# CS162
# Operating Systems and Systems Programming
# Lecture 14

## Memory 1: Virtual Memory, Segments and Page Tables

March 5th, 2024

Prof. John Kubiatowicz

http://cs162.eecs.Berkeley.edu

## Recall: Four requirements for occurrence of 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 $\{T_1, \ldots, T_n\}$ 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: Banker's Algorithm for Avoiding Deadlock

- Toward right idea:
  - State maximum (max) resource needs in advance
  - Allow particular thread to proceed if:
    (available resources - #requested) ≥ max remaining that might be needed by any thread
- Banker's algorithm (less conservative):
  - 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, substituting:

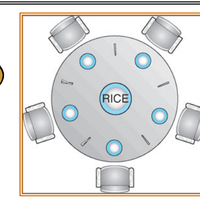
      $([Max_{node}]-[Alloc_{node}] <= [Avail])$ for $([Request_{node}] <= [Avail])$

  - Grant request if won't prevent some thread from allocating its maximum and finshing
- Keeps system in a "SAFE" state:
  - There exists a sequence $\{T_1, T_2, \ldots T_n\}$ with $T_1$ requesting all remaining resources, finishing, then $T_2$ requesting all remaining resources, etc..



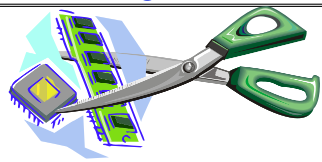
## Recall: Banker's Algorithm Example

- Banker's algorithm with dining lawyers
  - "Safe" (won't cause deadlock) if when try to grab chopstick either:
    - » Not last chopstick
    - » Is last chopstick but someone will have two afterwards




  - What if k-handed lawyers? Don't allow if:
    - » It's the last one, no one would have k
    - » It's 2nd to last, and no one would have k-1
    - » It's 3rd to last, and no one would have k-2
    - » …

# 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)



# 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
- 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
- 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)



# Alternative View: Interposing on Process Behavior

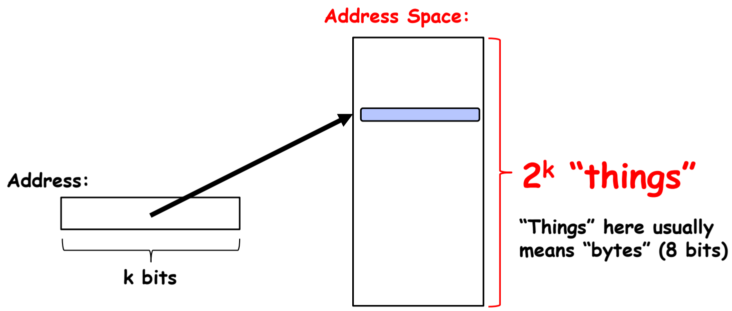
- OS interposes on process' I/O operations
  – How? All I/O happens via syscalls.
- OS interposes on process' CPU usage
  – How? Interrupt lets OS preempt current thread
- **Question: How can the OS interpose on process' memory accesses?**
  – Too slow for the OS to interpose *every* memory access
  – Translation: hardware support to accelerate the common case
  – Page fault: uncommon cases trap to the OS to handle



# Recall: Four Fundamental OS Concepts

- **Thread: Execution Context**
  – Fully describes program state
  – Program Counter, Registers, Execution Flags, Stack
- **Address space** (with or w/o **translation**)
  – Set of memory addresses accessible to program (for read or write)
  – May be distinct from memory space of the physical machine (in which case programs operate in a virtual address space)
- **Process: an instance of a running program**
  – Protected Address Space + One or more Threads
- **Dual mode operation / Protection**
  – Only the "system" has the ability to access certain resources
  – Combined with translation, isolates programs from each other and the OS from programs

