CPSC 213

Introduction to Computer Systems

Summer Session 2019, Term 2

Unit 2d - Aug 8 - NOT ON THE FINAL

Virtual Memory

Overview

Reading

- text: 9.1-9.2, 9.3.2-9.3.4

Learning Goals

- explain how multiple programs can reside in memory concurrently, but preserve the single-system illusion
- explain why one program can not access the memory of another program and why this is important
- give key benefit and key drawback of base-and-bounds translation
- give key benefit and key drawback of segmentation
- give key benefit of paging
- translate a virtual address to a physical address using any of these three schemes

Multiple Concurrent Program Executions

- The last lie
  - we've been assuming that the computer executes one program at a time
  - but, really multiple programs can execute simultaneously
- Each Program Execution is
  - called a ***process***
  - multiple threads executing a program with state stored in memory
  - compiler-assigned addresses for static things (e.g., code and globals)
  - memory is viewable and changeable only by the program execution
- Problem
  - there is only one memory that they must all share
  - compiler-assigned addresses overlap
    - its okay for multiple processes to share code (or anything that is read-only)
    - global variables must be private to each process, but they can be at the same address
  - programs can access any address
    - must ensure that each process's memory is completely isolated

Virtual Memory

Basic Idea

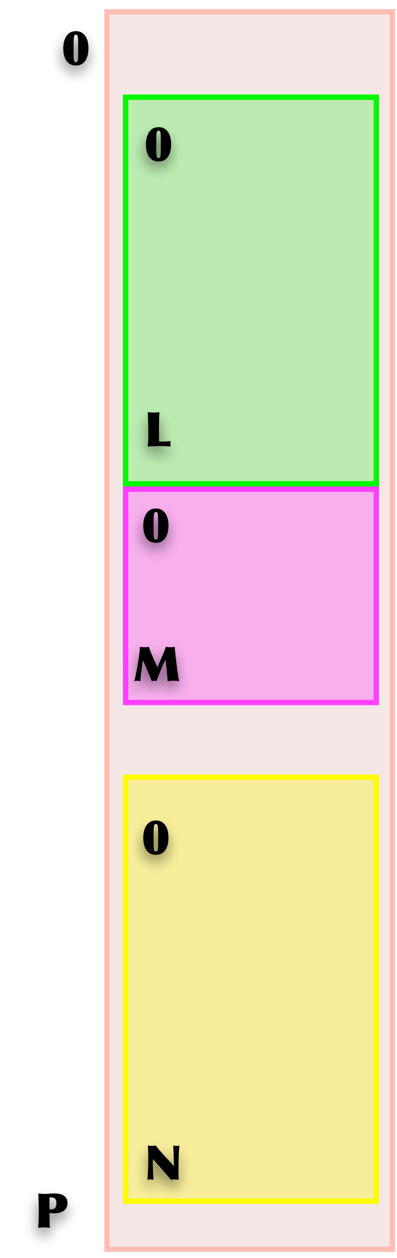
- each process is allocated a portion of physical memory
- allowed to use its own addresses for it
- disallowed from accessing any other part of memory

Changes to Program Execution

- hardware translates address of every memory access
  - by *memory management unit (MMU)*: part of CPU
- from process's *virtual* address to machine's real *physical* address

Virtual Address Space

- one per process
- maps process's virtual addresses to machine's physical addresses
- mapping data structure
  - created and maintained by operating system
  - accessed directly by hardware to translate addresses on every memory access



