CS162
Operating Systems and Systems Programming
Lecture 12

Address Translation

March 7th, 2019

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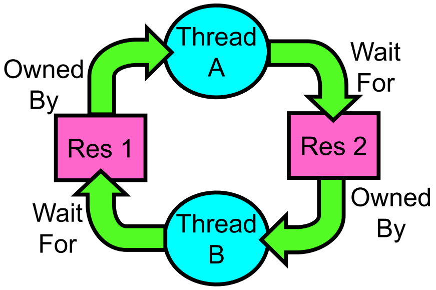
http://cs162.eecs.Berkeley.edu

Recall: Starvation vs Deadlock

- Starvation: thread waits indefinitely
  - Example, low-priority thread waiting for resources constantly in use by high-priority threads
- Deadlock: circular waiting for resources
  - Thread A owns Res 1 and is waiting for Res 2
    Thread B owns Res 2 and is waiting for Res 1



- Deadlock ⇒ Starvation but not vice versa
  - Starvation can end (but doesn't have to)
  - Deadlock can't end without external intervention

Recall: Four requirements for Deadlock

- Mutual exclusion
  - Only one thread at a time can use a resource.
- Hold and wait
  - Thread holding at least one resource is waiting to acquire additional resources held by other threads
- No preemption
  - Resources are released only voluntarily by the thread holding the resource, after thread is finished with it
- Circular wait
  - There exists a set $\{T_1, …, T_n\}$ of waiting threads
    - » T_1 is waiting for a resource that is held by T_2
    - » T_2 is waiting for a resource that is held by T_3
    - » …
    - » T_n is waiting for a resource that is held by T_1

Recall: Ways of preventing deadlock

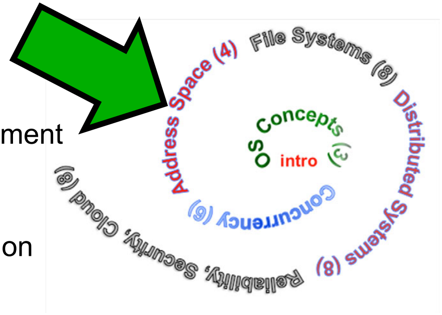
- Force all threads to request resources in a particular order preventing any cyclic use of resources
  - Example (x.P, y.P, z.P,…)
    - » Make tasks request disk, then memory, then…
- Banker's algorithm:
  - Allocate resources dynamically
    - » Evaluate each request and grant if some ordering of threads is still deadlock free afterward
    - » Technique: pretend each request is granted, then run deadlock detection algorithm, and grant request if result is deadlock free (conservative!)
  - Keeps system in a "SAFE" state, i.e. there exists a sequence $\{T_1, T_2, … T_n\}$ with T_1 requesting all remaining resources, finishing, then T_2 requesting all remaining resources, etc..
  - Algorithm allows the sum of maximum resource needs of all current threads to be greater than total resources

Can Priority Inversion cause Deadlock?

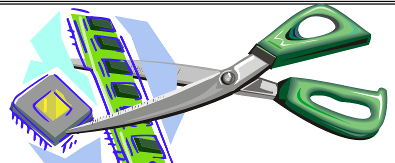
- Technically not – Consider this example:
  - 3 threads, T1, T2, T3 in priority order (T3 highest)
  - T1 grabs lock, T3 tries to acquire, then sleeps, T2 running
  - Will this make progress?
    - » No, as long as T2 is running
    - » But T2 could stop at any time and the problem would resolve itself… So, this is *not* a deadlock (it is a livelock)
  - Why is this a priority inversion?
    - » T3 is prevented from running by T2
- How does *priority donation* help?
  - Briefly raising T1 to the same priority as T3⇒T1 can run and release lock, allowing T3 to run
  - Does priority donation involve tacking lock away from T1?
    - » NO! That would break semantics of the lock and potentially corrupt any information protected by lock!

Next Objective

- Dive deeper into the concepts and mechanisms of memory sharing and address translation
- Enabler of many key aspects of operating systems
  - Protection
  - Multi-programming
  - Isolation
  - Memory resource management
  - I/O efficiency
  - Sharing
  - Inter-process communication
  - Debugging
  - Demand paging
- Today: Translation

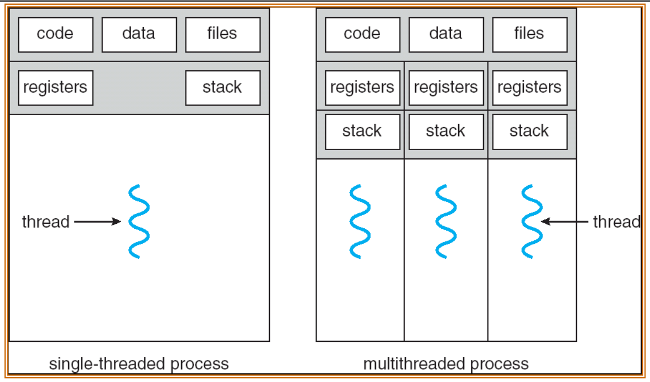


Virtualizing Resources



- Physical Reality:
  Different Processes/Threads share the same hardware
  - Need to multiplex CPU (Just finished: scheduling)
  - Need to multiplex use of Memory (starting today)
  - Need to multiplex disk and devices (later in term)
- Why worry about memory sharing?
  - The complete working state of a process and/or kernel is defined by its data in memory (and registers)
  - Consequently, cannot just let different threads of control use the same memory
    - » Physics: two different pieces of data cannot occupy the same locations in memory
  - Probably don't want different threads to even have access to each other's memory if in different processes (protection)

Recall: Single and Multithreaded Processes

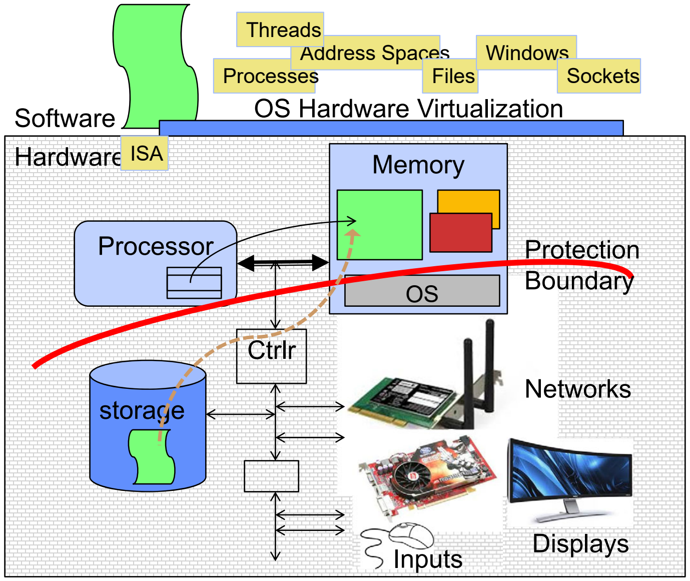


- Threads encapsulate concurrency
  - "Active" component of a process
- Address spaces encapsulate protection
  - Keeps buggy program from trashing the system
  - "Passive" component of a process