## THE BASICS: Address/Address Space

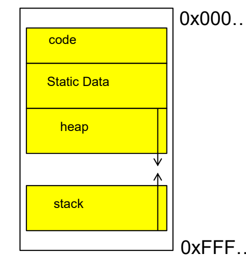



- What is $2^{10}$ bytes (where a byte is appreviated as "B")?
  - $2^{10}$ B = 1024B = 1 KB (for memory, 1K = 1024, *not* 1000)
- How many bits to address each byte of 4KB page?
  - 4KB = 4×1KB = 4× $2^{10}$= $2^{12}$ ⇒ 12 bits
- How much memory can be addressed with 20 bits? 32 bits? 64 bits?
  - Use $2^k$



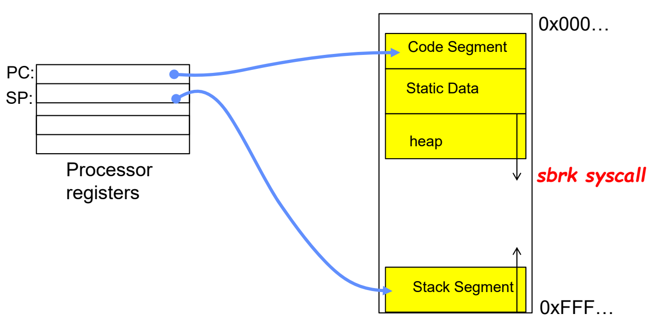
## Address Space, Process Virtual Address Space

- Definition: **Set of accessible addresses and the state associated with them**
  - $2^{32}$ = ~4 billion ***bytes*** on a 32-bit machine
- How many 32-bit numbers fit in this address space?
  - 32-bits = 4 bytes, so $2^{32}/4 = 2^{30}$=~1billion
- What happens when processor reads or writes to an address?
  - Perhaps acts like regular memory
  - Perhaps causes I/O operation
    - » (Memory-mapped I/O)
  - Causes program to abort (segfault)?
  - Communicate with another program
  - …