Implementing the MMU

- Lets 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);
  }
}
```

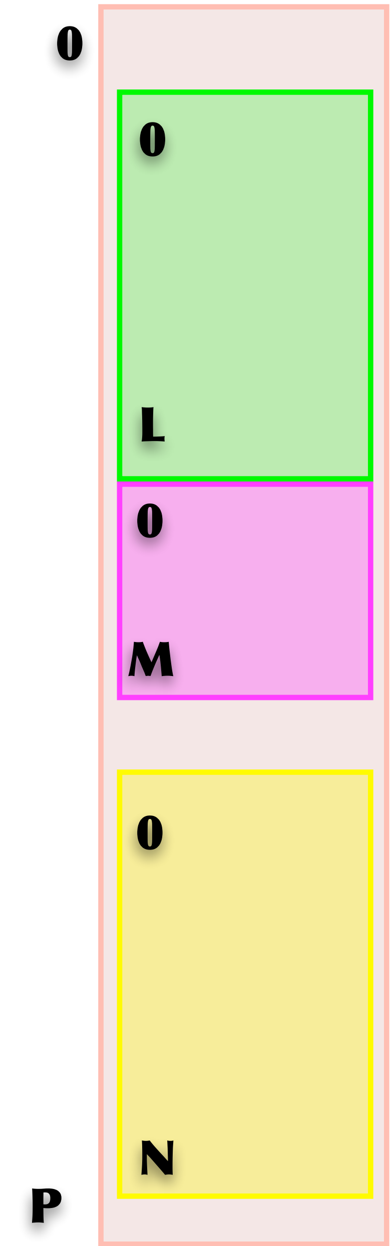
- Goal
  - translate any virtual address to a unique physical address (or none)
  - fast and efficient hardware implementation
- Lets look at a couple of alternatives ...

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

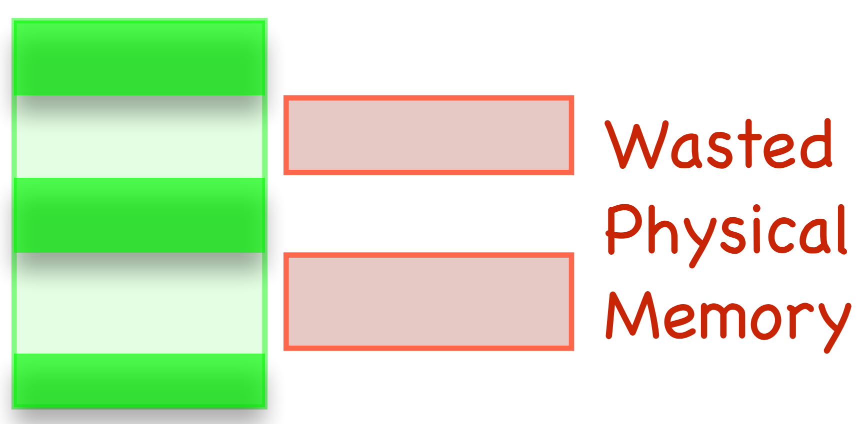
```
class AddressSpace {
  int baseVA, basePA, bounds;