Important Aspects of Memory Multiplexing

- Protection:
  - Prevent access to private memory of other processes
    - Different pages of memory can be given special behavior (Read Only, Invisible to user programs, etc).
    - Kernel data protected from User programs
    - Programs protected from themselves
- Controlled overlap:
  - Separate state of threads should not collide in physical memory. Obviously, unexpected overlap causes chaos!
  - Conversely, would like the ability to overlap when desired (for communication)
- Translation:
  - Ability to translate accesses from one address space (virtual) to a different one (physical)
  - When translation exists, processor uses virtual addresses, physical memory uses physical addresses
  - Side effects:
    - Can be used to avoid overlap
    - Can be used to give uniform view of memory to programs

Recall: Loading



Binding of Instructions and Data to Memory

Process view of memory

```
data1:  dw    32
              …
start:  lw    r1,0(data1)
        jal   checkit
loop:   addi  r1, r1, -1
        bnz   r1, loop
        …
checkit: …
```

Physi

```
0x0300  00    20
 …
0x0900  8C2000C0
0x0904  0C000280
0x0908  2021FFFF
0x090C  14200242
 …
0x0A00
```

```
Assume 4byte words
0x300 = 4 * 0x0C0
0x0C0 = 0000 1100 0000
0x300 = 0011 0000 0000
```

Binding of Instructions and Data to Memory

Process view of memory

```
data1:  dw    32
              …
start:  lw    r1,0(data1)
        jal   checkit
loop:   addi  r1, r1, -1
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        …
checkit: …
```

Physical addresses

```
0x0300  00000020
 …         …
0x0900  8C2000C0
0x0904  0C000280
0x0908  2021FFFF
0x090C  14200242
 …
0x0A00
```

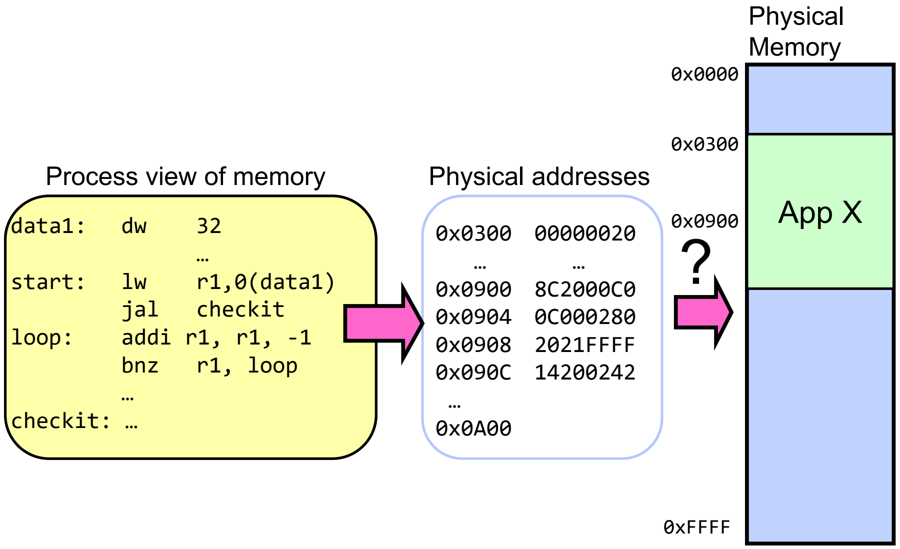
Physical Memory

```
0x0000
0x0300  00000020

0x0900  8C2000C0
        0C000340
        2021FFFF
        14200242

0xFFFF
```

Second copy of program from previous example



Process view of memory

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               …
start:   lw    r1,0(data1)
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Physical addresses

```
0x0300  00000020
  …       …
0x0900  8C2000C0
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 …
0x0A00
```
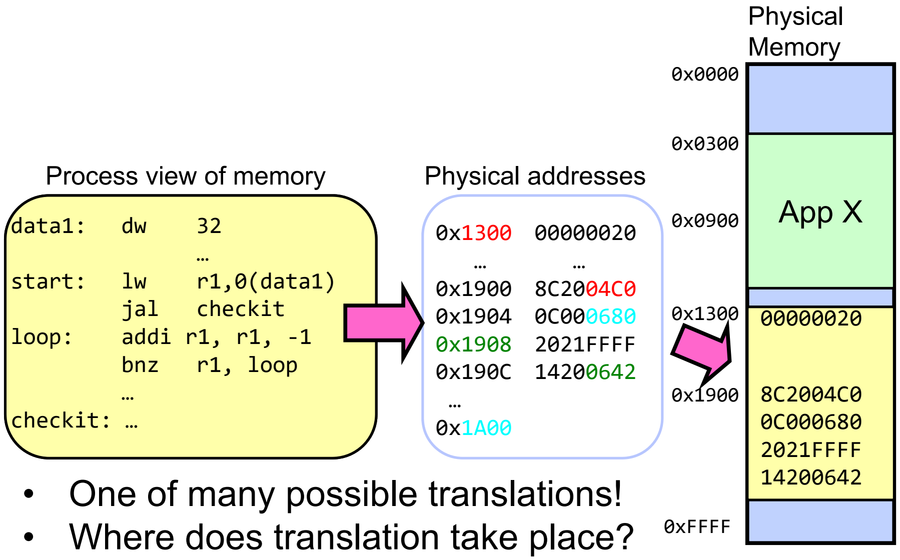

Need address translation!

Second copy of program from previous example



Process view of memory

```
data1:   dw    32
               …
start:   lw    r1,0(data1)
         jal   checkit
loop:    addi r1, r1, -1
         bnz   r1, loop
         …
checkit: …
```

Physical addresses

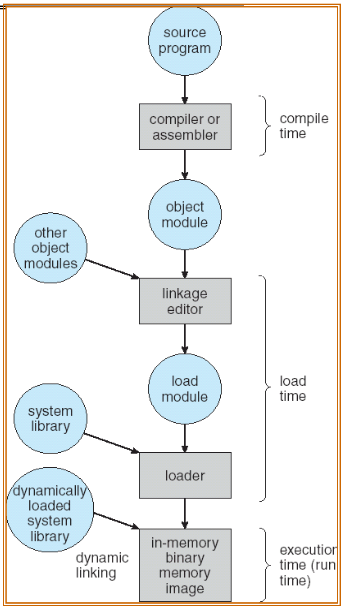
```
0x1300  00000020
  …       …
0x1900  8C2004C0
0x1904  0C000680
0x1908  2021FFFF
0x190C  14200642
 …
0x1A00
```

- One of many possible translations!
- Where does translation take place?

Compile time, Link/Load time, or Execution time?

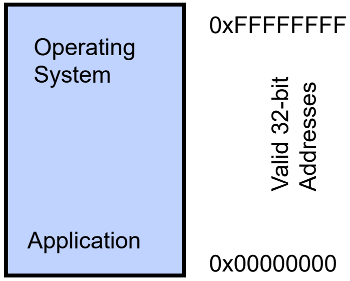
Multi-step Processing of a Program for Execution

- Preparation of a program for execution involves components at:
  - Compile time (i.e., “gcc”)
  - Link/Load time (UNIX “ld” does link)
  - Execution time (e.g., dynamic libs)
- Addresses can be bound to final values anywhere in this path
  - Depends on hardware support
  - Also depends on operating system
- Dynamic Libraries
  - Linking postponed until execution
  - Small piece of code (i.e. the *stub*), locates appropriate memory-resident library routine
  - Stub replaces itself with the address of the routine, and executes routine