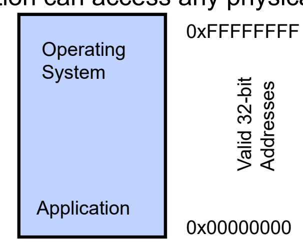

## Recall: Process Address Space: typical structure

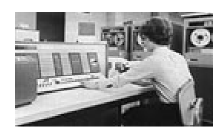





## Recall: Uniprogramming

- 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

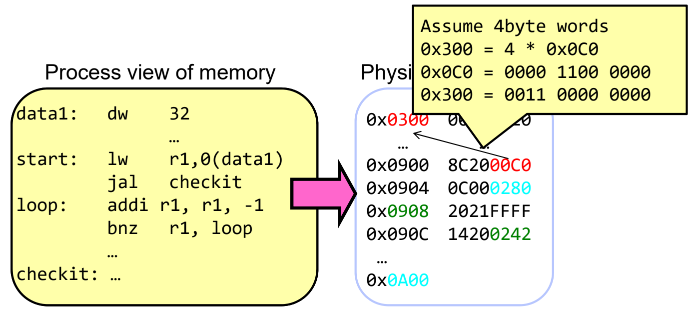
## Primitive Multiprogramming

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


  - 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



## Binding of Instructions and Data to Memory



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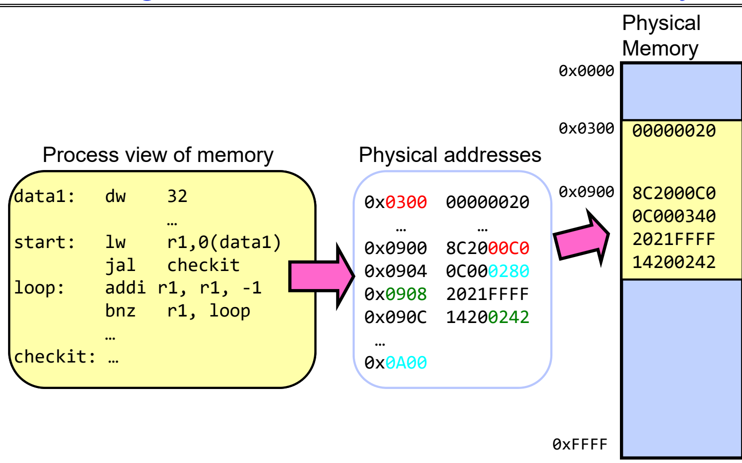
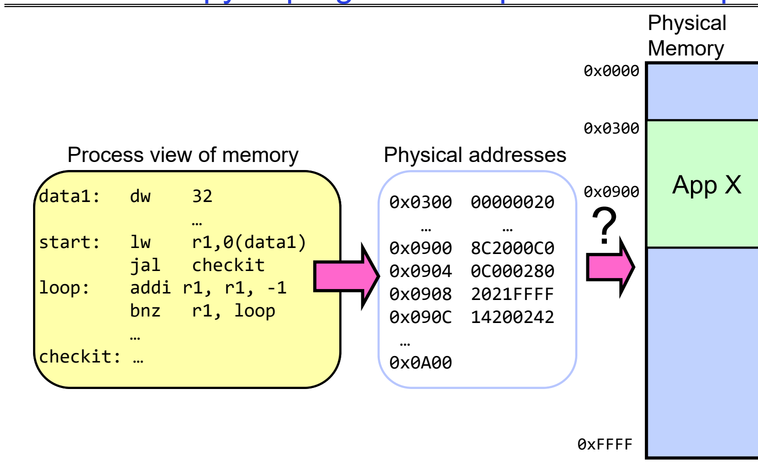


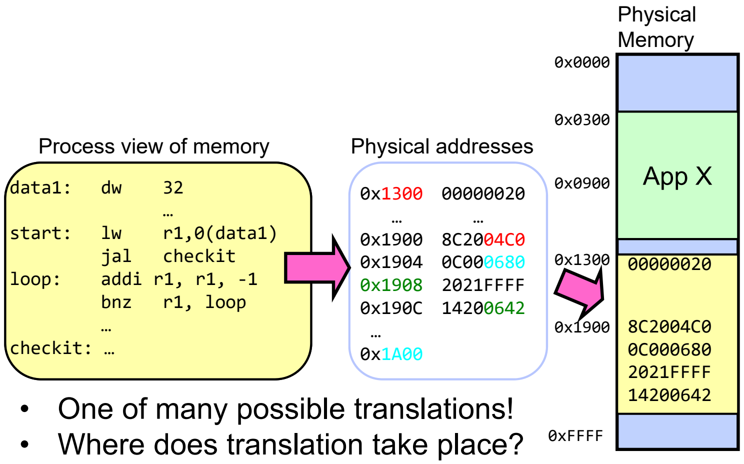



## Second copy of program from previous example




Need address translation!

## Second copy of program from previous example



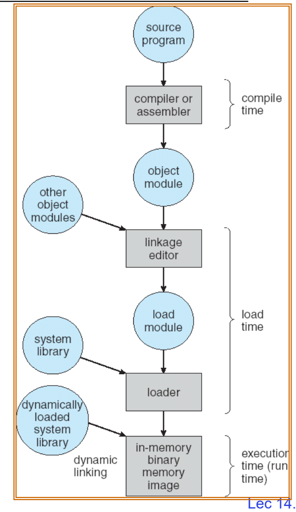

- One of many possible translations!
- Where does translation take place?

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



## From Program to Process

- 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






## Administrivia

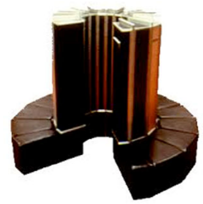
- Midterm 2: Thursday 3/14 from 8-10PM
  - A week from tomorrow!!!
  - All material up to Lecture 16 technically in bounds
  - Closed book: with two double-sided handwritten sheets of notes
- Homework 4 coming out
  - Released tomorrow, Wednesday 3/6
- Project 2 design document due this Friday!
- Starting next week – will have an opportunity to get extra credit participation points by attending lecture
  - Details to follow