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

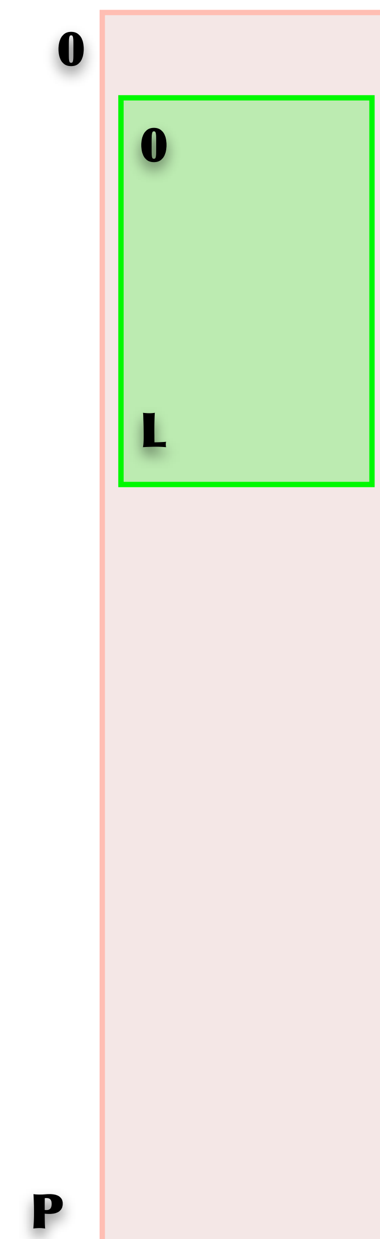
- Problems



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





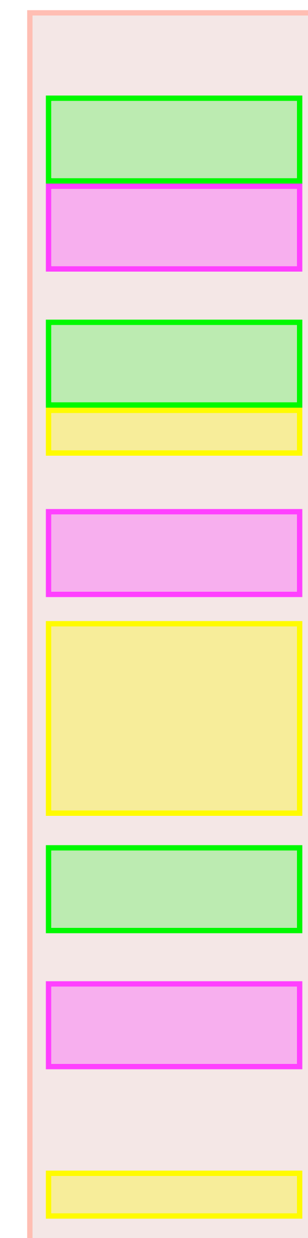
- Solution

Segmentation

- Address Space
  - a set of segments
- Segment
  - a single, variable-size, non-expandable chunk of physical memory
  - named by its base virtual address, physical address and length
- Implementation in Simulator