Recall: Uniprogramming

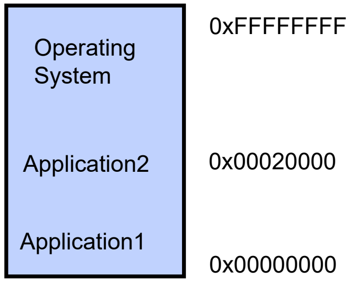
- Uniprogramming (no Translation or Protection)
  - Application always runs at same place in physical memory since only one application at a time
  - Application can access any physical address

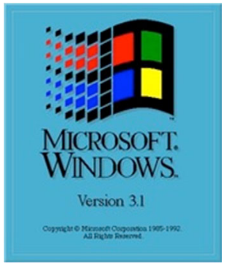


- Application given illusion of dedicated machine by giving it reality of a dedicated machine

Multiprogramming (primitive stage)

- Multiprogramming without Translation or Protection
  - Must somehow prevent address overlap between threads




MICROSOFT WINDOWS
Version 3.1
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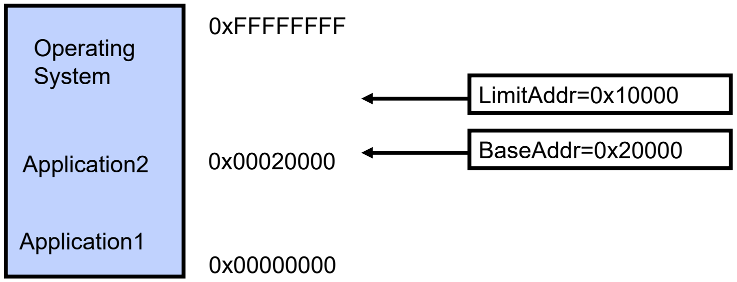
  - Use Loader/Linker: Adjust addresses while program loaded into memory (loads, stores, jumps)
    - » Everything adjusted to memory location of program
    - » Translation done by a linker-loader (relocation)
    - » Common in early days (… till Windows 3.x, 95?)
- With this solution, no protection: bugs in any program can cause other programs to crash or even the OS

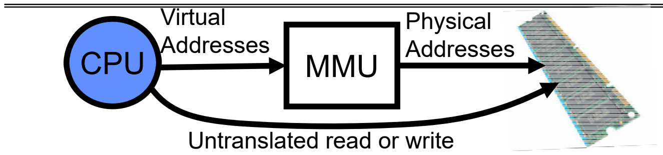
Multiprogramming (Version with Protection)

- Can we protect programs from each other without translation?



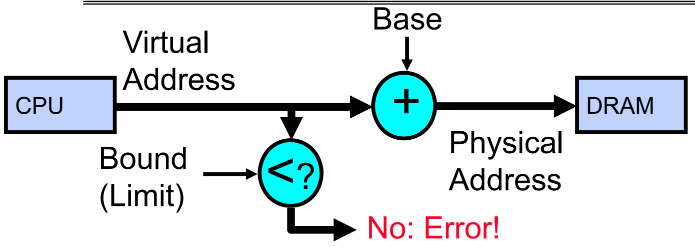
  - Yes: use two special registers *BaseAddr* and *LimitAddr* to prevent user from straying outside designated area
    - » Cause error if user tries to access an illegal address
  - During switch, kernel loads new base/limit from PCB (Process Control Block)
    - » User not allowed to change base/limit registers

Recall: General Address translation



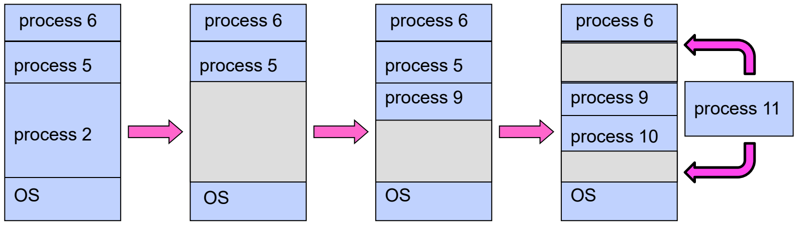
- Recall: Address Space:
  - All the addresses and state a process can touch
  - Each process and kernel has different address space
- Consequently, two views of memory:
  - View from the CPU (what program sees, virtual memory)
  - View from memory (physical memory)
  - Translation box (MMU) converts between the two views
- Translation ⇒ much easier to implement protection!
  - If task A cannot even gain access to task B's data, no way for A to adversely affect B
- With translation, every program can be linked/loaded into same region of user address space

Recall: Base and Bounds (was from CRAY-1)



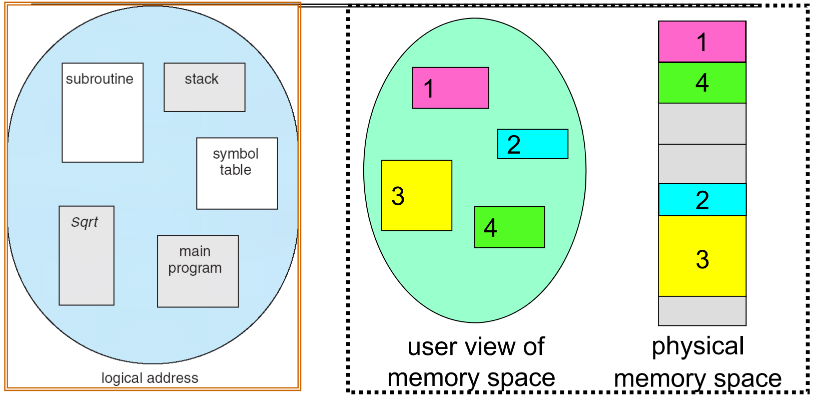
- Could use base/bounds for dynamic address translation – translation happens at execution:
  - Alter address of every load/store by adding "base"
  - Generate error if address bigger than limit
- Gives program the illusion that it is running on its own dedicated machine, with memory starting at 0
  - Program gets continuous region of memory
  - Addresses within program do not have to be relocated when program placed in different region of DRAM

Issues with Simple B&B Method



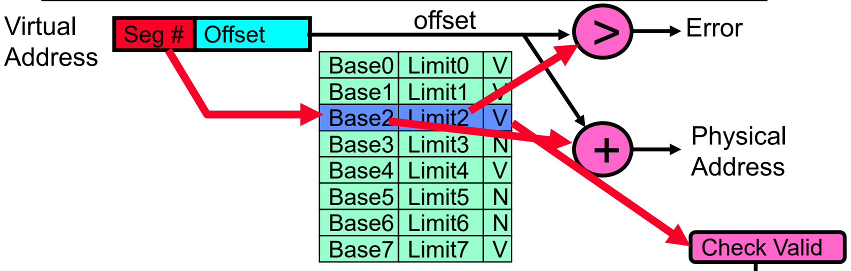
- Fragmentation problem over time
  - Not every process is same size ⇒ memory becomes fragmented over time
- Missing support for sparse address space
  - Would like to have multiple chunks/program (Code, Data, Stack, Heap, etc)
- Hard to do inter-process sharing
  - Want to share code segments when possible
  - Want to share memory between processes
  - Helped by providing multiple segments per process

More Flexible Segmentation



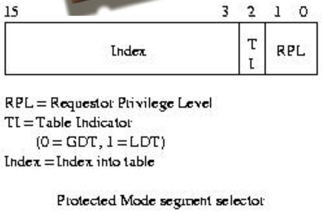
- Logical View: multiple separate segments
  - Typical: Code, Data, Stack
  - Others: memory sharing, etc
- Each segment is given region of contiguous memory
  - Has a base and limit
  - Can reside anywhere in physical memory