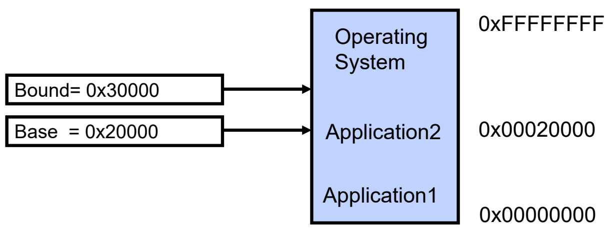
## Administrivia (Con’t)

- You need to know your units as CS/Engineering students!
- Units of Time: “s”: Second, “min”: 60s, “h”: 3600s, (of course)
  - Millisecond: 1ms ⇒ $10^{-3}$ s
  - Microsecond: 1µs ⇒ $10^{-6}$ s
  - Nanosecond: 1ns: ⇒ $10^{-9}$ s
  - Picosecond: 1ps ⇒ $10^{-12}$ s
- Integer Sizes: “b” ⇒ ”bit”, “B” ⇒ “byte” == 8 bits, “W”⇒”word”==? (depends. Could be 16b, 32b, 64b)
- Units of Space (memory), sometimes called the “binary system”
  - Kilo: 1KB ≡ 1KiB ⇒ 1024 bytes == $2^{10}$ bytes == 1024 ≈ $1.0\times10^3$
  - Mega: 1MB ≡ 1MiB ⇒ $(1024)^2$ bytes == $2^{20}$ bytes == 1,048,576 ≈ $1.0\times10^6$
  - Giga: 1GB ≡ 1GiB ⇒ $(1024)^3$ bytes == $2^{30}$ bytes == 1,073,741,824 ≈ $1.1\times10^9$
  - Tera: 1TB ≡ 1TiB ⇒ $(1024)^4$ bytes == $2^{40}$ bytes == 1,099,511,627,776 ≈ $1.1\times10^{12}$
  - Peta: 1PB ≡ 1PiB ⇒ $(1024)^5$ bytes == $2^{50}$ bytes == 1,125,899,906,842,624 ≈ $1.1 \times 10^{15}$
  - Exa: 1EB ≡ 1EiB ⇒ $(1024)^6$ bytes == $2^{60}$ bytes == 1,152,921,504,606,846,976 ≈ $1.2 \times 10^{18}$
- Units of Bandwidth, Space on disk/etc, Everything else…, sometimes called the “decimal system”
  - Kilo: 1KB/s ⇒ $10^3$ bytes/s, 1KB ⇒ $10^3$ bytes
  - Mega: 1MB/s ⇒ $10^6$ bytes/s, 1MB ⇒ $10^6$ bytes
  - Giga: 1GB/s ⇒ $10^9$ bytes/s, 1GB ⇒ $10^9$ bytes
  - Tera: 1TB/s ⇒ $10^{12}$ bytes/s, 1TB ⇒ $10^{12}$ bytes
  - Peta: 1PB/s ⇒ $10^{15}$ bytes/s, 1PB ⇒ $10^{15}$ bytes
  - Exa: 1EB/s ⇒ $10^{18}$ bytes/s, 1EB ⇒ $10^{18}$ bytes

# Multiprogramming with Protection



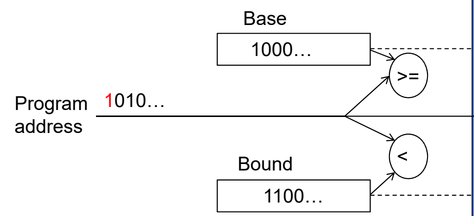
- Can we protect programs from each other without translation?
  – **Yes: Base and Bound!**
  – **Used by, e.g., Cray-1 supercomputer**