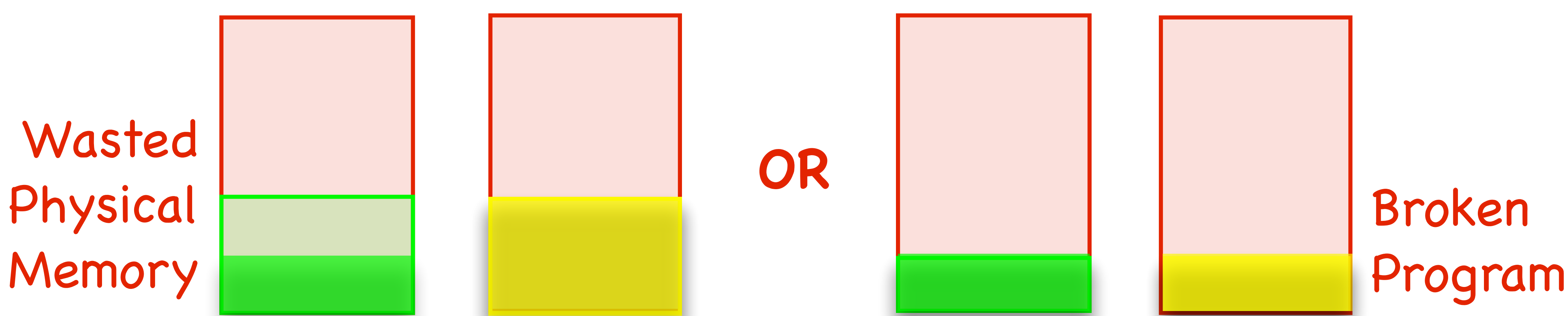
```
class AddressSpace {
  Segment segment[];

  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



Memory Use is Not Known Statically

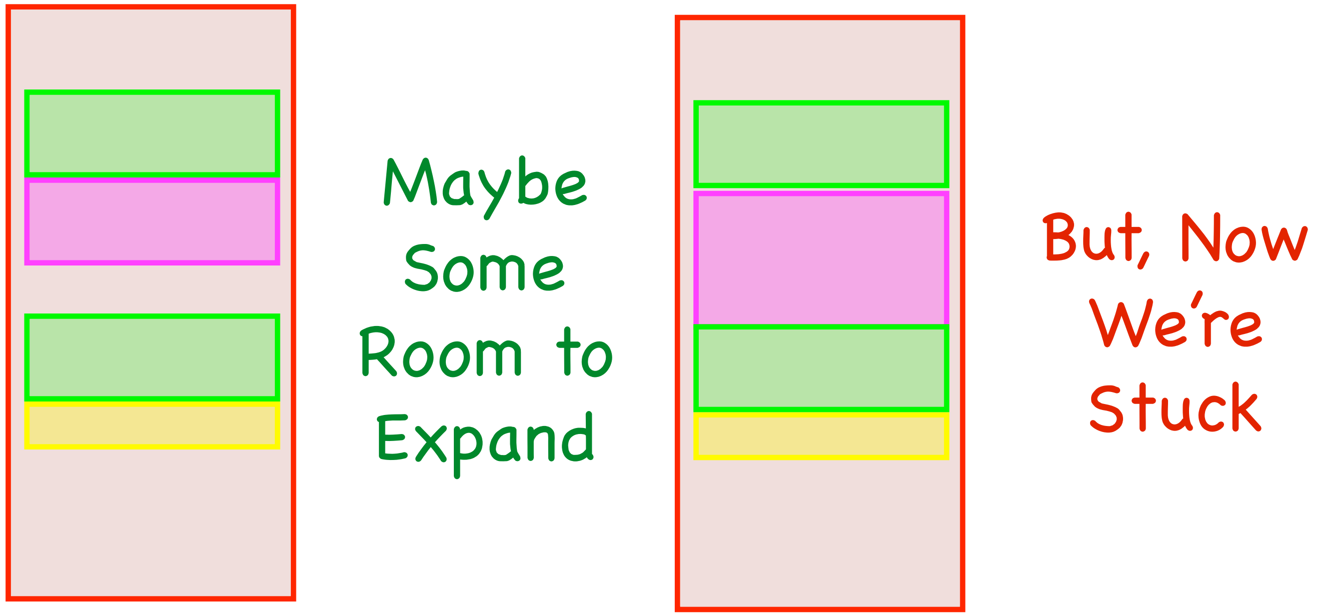
- Issue
  - segments are **not expandable**; their size is fixed when segment is created
  - some segments such as stack and heap change size dynamically
- Problem
  - segment size is chosen when segment is created
  - too large and internal fragmentation wastes memory
  - too small and stack or heap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



- Solution
  - allow segments to expand?

There May Be No Room to Expand

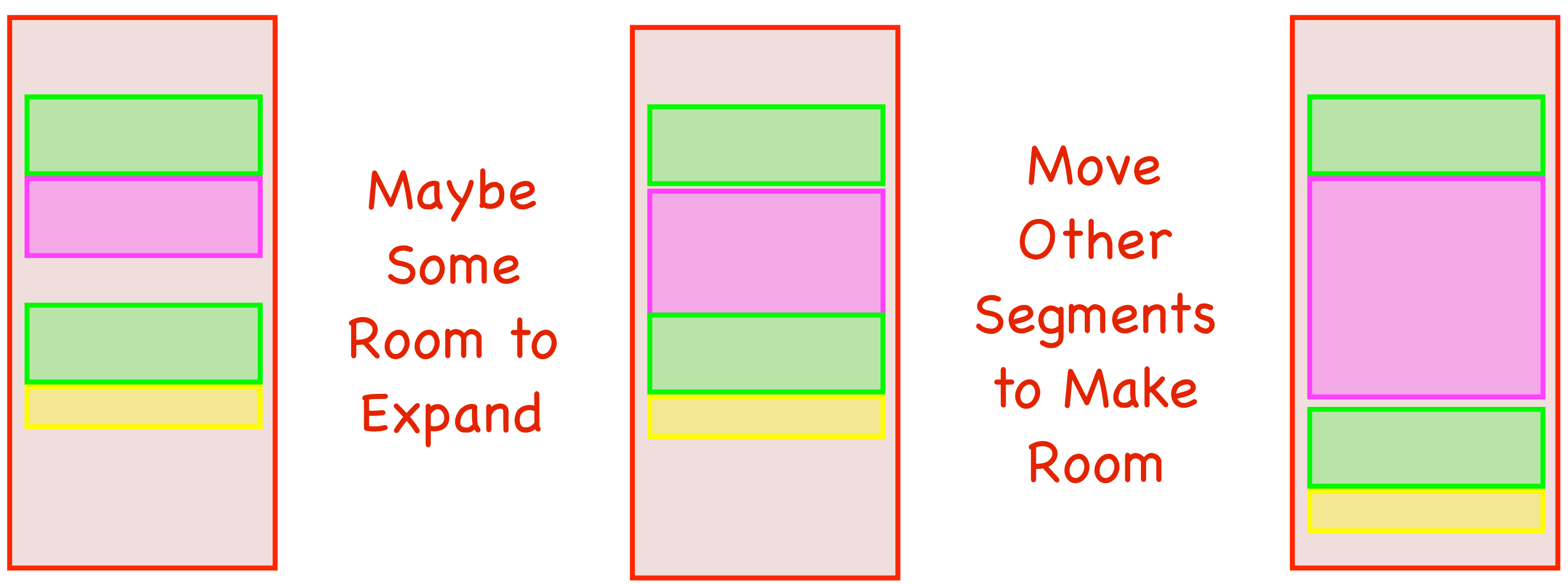
- Issue
  - segments are contiguous chunks of physical memory
  - a segment can only expand to fill space between it and the next segment
- Problem