Implementation of Multi-Segment Model



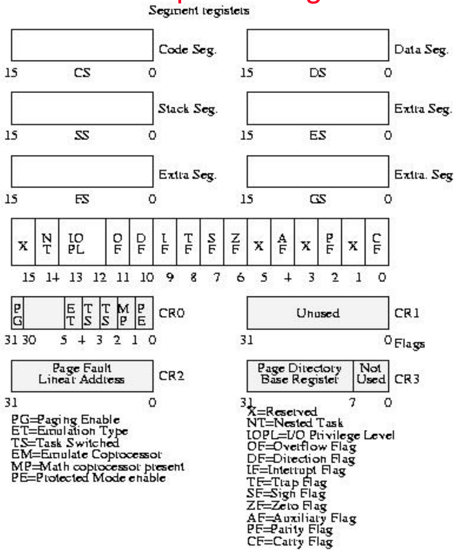
- Segment map resides in processor
  - Segment number mapped into base/limit pair
  - Base added to offset to generate physical address
  - Error check catches offset out of range
- As many chunks of physical memory as entries
  - Segment addressed by portion of virtual address
  - However, could be included in instruction instead:
    - » x86 Example: mov [es:bx],ax.
- What is "V/N" (valid / not valid)?
  - Can mark segments as invalid; requires check as well

Intel x86 Special Registers



Typical Segment Register
Current Priority is RPL
Of Code Segment (CS)

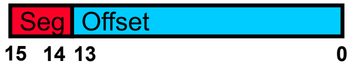
80386 Special Registers



Administrivia

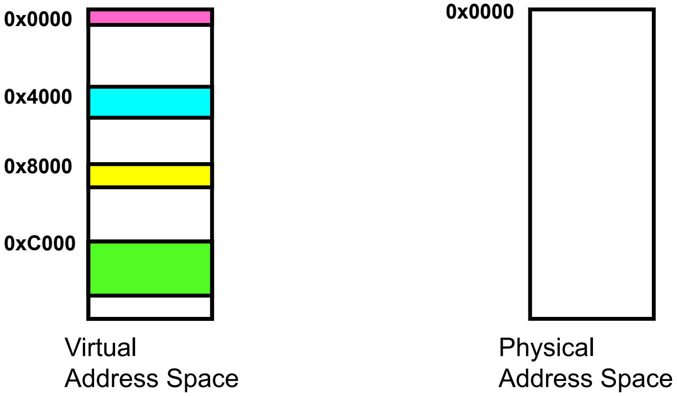
- Project 1
  - Code Due tomorrow (3/8)
  - Final Report due Tuesday (3/12)
- Midterm 1 Regrade Requests
  - Due Monday (3/11)
  - Don't just send request to send it! (We may regrade everything if it is a specious request for points – you might lose points…!)
- Midterm 2: Thursday 4/4
  - Ok, this is a few weeks and after Spring Break
  - Will definitely include Scheduling material (lecture 10)
  - Up to and including some material from lecture 17
  - Probably try to have a Midterm review in early part of that week…. Stay tuned

Example: Four Segments (16 bit addresses)



Virtual Address Format

Seg ID #	Base	Limit
0 (code)	0x4000	0x0800
1 (data)	0x4800	0x1400
2 (shared)	0xF000	0x1000
3 (stack)	0x0000	0x3000



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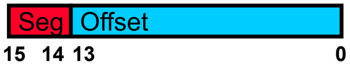

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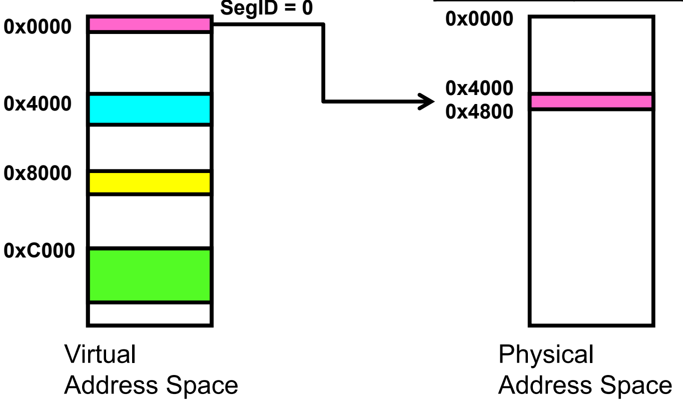

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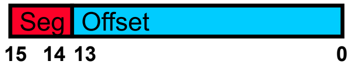

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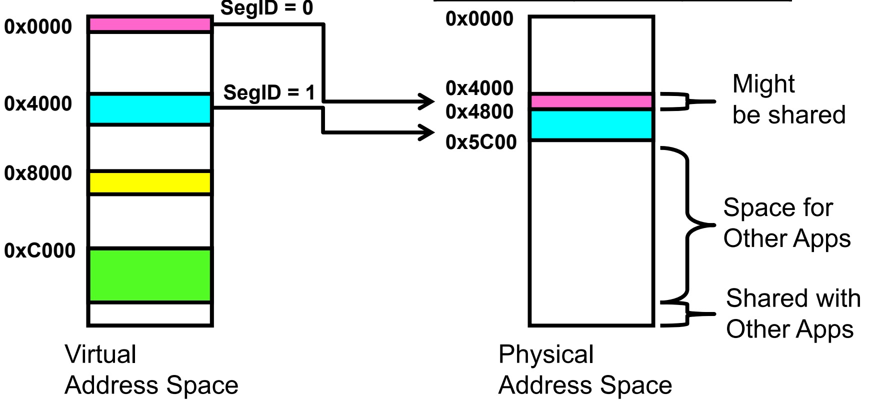

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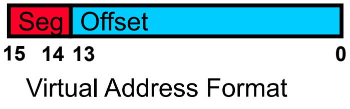

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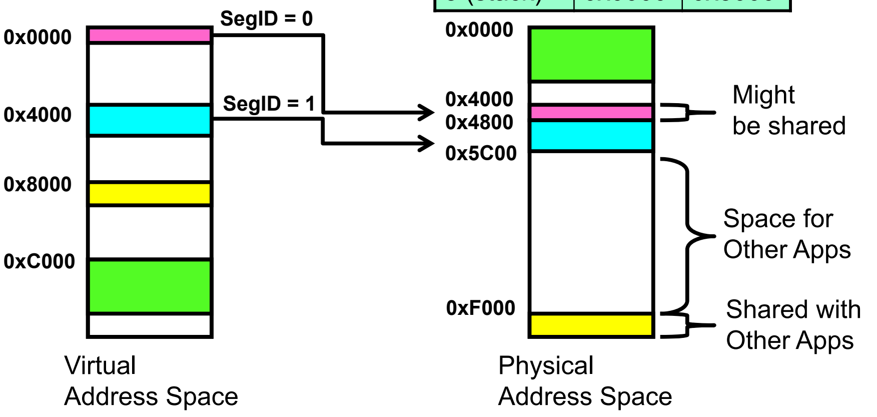

Example of Segment Translation (16bit address)

```
0x240   main:     la $a0, varx
0x244             jal strlen
 …                 …
0x360   strlen:   li   $v0, 0  ;count
0x364   loop:     lb   $t0, ($a0)
0x368             beq  $r0,$t0, done
 …                 …
0x4050  varx      dw   0x314159
```

Seg ID #	Base	Limit
0 (code)	0x4000	0x0800
1 (data)	0x4800	0x1400
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Let's simulate a bit of this code to see what happens (PC=0x240):

