Lecture 9: Memory Management
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- **Project 2 released**
  - This lecture gets you jumpstarted
- **Homework 3 released**
  - Do VM worksheet before part 2 of project 2
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)
Virtual Memory

- The abstraction that the OS provides for managing memory is virtual memory (VM)
  - Virtual memory enables a program to execute with less than its complete data in physical memory
    - A program can run on a machine with less memory than it “needs”
    - Can also run on a machine with “too much” physical memory
  - Many programs do not need all of their code and data at once (or ever) ➔ no need to allocate physical memory for it
  - OS will adjust amount of physical memory allocated 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...

• With early computers…
  ♦ Programs used physical addresses directly (e.g., early PCs)
  ♦ OS loads job, runs it, unloads it

• Multiprogramming changes all of this
  ♦ Want multiple processes in memory at once
    » Overlap I/O and CPU of multiple jobs
  ♦ Can do it a number of ways
    » Fixed and variable partitioning, paging, segmentation
  ♦ Requirements
    » Need protection – restrict which addresses jobs can use
    » Fast translation – lookups need to be fast
    » Fast change – updating memory hardware on context switch
Virtual Addresses

• To make it easier to manage the memory of processes running in the system, we’re going to make them use virtual addresses (logical addresses)
  ♦ Virtual addresses are independent of the actual physical location of the data referenced
  ♦ OS determines location of data in physical memory
  ♦ Instructions executed by the CPU issue virtual addresses
  ♦ Virtual addresses are translated by hardware into physical addresses (with help from OS)

• The set of virtual addresses that can be used by a process comprises its virtual address space (VAS)
  ♦ VAS often larger than physical memory (64-bit addresses)
  ♦ But can also be smaller (32-bit VAS with 8 GB of DRAM)
Virtual Addresses

- Many ways to do this translation…
  - Start with old, simple ways, progress to current techniques
Fixed Partitions

- Physical memory is broken up into fixed partitions
  - Hardware requirements: base register
  - Physical address = virtual address + base register
  - Base register loaded by OS when it switches to a process
  - Size of each partition is the same and fixed
  - How do we provide protection?

- Advantages
  - Easy to implement, fast context switch

- Problems
  - Internal fragmentation: memory in a partition not used by a process is not available to other processes
  - Partition size: one size does not fit all (very large processes)
Fixed Partitions

Base Register

P4’s Base

Virtual Address

Offset

Physical Memory

P1
P2
P3
P4
P5
Variable Partitions

• Natural extension – physical memory is broken up into variable sized partitions
  ♦ Hardware requirements: base register and limit register
  ♦ Physical address = virtual address + base register
  ♦ Why do we need the limit register? Protection
    » If (physical address > base + limit) then fault (exception)

• Advantages
  ♦ No internal fragmentation: allocate just enough for process

• Problems
  ♦ External fragmentation: process creation and termination produces empty holes scattered throughout memory
Variable Partitions

Virtual Address

Offset

Base Register

P3’s Base

Limit Register

P3’s Limit

Yes?

No?

Protection Fault

P1

P2

P3
Paging

- Paging solves the external fragmentation problem by using fixed-sized units in both physical and virtual memory.
Programmer/Process View

- Programmers (and processes) view memory as one contiguous address space from 0 through N
  - Virtual address space (VAS)
- In reality, pages are scattered throughout physical memory
  - The mapping is invisible to the process
- Protection is provided because a process cannot reference memory outside of its VAS
  - The address “0x1000” maps to different physical addresses in different processes
Paging

- Translating addresses
  - Virtual address has two parts: virtual page number and offset
  - Virtual page number (VPN) is an index into a page table
  - Page table determines page frame number (PFN)
  - Physical address is PFN::offset ("::" means concatenate)

- Page tables
  - Map virtual page number (VPN) to page frame number (PFN)
    - VPN is the index into the table that determines PFN
    - Will also refer to PFN as “physical page number”
  - One page table entry (PTE) per page in virtual address space
    - Or, one PTE per VPN
Page Lookups

(Simple page table used by Nachos)
Paging Example

- Pages are 4K
  - 4K → offset is 12 bits → VPN is 20 bits \(2^{20}\) VPNs
- Virtual address is 0x7468
  - Virtual page is 0x7, offset is 0x468 (lowest 12 bits of address)
- Page table entry 0x7 contains 0x2
  - Page frame number is 0x2
    - Virtual page 0x7 is at address 0x2000 (physical page 2)
- Physical address = 0x2 :: 0x468 = 0x2468
Page Lookups

Virtual Address: 0x7468

0x7

Page Table

Page number

Offset

0x2

Physical Address: 0x2468

0x468

Page frame

Offset

Physical Memory
Page Tables

- Page tables completely define the mapping between virtual pages and physical pages for an address space.
- Each process has an address space, so each process has a page table.
- Page tables are data structures maintained in the OS.
Page Table Entries (PTEs)

- Page table entries control mapping
  - 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
    » PTE for page 0 often set no-read, no-write, no-execute
  - The **page frame number** (PFN) determines physical page
Paging Advantages

• Easy to allocate memory
  ♦ Memory comes from a free list of fixed-sized 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 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 – hierarchical page tables (more later)
Segmentation

- Segmentation is a technique that partitions memory into logically related data units
  - Module, procedure, stack, data, file, etc.
  - Virtual addresses become `<segment #, offset>`
    - x86 stores segment #s in registers (CS, DS, SS, ES, FS, GS)
  - Units of memory from programmer’s perspective

- Natural extension of variable-sized partitions
  - Variable-sized partitions = 1 segment/process
  - Segmentation = many segments/process

- Hardware support
  - Multiple base/limit pairs, one per segment (segment table)
  - Segments named by #, used to index into table
Linear Address Space

Address Space

0x00000000

0xFFFFFFFF

Stack

Heap

Static Data (Data Segment)

Code (Text Segment)
Segmented Address Space

Each segment is a linear virtual memory region.
Segment Lookups

Segment Table

<table>
<thead>
<tr>
<th>Segment #</th>
<th>Offset</th>
<th>limit</th>
<th>base</th>
</tr>
</thead>
</table>

Virtual Address

Physical Memory

Protection Fault (aka Segmentation Fault!)

Yes?

No?
Segmentation and Paging

- Can combine segmentation and paging
  - x86 in 32-bit mode supports segments and paging
- Use segments to manage logically related units
  - Segments vary in size, but usually large (many pages)
- Use pages to partition segments into fixed-size chunks
  - Makes segments easier to manage within physical memory
    - Segments become “pageable” – rather than moving segments into and out of memory, just move page portions of segment
  - Need to allocate page table entries only for those pieces of the segments that have themselves been allocated
- Tends to be complex
  - Need both segment tables and page tables
Summary

• Virtual memory
  ♦ Processes use virtual addresses
  ♦ Hardware translates virtual address into physical addresses with OS support

• Various techniques
  ♦ Fixed partitions – easy to use, but internal fragmentation
  ♦ Variable partitions – more efficient, but external fragmentation
  ♦ Paging – use small, fixed size chunks, efficient for OS
  ♦ Segmentation – manage from programmer’s perspective
  ♦ Combine paging and segmentation to get benefits of both
Next time...

- Chapters 19, 20