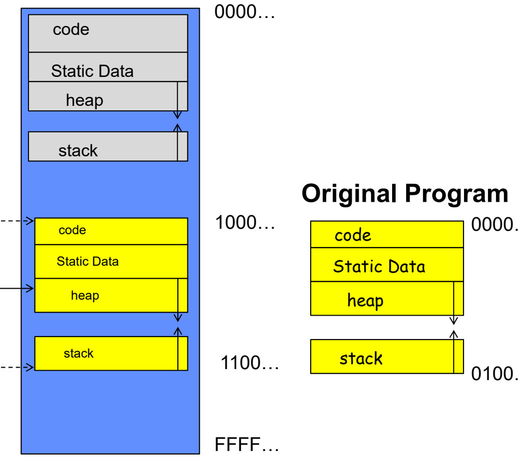





# Recall: Base and Bound (No Translation)

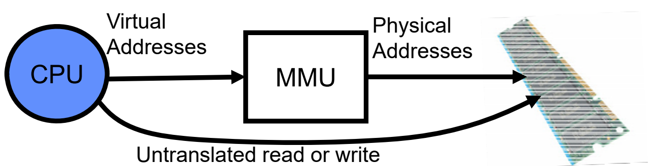
- Still protects OS and isolates program
- Requires relocating loader
- No addition on address path





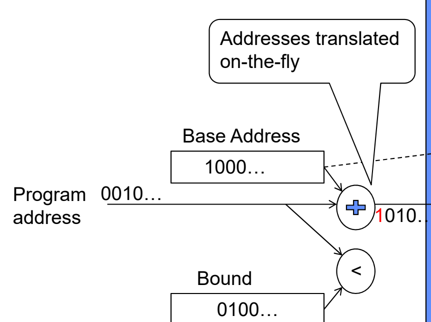

# Recall: General Address translation

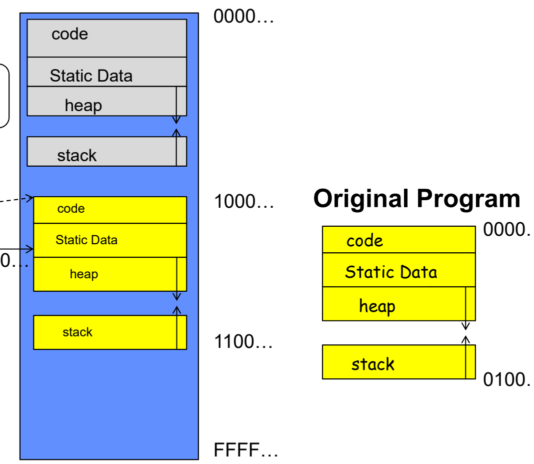



- Consequently, two views of memory:
  – View from the CPU (what program sees, virtual memory)
  – View from memory (physical memory)
  – Translation box (Memory Management Unit or MMU) converts between two views
- Translation ⇒ much easier to implement protection!
  – If task A cannot even gain access 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



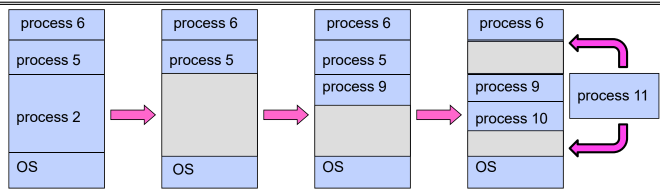
# Recall: Base and Bound (with Translation)




- Hardware relocation
- Can the program touch OS?
- Can it touch other programs?

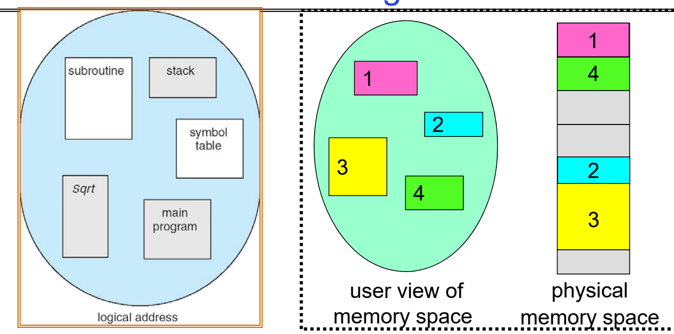
## Issues with Simple B&B Method




- Fragmentation problem over time
  - Not every process is same size ⇒ memory becomes fragmented over time
  - Fragmentation: wasted space both *external* (between blocks) and *internal* (inside blocks)
- 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