1. Fetch 0x0240 (0000 0010 0100 0000). Virtual segment #? 0; Offset? 0x240
   Physical address? Base=0x4000, so physical addr=0x4240
   Fetch instruction at 0x4240. Get "la $a0, varx"
   Move 0x4050 → $a0, Move PC+4→PC

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0x244             jal strlen
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2. Fetch 0x244. Translated to Physical=0x4244. Get "jal strlen"
   Move 0x0248 → $ra (return address!), Move 0x0360 → PC

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 …                 …
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   Move 0x4050 → $a0, Move PC+4→PC
2. Fetch 0x244. Translated to Physical=0x4244. Get "jal strlen"
   Move 0x0248 → $ra (return address!), Move 0x0360 → PC
3. Fetch 0x360. Translated to Physical=0x4360. Get "li $v0, 0"
   Move 0x0000 → $v0, Move PC+4→PC

Example of Segment Translation (16bit address)

```
0x0240  main:    la $a0, varx
0x0244           jal strlen
  …              …
0x0360  strlen:  li   $v0, 0  ;count
0x0364  loop:    lb   $t0, ($a0)
0x0368           beq  $r0,$t0, done
  …              …
0x4050  varx     dw   0x314159
```

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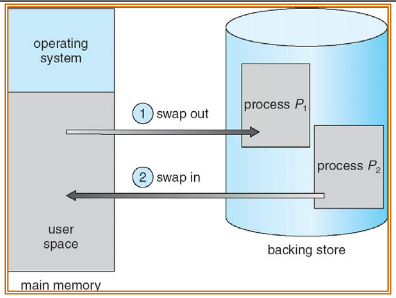
   Fetch instruction at 0x4240. Get "la $a0, varx"
   Move 0x4050 → $a0, Move PC+4→PC
2. Fetch 0x0244. Translated to Physical=0x4244. Get "jal strlen"
   Move 0x0248 → $ra (return address!), Move 0x0360 → PC
3. Fetch 0x0360. Translated to Physical=0x4360. Get "li $v0, 0"
   Move 0x0000 → $v0, Move PC+4→PC
4. Fetch 0x0364. Translated to Physical=0x4364. Get "lb $t0, ($a0)"
   Since $a0 is 0x4050, try to load byte from 0x4050
   Translate 0x4050 (0100 0000 0101 0000). Virtual segment #? 1; Offset? 0x50
   Physical address? Base=0x4800, Physical addr = 0x4850,
   Load Byte from 0x4850→$t0, Move PC+4→PC

Observations about Segmentation

- Virtual address space has holes
  - Segmentation efficient for sparse address spaces
  - A correct program should never address gaps (except as mentioned in moment)
    - » If it does, trap to kernel and dump core
- When it is OK to address outside valid range?
  - This is how the stack and heap are allowed to grow
  - For instance, stack takes fault, system automatically increases size of stack
- Need protection mode in segment table
  - For example, code segment would be read-only
  - Data and stack would be read-write (stores allowed)
  - Shared segment could be read-only or read-write
- What must be saved/restored on context switch?
  - Segment table stored in CPU, not in memory (small)
  - Might store all of processes memory onto disk when switched (called "swapping")

What if not all segments fit into memory?

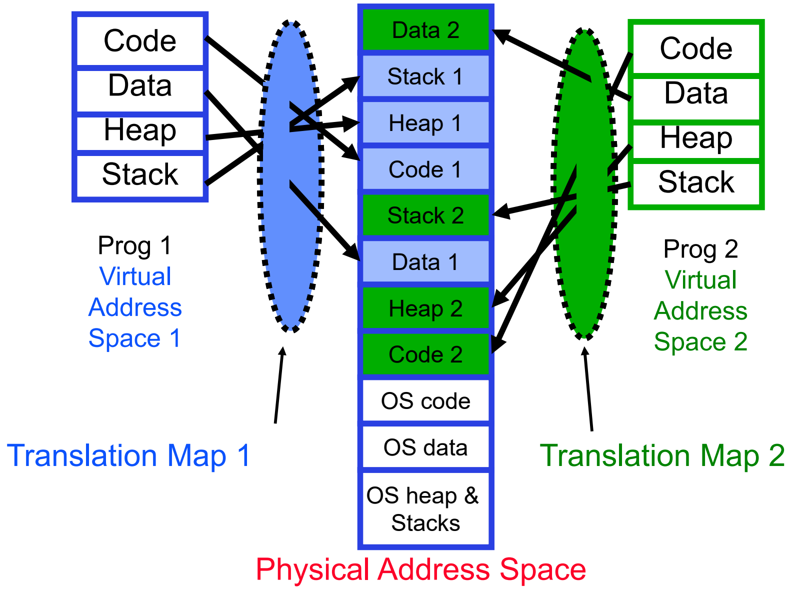


- Extreme form of Context Switch: Swapping
  - In order to make room for next process, some or all of the previous process is moved to disk
    - » Likely need to send out complete segments
  - This greatly increases the cost of context-switching
- What might be a desirable alternative?
  - Some way to keep only active portions of a process in memory at any one time
  - Need finer granularity control over physical memory

Problems with Segmentation

- Must fit variable-sized chunks into physical memory
- May move processes multiple times to fit everything
- Limited options for swapping to disk
- Fragmentation: wasted space
  - External: free gaps between allocated chunks
  - Internal: don't need all memory within allocated chunks

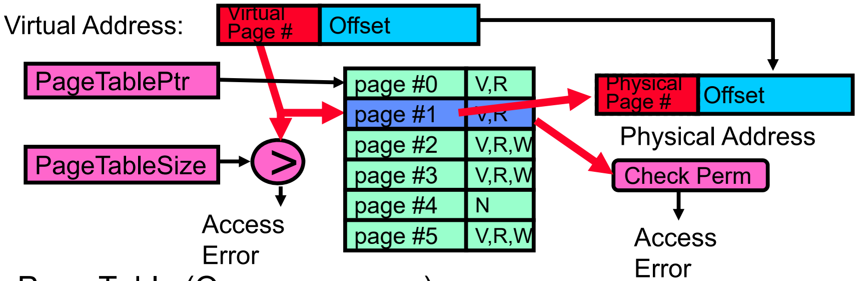
Recall: General Address Translation



Paging: Physical Memory in Fixed Size Chunks

- Solution to fragmentation from segments?
  - Allocate physical memory in fixed size chunks ("pages")
  - Every chunk of physical memory is equivalent
    - » Can use simple vector of bits to handle allocation:
      `00110001110001101 … 110010`
    - » Each bit represents page of physical memory
      `1` ⇒ allocated, `0` ⇒ free
- Should pages be as big as our previous segments?
  - No: Can lead to lots of internal fragmentation
    - » Typically have small pages (1K-16K)
  - Consequently: need multiple pages/segment

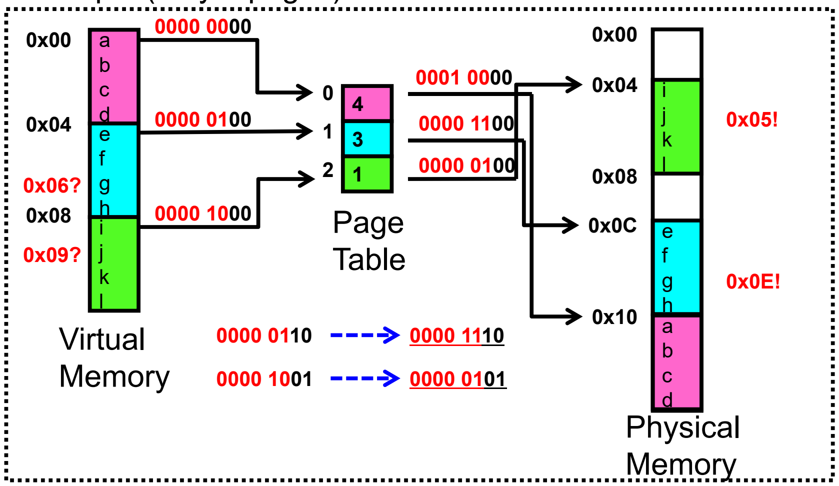
How to Implement Paging?



