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

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

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

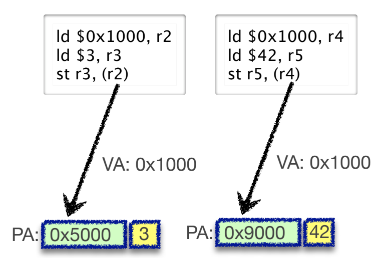
- synchronization does not solve problem
  - it's a problem through the whole program
  - not a short critical section with deliberate use of shared memory to communicate between threads

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



Implementing the MMU

- Let's think of this in the simulator ...
  - introduce a class to simulate the MMU hardware

```
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

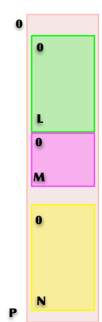
```
class MMU extends MainMemory {
  byte []      physicalMemory;
  AddressSpace currentAddressSpace;

  void setAddressSpace (AddressSpace* as);

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

- 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 ...

Base and Bounds

- 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

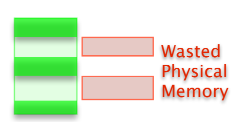
```
class AddressSpace {
  int baseVA, basePA, bounds;

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

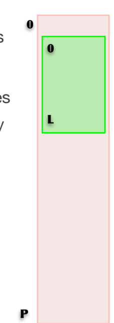


- Problems

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



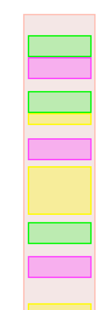


- Solution

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

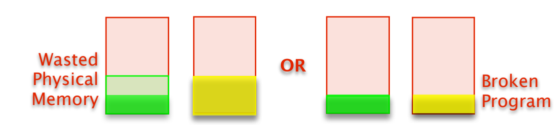
```
class AddressSpace {
  Segment segment[];

  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

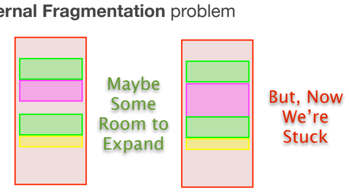
- Issue
  - segments are **not expandable**; their size is static
  - some segments such as stack and heap change size dynamically
- Problem
  - segment size is chosen when segment is created
  - too large and internal fragmentation wastes memory
  - too small and stack or heap restricted



- Solution
  - allow segments to expand?

But, There May Be No Room to Expand

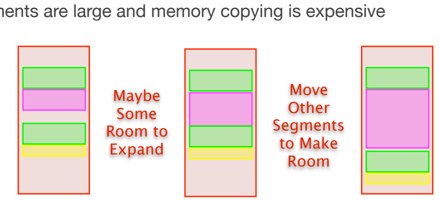
- Issue
  - segments are contiguous chunks of physical memory
  - a segment can only expand to fill space between it and the next segment
- Problem
  - there is no guarantee there will be room to expand a segment
  - the available memory space is not where we want it (i.e., adjacent to segment)
  - this is the **External Fragmentation** problem



- Solution

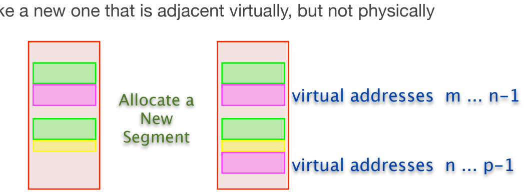
But, Moving Segments is Expensive

- 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



Expand Segments by Adding Segments

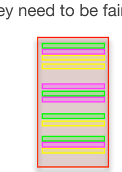
- What we know
  - segments should be non-expandable
  - size can not be effectively determined statically
- Idea
  - instead of expanding a segment
  - make a new one that is adjacent virtually, but not physically



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

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

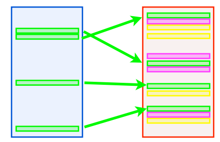
- What is wrong with this approach if there are many segments?

```
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);
 }}
```

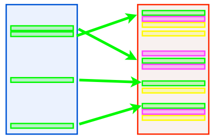
- Now what?
  - is there another way to locate the segment, when segments are fixed size?

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

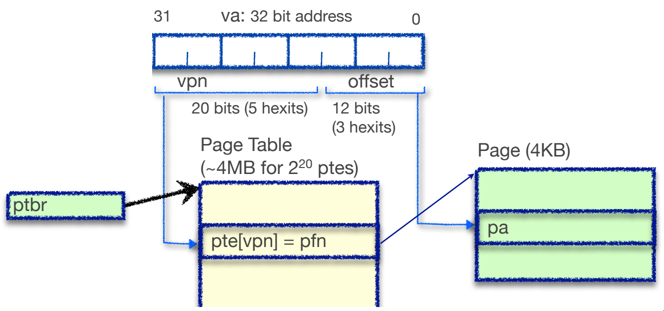
```
class PageTableEntry {
 boolean isValid;
 int     pfn;
}
```

```
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

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

- 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



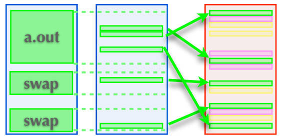
Question

- 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

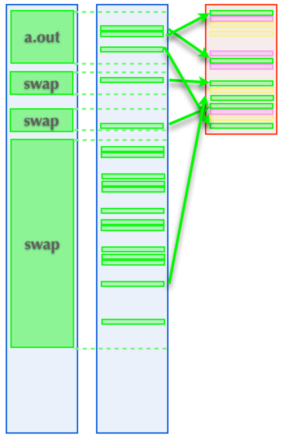
Demand Paging



- 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



Context Switch

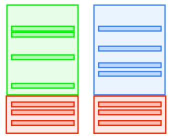
- A context switch is
  - switching between threads from different ***processes***
  - each process has a private address space and thus its own page table
- Implementing a context switch
  - change PTBR (page table base register) to point to new process's page table
  - switch threads (save regs, switch 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) `boolean isKernelMode;`
  - 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

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

```
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 by 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