  - there is no guarantee there will be room to expand a segment
  - the available memory space is not where we want it (i.e., adjacent to segment)
  - this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



- Solution

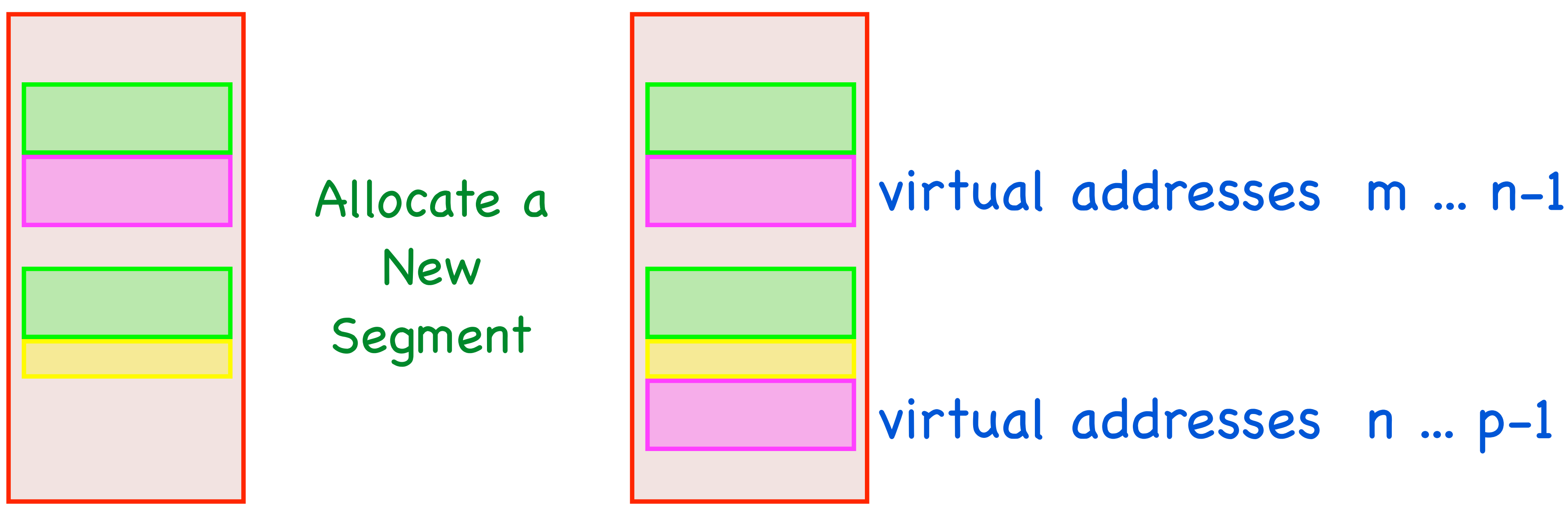
Moving Segments is Expensive

- 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

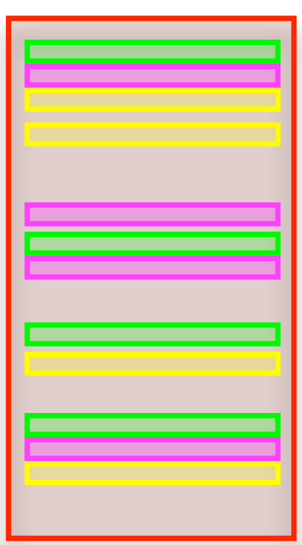
- What we know
  - segments should be non-expandable
  - size can not be effectively determined statically
- Idea
  - instead of expanding a segment
  - make a new one that is adjacent virtually, but not physically



- 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

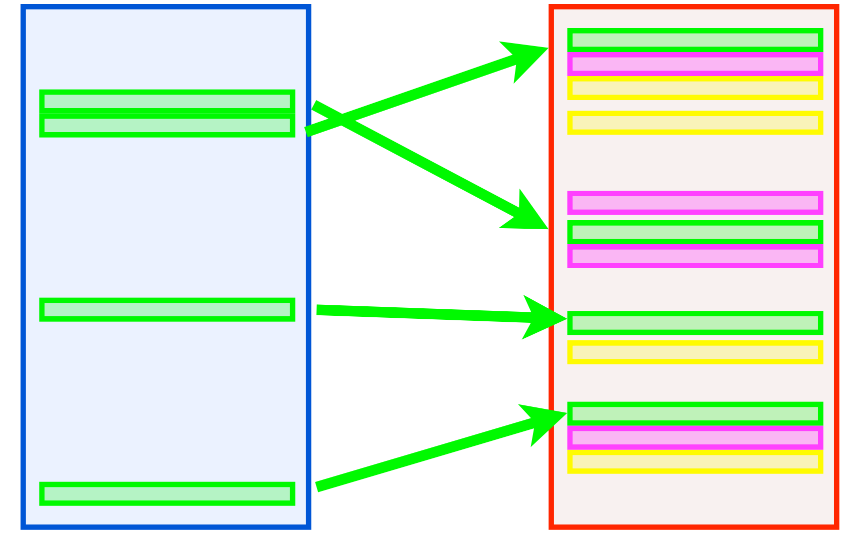
Translation with Many Segments

- 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
- every page of virtual address space has a number (**`VPN`**)
