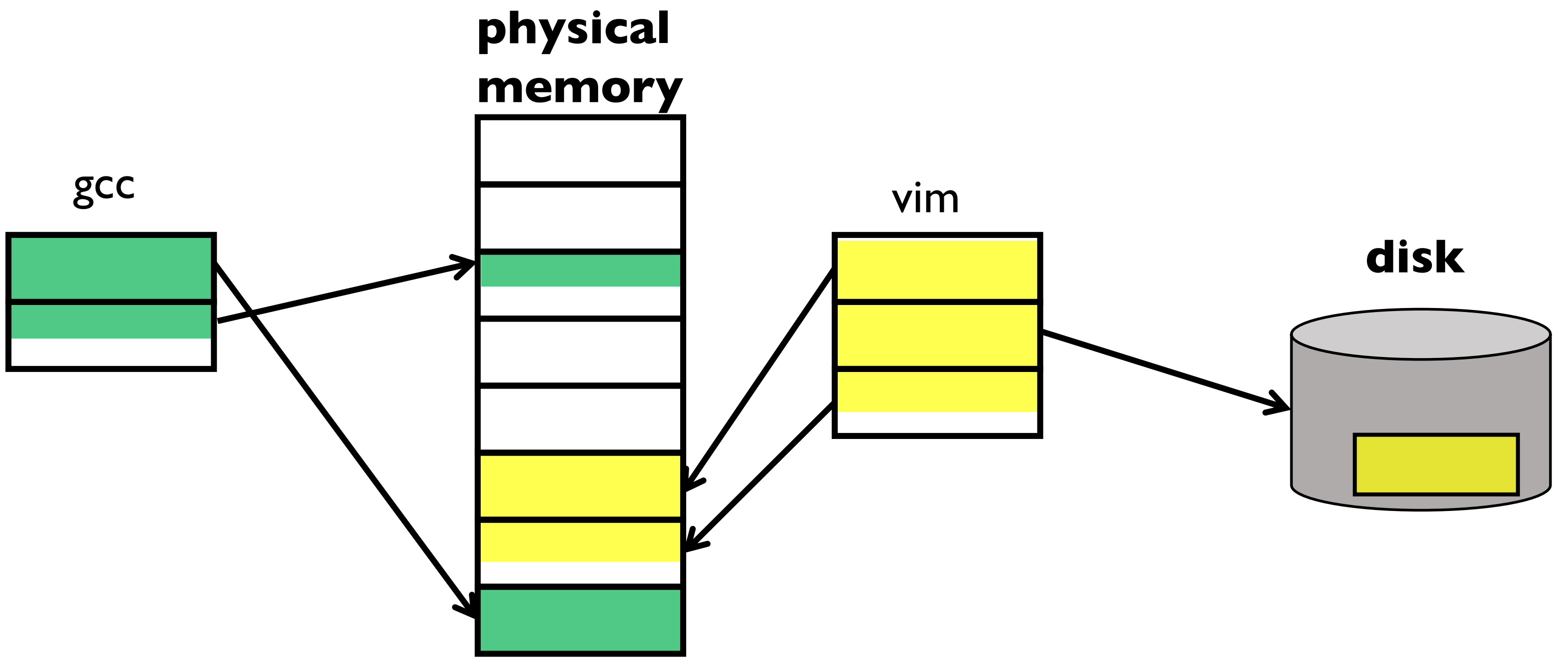


Eliminates external fragmentation

Simplifies allocation, free, and backing storage (swap)

Average internal fragmentation of .5 pages per "segment"

Simplified Allocation



Allocate any physical page to any process

Can store idle virtual pages on disk

Paging Data Structures

Pages are fixed size, e.g., 4K

- Virtual address has two parts: virtual page number and offset
- Least significant 12 ($log_2 4k$) bits of address are page offset
- Most significant bits are *page number*

Page tables

- Map virtual page number (VPN) to physical page number (PPN)
  - VPN is the index into the table that determines PPN
  - PPN also called page frame number
- Also includes bits for protection, validity, etc.
- One page table entry (PTE) per page in virtual address space

Page Table Entries (PTEs)