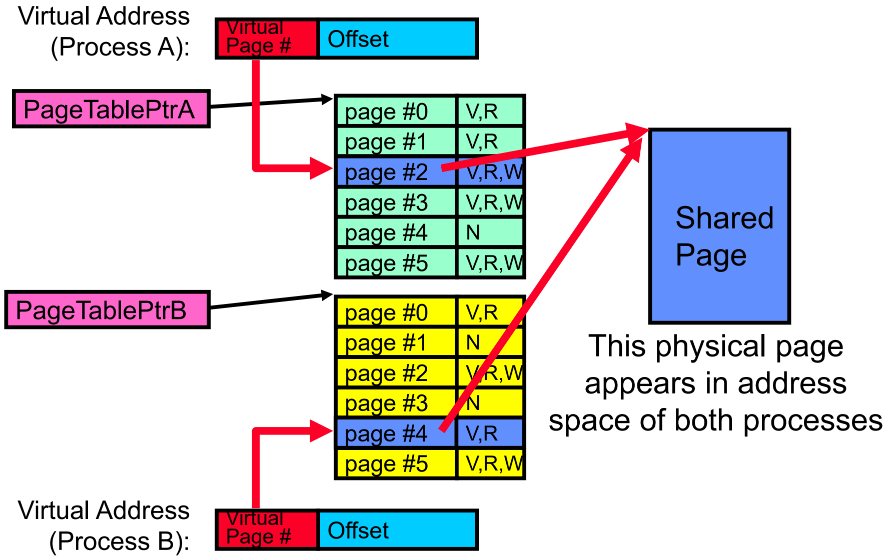
- Page Table (One per process)
  - Resides in physical memory
  - Contains physical page and permission for each virtual page
    - » Permissions include: Valid bits, Read, Write, etc
- Virtual address mapping
  - Offset from Virtual address copied to Physical Address
    - » Example: 10 bit offset ⇒ 1024-byte pages
  - Virtual page # is all remaining bits
    - » Example for 32-bits: 32-10 = 22 bits, i.e. 4 million entries
    - » Physical page # copied from table into physical address
  - Check Page Table bounds and permissions

Simple Page Table Example

Example (4 byte pages)

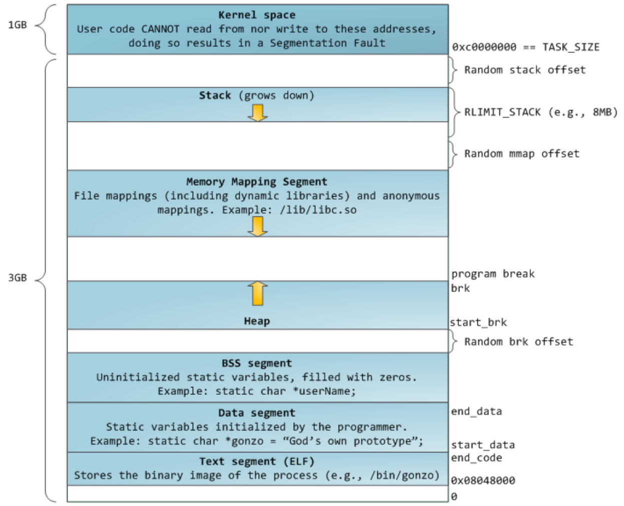


What about Sharing?



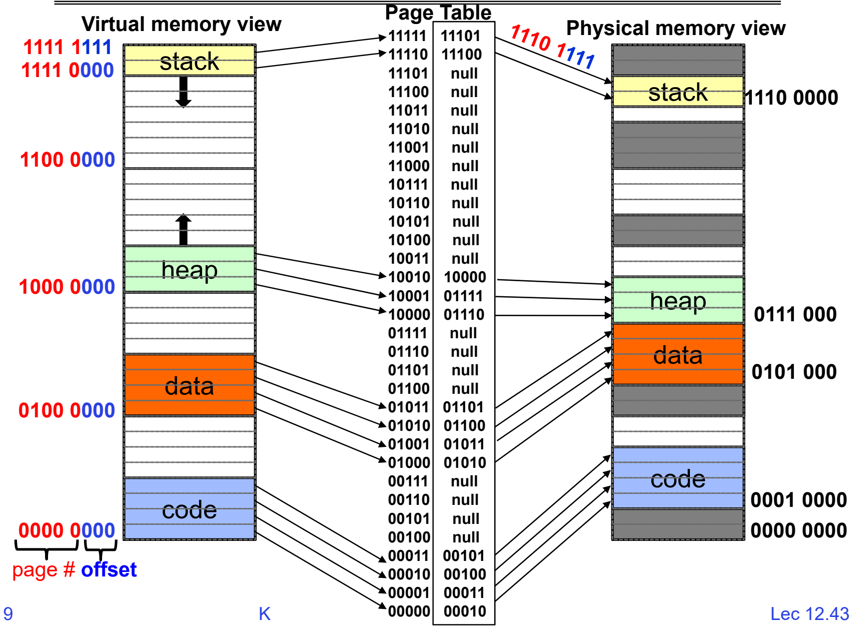
This physical page appears in address space of both processes

Example: Memory Layout for Linux 32-bit (Pre-Meltdown patch!)


1GB
Kernel space
User code CANNOT read from nor write to these addresses, doing so results in a Segmentation Fault
0xc0000000 == TASK_SIZE
Random stack offset
Stack (grows down)
RLIMIT_STACK (e.g., 8MB)
Random mmap offset
Memory Mapping Segment
File mappings (including dynamic libraries) and anonymous mappings. Example: /lib/libc.so
3GB
program break
brk
Heap
start_brk
Random brk offset
BSS segment
Uninitialized static variables, filled with zeros.
Example: static char *userName;
end_data
Data segment
Static variables initialized by the programmer.
Example: static char *gonzo = "God's own prototype";
start_data
end_code
Text segment (ELF)
Stores the binary image of the process (e.g., /bin/gonzo)
0x08048000
0