- virtual address (**`VA`**) is comprised of
  - **`VPN     = VA / PAGE_SIZE`**
  - **`OFFSET  = VA % PAGE_SIZE`**
- every page *frame* of physical memory has a number too (**`PFN`**) that yields physical address (**`PA`**)
  - **`PA      = PFN * PAGE_SIZE + OFFSET`**

Page Table

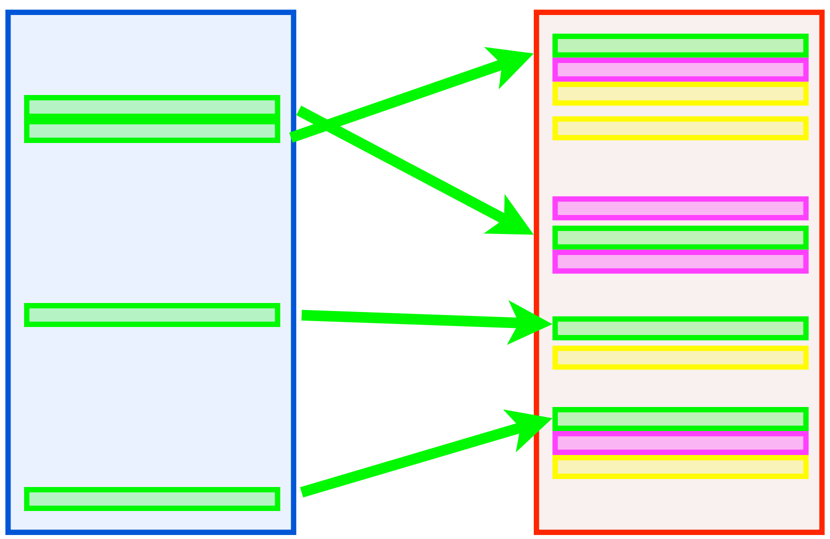
- stored in memory
  - (address with physical addresses or operating-system's virtual addresses)
- one for every address space
- array of page-table entries, one for virtual page in address space
- indexed by VPN

Page Table Entry

- indicates whether virtual page is valid
- if valid stores the page's PFN
- also stores access permissions
  - is reading okay? is writing okay? is executing okay?
- stores a bit of other stuff too (e.g., access and dirty flags)

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