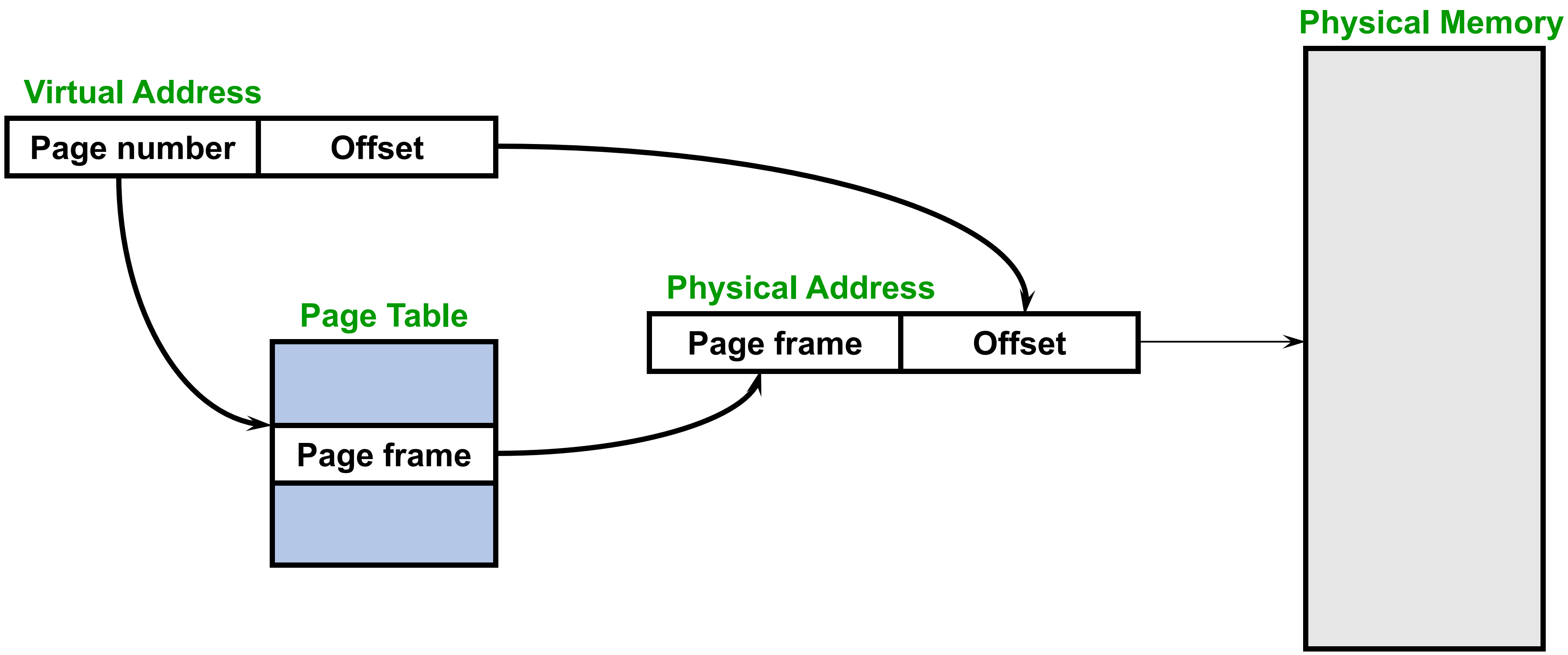
Physical Page Number	M	R	V	Prot

Page table entries control mapping

- The Physical page number (PPN) determines physical page
- The Modify bit says whether or not the page has been written
  - It is set when a write to the page occurs
- The Reference bit says whether the page has been accessed
  - It is set when a read or write to the page occurs
- The Valid bit says whether or not the PTE can be used
  - It is checked each time the virtual address is used
- The Protection bits say what operations are allowed on page
  - Read, write, execute

Why the PTEs do not store Virtual Page Number (VPN)?

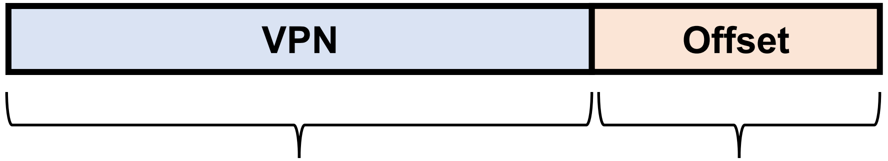
Page Lookups



Paging Example

32-bit machines, pages are 4KB-sized

Virtual Address



What is the maximum number of VPNs?

Virtual address is `0x7468`

`0x7468`

Page Table

VPN	Prot	...
0x2	r	

Physical Address

Paging Advantages

Easy to allocate memory

- Memory comes from a free list of fixed size chunks
- Allocating a page is just removing it from the list
- External fragmentation not a problem

Easy to swap out chunks of a program

- All chunks are the same size
- Use valid bit to detect references to swapped pages
- Pages are a convenient multiple of the disk block size

Paging Limitations

Can still have *internal fragmentation*

- Process may not use memory in multiples of a page

Memory reference overhead

- 2 or more references per address lookup (page table, then memory)
- Solution – use a hardware cache of lookups (more later)

Memory required to hold page table can be significant

- Need one PTE per page
- 32 bit address space w/ 4KB pages = 2^{20} PTEs
- 4 bytes/PTE = 4MB/page table
- 25 processes = 100MB just for page tables!
- Solution – page the page tables (more later)

x86 Paging

Paging enabled by bits in a control register (`%cr0`)

- Only privileged OS code can manipulate control registers

Normally 4KB pages

`%cr3`: points to 4KB page directory

- See `pagedir_activate()` in Pintos `userprog/pagedir.c`

x86 Paging and Segmentation

x86 architecture supports both paging and segmentation

- Segment register base + pointer val = *linear address*
- Page translation happens on linear addresses

Two levels of protection and translation check

- Segmentation model has four privilege levels (*CPL* 0–3)
- Paging only two, so 0–2 = kernel, 3 = user

Why do you want both paging and segmentation?

Why Want Both Paging and Segmentation?

Short answer: You don't – just adds overhead

- Most OSes use "flat mode" – set base = 0, bounds = `0xffffffff` in all segment registers, then forget about it
- x86-64 architecture removes much segmentation support

Long answer: Has some fringe/incidental uses

- Use segments for logically related units + pages to partition segments into fixed size chunks
  - Tend to be complex
- VMware runs guest OS in CPL 1 to trap stack faults

Summary

Virtual memory

- Processes use virtual addresses
- OS + hardware translates virtual address into physical addresses

Various techniques

- Load-time Linking – requires patching for each run
- Base + Bounds – cheap, but difficult to grow and cannot share
- Segmentation – manage in chunks from user's perspective
- Paging – use small, fixed size chunks, efficient for OS
- Combine paging and segmentation

Next time…

Chapters 19, 20