http://static.duartes.org/img/blogPosts/linuxFlexibleAddressSpaceLayout.png

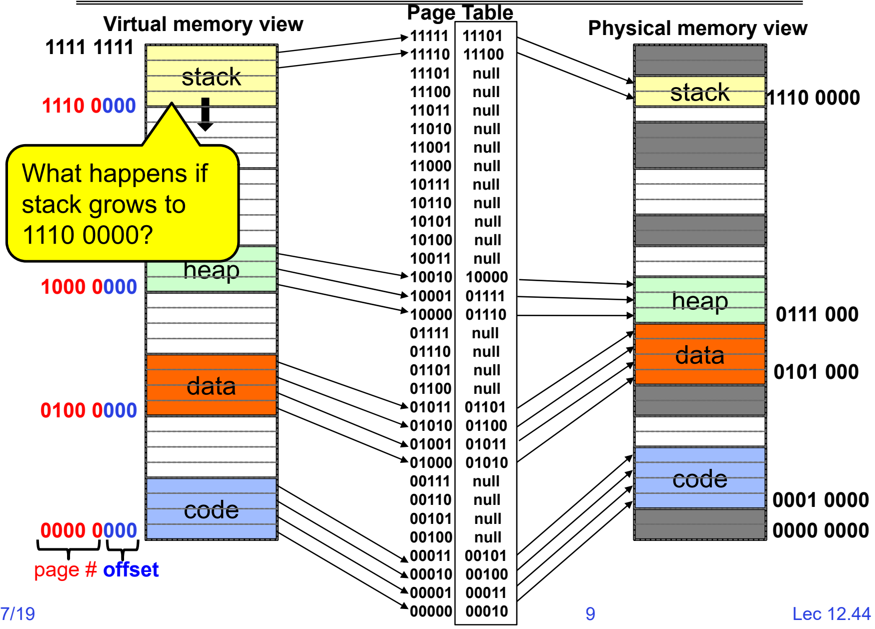
Summary: Paging



Page Table

11111	11101
11110	11100
11101	null
11100	null
11011	null
11010	null
11001	null
11000	null
10111	null
10110	null
10101	null
10100	null
10011	null
10010	10000
10001	01111
10000	01110
01111	null
01110	null
01101	null
01100	null
01011	01101
01010	01100
01001	01011
01000	01010
00111	null
00110	null
00101	null
00100	null
00011	00101
00010	00100
00001	00011
00000	00010

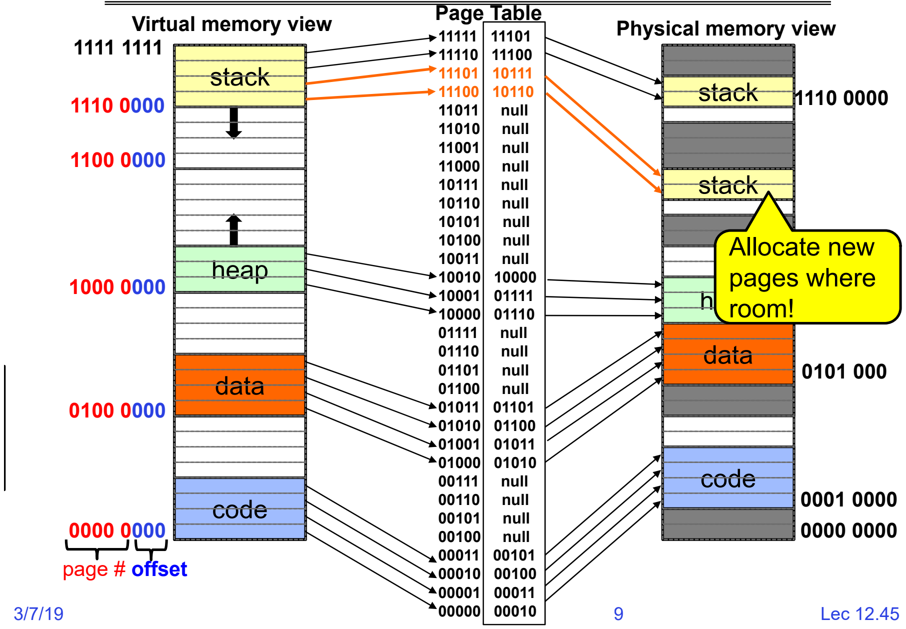
Summary: Paging



Page Table

11111	11101
11110	11100
11101	null
11100	null
11011	null
11010	null
11001	null
11000	null
10111	null
10110	null
10101	null
10100	null
10011	null
10010	10000
10001	01111
10000	01110
01111	null
01110	null
01101	null
01100	null
01011	01101
01010	01100
01001	01011
01000	01010
00111	null
00110	null
00101	null
00100	null
00011	00101
00010	00100
00001	00011
00000	00010

Summary: Paging

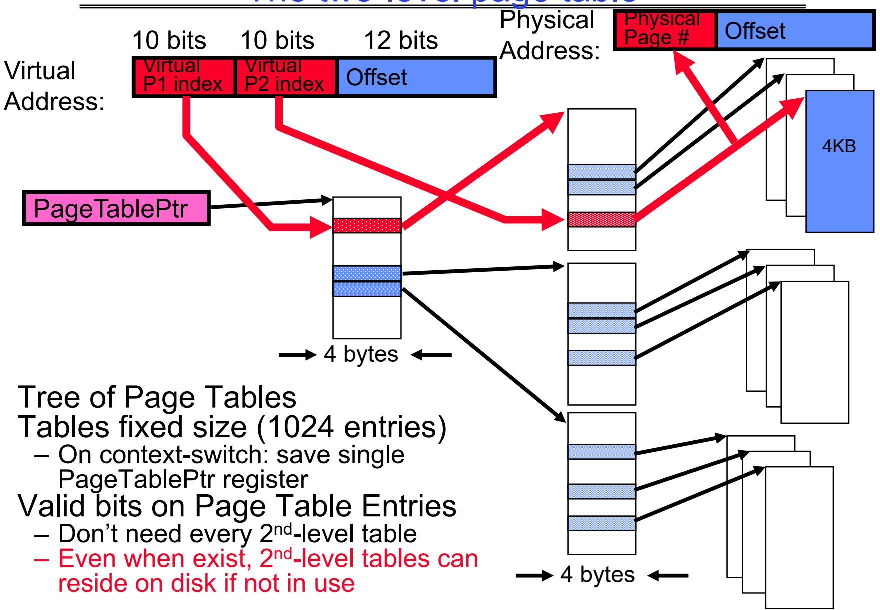


Page Table	
11111	11101
11110	11100
11101	10111
11100	10110
11011	null
11010	null
11001	null
11000	null
10111	null
10110	null
10101	null
10100	null
10011	null
10010	10000
10001	01111
10000	01110
01111	null
01110	null
01101	null
01100	null
01011	01101
01010	01100
01001	01011
01000	01010
00111	null
00110	null
00101	null
00100	null
00011	00101
00010	00100
00001	00011
00000	00010

Page Table Discussion

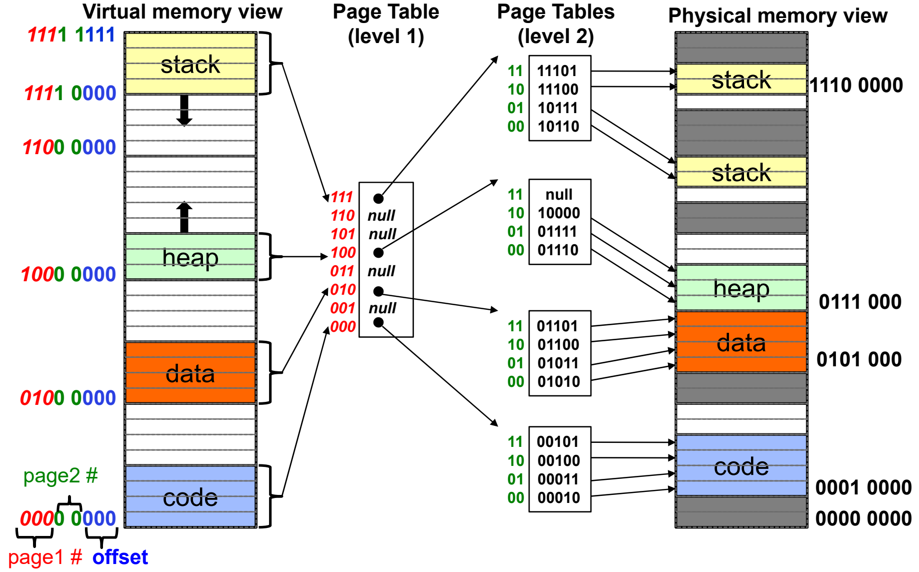
- What needs to be switched on a context switch?
  - Page table pointer and limit
- Analysis
  - Pros
    - » Simple memory allocation
    - » Easy to share
  - Con: What if address space is sparse?
    - » E.g., on UNIX, code starts at 0, stack starts at (2^{31}-1)
    - » With 1K pages, need 2 million page table entries!
  - Con: What if table really big?
    - » Not all pages used all the time ⇒ would be nice to have working set of page table in memory
- How about multi-level paging or combining paging and segmentation?

