Lecture 9: Memory Management
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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-and-fuzzy
- Survey techniques for implementing virtual memory
  - Fixed and variable partitioning
  - Paging
  - Segmentation
- Focus on hardware support and lookup procedure
  - Next lecture we’ll go into sharing, protection, efficient implementations, and other VM tricks and features
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 memory for it
  - OS will adjust amount of 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…
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
  - 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 memory)
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

Virtual Address
Offset

Base Register
P4’s Base

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 exception fault

- 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

+
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 storage
- The mapping is invisible to the program
- Protection is provided because a program 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
  - One page table entry (PTE) per page in virtual address space
    » Or, one PTE per VPN

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Page Lookups

Virtual Address

Page number  Offset

Page Table

Page frame

Physical Address

Page frame  Offset

Physical Memory

(Also used by Nachos)
Paging Example

- Pages are 4K
  - VPN is 20 bits ($2^{20}$ VPNs), offset is 12 bits
- Virtual address is 0x7468
  - Virtual page is 0x7, offset is 0x468
- Page table entry 0x7 contains 0x2
  - Page frame number is 0x2
  - Seventh virtual page is at address 0x2000 (2nd physical page)
- Physical address = 0x2000 + 0x468 = 0x2468
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
  - The **page frame number** (PFN) determines physical page
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 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)
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

- Stack
- Heap
- Static Data (Data Segment)
- Code (Text Segment)

Address Space

0x00000000

0xFFFFFFFF
Segmented Address Space

- Stack
  - Base & Limit: 0x00000000
- Heap
  - Base & Limit: 0x00000000
- Static Data (Data Segment)
  - Base & Limit: 0x00000000
- Code (Text Segment)
  - Base & Limit: 0x00000000

Segment Descriptor Table

Base & Limit

0x00000000
Segment Lookups

Virtual Address

Segment #  Offset

Yes?

<

No?

Protection Fault

Segment Table

limit  base

Physical Memory
Segment Table

- **Extensions**
  - Can have one segment table per process
    - Segment #s are then process-relative (why do this?)
  - Can easily share memory
    - Put same translation into base/limit pair
    - Can share with different protections (same base/limit, diff prot)

- **Problems**
  - Cross-segment addresses
    - Segments need to have same #s for pointers to them to be shared among processes
  - Large segment tables
    - Keep in main memory, use hardware cache for speed
  - Large segments
    - Internal fragmentation, paging to/from disk is expensive
Segmentation and Paging

- Can combine segmentation and paging
  - The x86 supports segments and paging
- Use segments to manage logically related units
  - Module, procedure, stack, file, data, etc.
  - Segments vary in size, but usually large (multiple 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…
Summary

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

- 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 in chunks from user’s perspective
  - Combine paging and segmentation to get benefits of both
Next time...

- Chapters 19, 20