CPSC 213

Introduction to Computer Systems

Unit 2d

Virtual Memory
Reading

- Companion
  - 5

- Text
  - Physical and Virtual Addressing, Address Spaces, Page Tables, Page Hits, Page Faults
  - 2ed: 9.1-9.2, 9.3.2-9.3.4
  - 1ed: 10.1-10.2, 10.3.2-10.3.4
Multiple Concurrent Program Executions

- So far we have
  - a single program
  - multiple threads

- Allowing threads from different program executions
  - we often have more than one thing we want to do at once(ish)
  - threads spend a lot of time blocked, allowing other threads to run
  - but, often there aren’t enough threads in one program to fill all the gaps

- What is a program execution
  - an instance of a program running with its own state stored in memory
  - compiler-assigned addresses for all static memory state (globals, code etc.)
  - security and failure semantics suggest memory isolation for each execution

- But, we have a problem
  - there is only one memory shared by all programs ...
Physical Address Space Collisions

- each program has assumed it is free to read/write anywhere in memory
- doesn’t work when multiple programs run at once

\[
\begin{align*}
\text{ld} & \quad \text{$0x1000$, $r2$} \\
\text{ld} & \quad \text{$3$, $r3$} \\
\text{st} & \quad \text{$r3$, ($r2$)} \\
\text{ld} & \quad \text{$0x1000$, $r4$} \\
\text{ld} & \quad \text{$42$, $r5$} \\
\text{st} & \quad \text{$r5$, ($r4$)} \\
\end{align*}
\]

- synchronization does not solve problem
  - it’s a problem through the whole program
  - not a short critical section with deliberate use of shared memory to communicate between threads
Virtual Memory

Virtual Address Space
- an abstraction of the *physical* address space of main (i.e., *physical*) memory
- programs access memory using virtual addresses
- hardware translates virtual address to physical memory addresses

Process
- a program execution with a private virtual address space
- associated with authenticated user for access control & resource accounting
- running a program with 1 or more threads

MMU
- memory management unit
- the hardware that translates virtual address to physical address
- performs this translation on *every* memory access by program
Virtual Address Translation

- each program uses the same virtual address, but they map to different physical addresses

```
ld $0x1000, r2
ld $3, r3
st r3, (r2)

ld $0x1000, r4
ld $42, r5
st r5, (r4)
```
Implementing the MMU

Let's think of this in the simulator ...

- introduce a class to simulate the MMU hardware

```java
class MMU extends MainMemory {
    byte [] physicalMemory;
    AddressSpace currentAddressSpace;

    void setAddressSpace (AddressSpace* as);

    byte readByte (int va) {
        int pa = currentAddressSpace.translate (va);
        return physicalMemory.read (pa);
    }
}
```

- currentAddressSpace is a hardware register
- the address space performs virtual-to-physical address translation
Implementing Address Translation

Goal
- translate any virtual address to a unique physical address (or none)
- fast and efficient hardware implementation

Let's look at a couple of alternatives ...

```java
class MMU extends MainMemory {
    byte [] physicalMemory;
    AddressSpace currentAddressSpace;

    void setAddressSpace (AddressSpace* as);

    byte readByte (int va) {
        int pa = currentAddressSpace.translate (va);
        return physicalMemory.read (pa);
    }
}
```
An address space is
- a single, variable-size, non-expandable chunk of physical memory
- named by its base physical address and its length

As a class in the simulator

```java
class AddressSpace {
    int baseVA, basePA, bounds;

    int translate (int va) {
        int offset = va - baseVA;
        if (offset < 0 || offset > bounds)
            throw new IllegalAddressException ();
        return basePA + offset;
    }
}
```

Problems
But, Address Space Use May Be Sparse

- **Issue**
  - the address space of a program execution is divided into regions
  - for example: code, globals, heap, shared-libraries and stack
  - there are large gaps of unused address space between these regions

- **Problem**
  - a single base-and-bounds mapping from virtual to physical addresses
  - means that gaps in virtual address space will waste physical memory
  - this is the **Internal Fragmentation** problem

- **Solution**
Segmentation

- An address space is
  - a set of segments

- A segment is
  - a single, variable-size, non-expandable chunk of physical memory
  - named by its base virtual address, physical address and length

- Implementation in Simulator

```java
class AddressSpace {
    Segment segment[];

    int translate (int va) {
        for (int i=0; i<segments.length; i++) {
            int offset = va - segment[i].baseVA;
            if (offset >= 0 && offset < segment[i].bounds) {
                pa = segment[i].basePA + offset;
                return pa;
            }
        }
        throw new IllegalAddressException (va);
    }
}
```