```
class PageTableEntry {
  boolean isValid;
  boolean isReadAllowed;
  boolean isWriteAllowed;
  boolean isExecuteAllowed;
  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

```
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

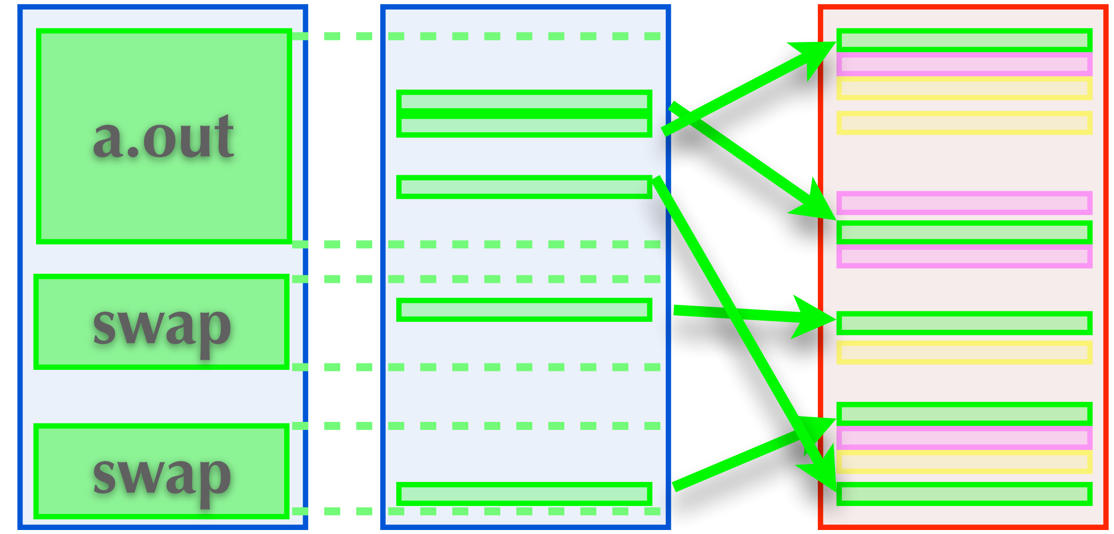
```
0x00000000
0x80000007
0x80000321
0x8000006b
0x8000005a
0x80000040
0x00000000
```

- 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

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

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 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 much slower than just changing threads
  - mainly because caching techniques used to make translation fast

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 know 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