Fix for sparse address space: The two-level page table



- Tree of Page Tables
- Tables fixed size (1024 entries)
  - On context-switch: save single PageTablePtr register
- Valid bits on Page Table Entries
  - Don't need every 2nd-level table
  - Even when exist, 2nd-level tables can reside on disk if not in use

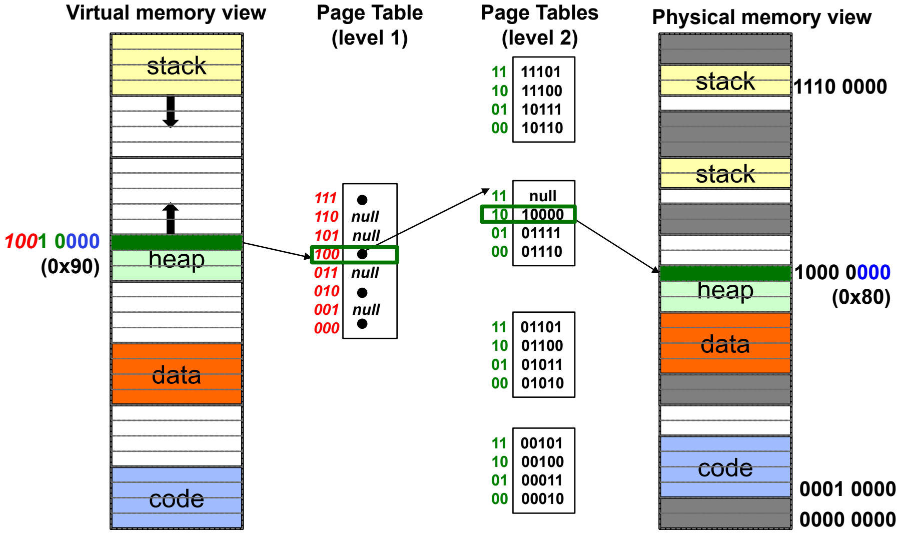
Summary: Two-Level Paging



Page Table (level 1)	
111	●
110	null
101	null
100	●
011	null
010	●
001	null
000	●

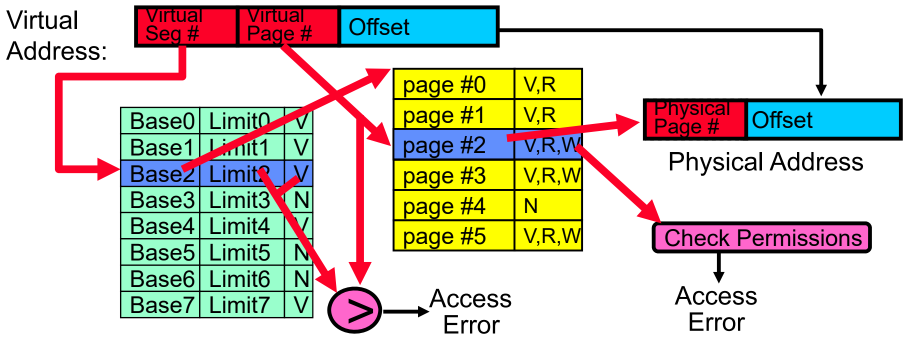
Page Tables (level 2)	
11	11101
10	11100
01	10111
00	10110
11	null
10	10000
01	01111
00	01110
11	01101
10	01100
01	01011
00	01010
11	00101
10	00100
01	00011
00	00010

Summary: Two-Level Paging



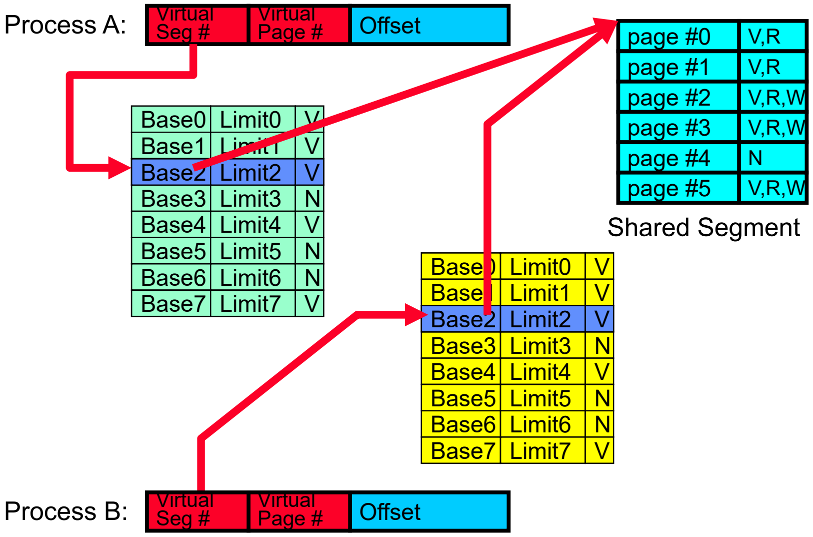
Multi-level Translation: Segments + Pages

- What about a tree of tables?
  - Lowest level page table ⇒ memory still allocated with bitmap
  - Higher levels often segmented
- Could have any number of levels. Example (top segment):



- What must be saved/restored on context switch?
  - Contents of top-level segment registers (for this example)
  - Pointer to top-level table (page table)

What about Sharing (Complete Segment)?



Multi-level Translation Analysis

- Pros:
  - Only need to allocate as many page table entries as we need for application
    - » In other wards, sparse address spaces are easy
  - Easy memory allocation
  - Easy Sharing
    - » Share at segment or page level (need additional reference counting)
- Cons:
  - One pointer per page (typically 4K – 16K pages today)
  - Page tables need to be contiguous
    - » However, previous example keeps tables to exactly one page in size
  - Two (or more, if >2 levels) lookups per reference
    - » Seems very expensive!

Summary

- Segment Mapping
  - Segment registers within processor
  - Segment ID associated with each access
    - » Often comes from portion of virtual address
    - » Can come from bits in instruction instead (x86)
  - Each segment contains base and limit information
    - » Offset (rest of address) adjusted by adding base
- Page Tables
  - Memory divided into fixed-sized chunks of memory
  - Virtual page number from virtual address mapped through page table to physical page number
  - Offset of virtual address same as physical address
  - Large page tables can be placed into virtual memory
- Multi-Level Tables
  - Virtual address mapped to series of tables
  - Permit sparse population of address space