- Problem
But, Memory Use is Not Known Statically

- **Issue**
  - segments are **not expandable**; their size is static
  - some segments such as stack and heap change size dynamically

- **Problem**
  - segment size is chosen when segment is created
  - too large and internal fragmentation wastes memory
  - too small and stack or heap restricted

- **Solution**
  - allow segments to expand?
But, There May Be No Room to Expand

- **Issue**
  - segments are contiguous chunks of physical memory
  - a segment can only expand to fill space between it and the next segment

- **Problem**
  - there is no guarantee there will be room to expand a segment
  - the available memory space is not where we want it (i.e., adjacent to segment)
  - this is the **External Fragmentation** problem

- **Solution**
But, Moving Segments is Expensive

- **Issue**
  - if there is space in memory to store expanding segment, but not where it is
  - could move expanding segment or other segments to make room
  - external fragmentation is resolved by moving things to consolidate free space

- **Problem**
  - moving is possible, but expensive
  - to move a segment, all of its data must be copied
  - segments are large and memory copying is expensive

```
Maybe Some Room to Expand
Move Other Segments to Make Room
```
Expand Segments by Adding Segments

- **What we know**
  - segments should be non-expandable
  - size can not be effectively determined statically

- **Idea**
  - instead of expanding a segment
  - make a new one that is adjacent virtually, but not physically

- **Problem**
  - oh no! another problem! what is it? why does it occur?

![Diagram showing the allocation of new segments and virtual addresses](image)
Eliminating External Fragmentation

The problem with what we are doing is

- allocating variable size segments leads to external fragmentation of memory
- this is an inherent problem with variable-size allocation

What about **fixed sized allocation**

- could we make every segment the same size?
- this eliminates external fragmentation
- but, if we make segments too big, we’ll get internal fragmentation
- so, they need to be fairly small and so we’ll have lots of them

Problem
Translation with Many Segments

- What is wrong with this approach if there are many segments?

```java
class AddressSpace {
    Segment segment[];

    int translate (int va) {
        for (int i=0; i<segments.length; i++) {
            int offset = va - segment[i].baseVA;
            if (offset > 0 && offset < segment[i].bounds) {
                pa = segment[i].basePA + offset;
                return pa;
            }
        }
        throw new IllegalAddressException (va);
    }
}
```

- Now what?
  - is there another way to locate the segment, when segments are fixed size?
Paging

- Key Idea
  - Address Space is divided into set of fixed-size segments called pages
  - number pages in virtual address order
  - page number = virtual address / page size

- Page Table
  - indexed by virtual page number (vpn)
  - stores **base physical address** (actually address / page size (pfn) to save space)
  - stores **valid flag**, because some segment numbers may be unused
New terminology

- **page** a small, fixed-sized (4-KB) segment
- **page table** virtual-to-physical translation table
- **pte** page table entry
- **vpn** virtual page number
- **pfn** physical page frame number
- **offset** byte offset of address from beginning of page

Address Translation using a Page Table

```java
class PageTableEntry {
    boolean isValid;
    int pfn;
}

class AddressSpace {
    PageTableEntry pte[];

    int translate (int va) {
        int vpn = va / PAGE_SIZE;
        int offset = va % PAGE_SIZE;
        if (pte[vpn].isValid)
            return pte[vpn].pfn * PAGE_SIZE + offset;
        else
            throw new IllegalAddressException (va);
    }
}
```
Address Translation

