Reading

- Companion
  - 5

- Text
  - 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 ...
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
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

- Lets 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

  ```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
Expand Segments by Adding Segments

What we know
- segments should be non-expandable
- size cannot 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?

```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?
### 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

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);
    }
}
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
- Page table has $2^{20}$ pte’s and so is 4-MB in size

The simulator code

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

class AddressSpace {
    PageTableEntry pte[];

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

Consider this page table

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) \(0x3a0\)
Translation and Exceptions

- **Virtual-to-Physical translation**
  - occurs on every memory reference
  - handled by hardware (sometimes with some software)
  - aided by a cache of recent translations
  - but, in general requires reading page table entry from memory

- **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

- **Handling a page fault**
  - extending the heap or stack, handler can just deliver a new zero-filled page
  - what about the code, global variables, or existing parts of heap or stack?
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

- **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

- **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 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
Inter-Process Communication

- With one process the 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 processes 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