- The bit-shifty version
  - assume that page size is 4-KB = 4096 = 2^{12}
  - assume addresses are 32 bits
  - then, vpn and pfn are 20 bits and offset is 12 bits
  - pte is pfn plus valid bit, so 21 bits or so, say 4 bytes

```c
int translate (int va) {
    int vpn   = va >>> 12;
    int offset = va & 0xfff;
    if (pte[vpn].isValid)
        return pte[vpn].pfn << 12 | offset;
}```
Consider this page table

0x00000000
0x80000007
0x80000321
0x8000006b
0x8000005a
0x80000040
0x00000000

Is 0x43a0 a valid virtual address and if so what is the corresponding physical address?

• (A) Not valid
• (B) 0x43a0
• (C) 0x5a3a0
• (D) 0x73a0
• (E) 0x3a0
Demand Paging

- **Key Idea**
  - some application data is not in memory
  - transfer from disk to memory, only when needed

- **Page Table**
  - only stores entries for pages that are in memory
  - pages that are only on disk are marked invalid
  - access to non-resident page causes a page-fault interrupt

- **Page Fault**
  - is an exception raised by the CPU
  - when a virtual address is invalid
  - an exception is just like an interrupt, but generated by CPU not IO device
  - page fault handler runs each time a page fault occurs

- **Memory Map**
  - a second data structure managed by the OS
  - divides virtual address space into regions, each *mapped* to a file
  - page-fault interrupt handler checks to see if faulted page is mapped
  - if so, gets page from disk, update Page Table and restart faulted instruction
Demand Paging

- Virtual vs Physical Memory Size
  - VM can be even larger than available PM with demand paging!

- Page Replacement
  - pages can now be removed from memory, transparent to program
  - a replacement algorithm choose which pages should be resident and swaps out others
A context switch is
- switching between threads from different **processes**
- each process has a private address space and thus its own page table

Implementing a context switch
- change PTBR (page table base register) to point to new process’s page table
- switch threads (save regs, switch stacks, restore regs)

Context Switch vs Thread Switch
- changing page tables can be considerably slower than just changing threads
  - mainly because caching techniques used to make translation fast
  - many pages may need reloading from disk because of demand paging
- (lots more on caching in CPSC 313!)
Hardware Enforced Encapsulation

- **Goal**
  - define a set of interfaces (APIs) whose implementations are protected
  - implementation code and data can only be accessed through interface

- **Obstacle**
  - can not use language protection without excluding languages like C

- **Use Hardware for Protection**
  - virtual memory already provides a way to protect memory
  - data in one address space can not even be named by thread in another
  - so, we’ve got the protected implementation part
  - we’ll need to add the interface part
The Operating System

- The operating system is
  - a C/assembly program
  - implements a set of abstractions for applications
  - it encapsulates the implementation of these abstractions, including hardware

- The Operating System’s Address Space
  - a part of every application’s page table is reserved for the OS
  - all code and data of OS is part of every page table (exact copies)
  - and so the operating system is part of every application’s address space

- Dual Protection Domains
  - each address space splits into application and system protection domain
  - CPU can run in one of two modes: user and kernel
  - when in user mode, the OS part of virtual memory is inaccessible
  - when in kernel mode, all of virtual memory is accessible
Hardware Encapsulation and VM

- **Hardware**
  - mode register (user or kernel)
  - certain instructions only legal in kernel mode
  - page table entries have protection flag (user or kernel)
  - attempting to access a kernel page while in user mode causes fault
  - special instructions for switching between user and kernel modes

- **Translation**

```java
class PageTableEntry {
    boolean isValid;
    boolean isKernel;
    int pfn;
}
```

```java
int translate (int va) {
    int vpn    = va >>> 12;
    int offset = va & 0xfff;
    if (pte[vpn].isValid && (isKernelMode || !pte[vpn].isKernel))
        return pte[vpn].pfn << 12 | offset;
    else
        throw new IllegalAddressException (va);
}
```
Inter-Process Communication

- **With one process**
  - threads communicate through shared memory

- **Different processes do not share memory**
  - they can not communicate in the same way

- **IPC**
  - basic mechanism is send and receive unformatted messages
  - a message is an array of bytes
  - sender and receiver have named endpoints (e.g., socket or port)
  - operating system provides the glue
    - the OS can access every process's memory
    - it copies from sender message and into receiver’s memory

- what is send/receive not like?
- what is send/receive like?
Summary

Process
- a program execution
- a private virtual address space and a set of threads
- private address space required for static address allocation and isolation

Virtual Address Space
- a mapping from virtual addresses to physical memory addresses
- programs use virtual addresses
- the MMU translates them to physical address used by the memory hardware

Paging
- a way to implement address space translation
- divide virtual address space into small, fixed sized virtual page frames
- page table stores base physical address of every virtual page frame
- page table is indexed by virtual page frame number
- some virtual page frames have no physical page mapping
- some of these get data on demand from disk
Address Space Translation Tradeoffs

- Single, variable-size, non-expandable segment
  - internal fragmentation of segment due to sparse address use

- Multiple, variable-size, non-expandable segments
  - internal fragmentation of segments when size isn’t known statically
  - external fragmentation of memory because segments are variable size
  - moving segments would resolve fragmentation, but moving is costly

- Expandable segments
  - expansion must be physically contiguous, but there may not be room
  - external fragmentation of memory requires moving segments to make room

- Multiple, fixed-size, non-expandable segments
  - called pages
  - need to be small to avoid internal fragmentation, so there are many of them
  - since there are many, need indexed lookup instead of search