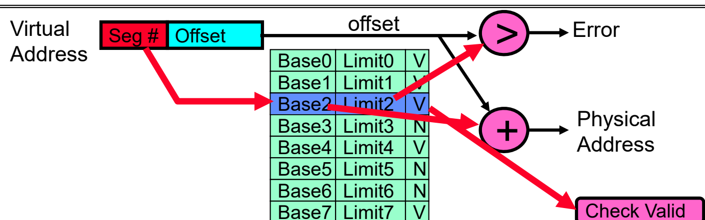
## More Flexible Segmentation




- 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

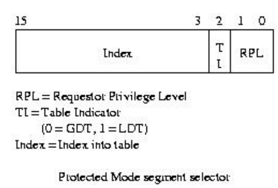



Access Error

- 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

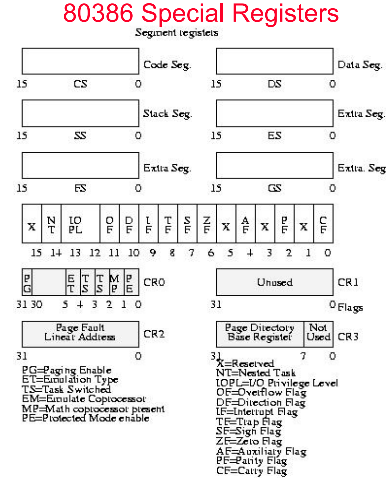


## Intel x86 Special Registers





80386 Special Registers

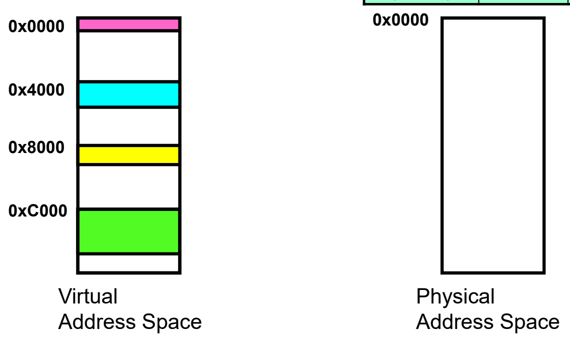



- Typical Segment Register
  - Current Priority is RPL of Code Segment (CS)
- Segmentation can't be just "turned off"
  - What if we just want to use paging?
  - Set base and bound to all of memory, in all segments

# 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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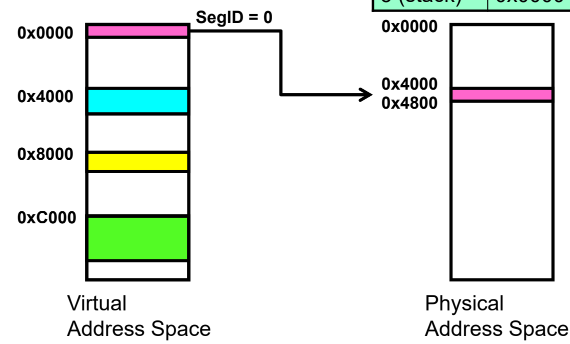




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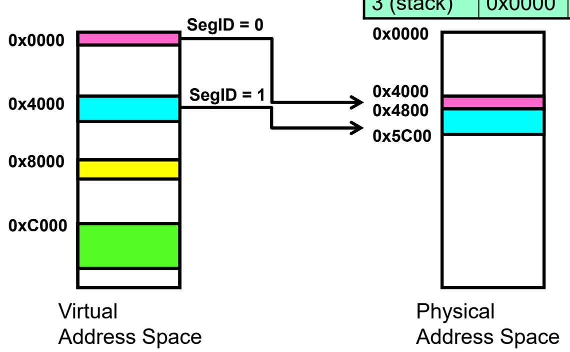




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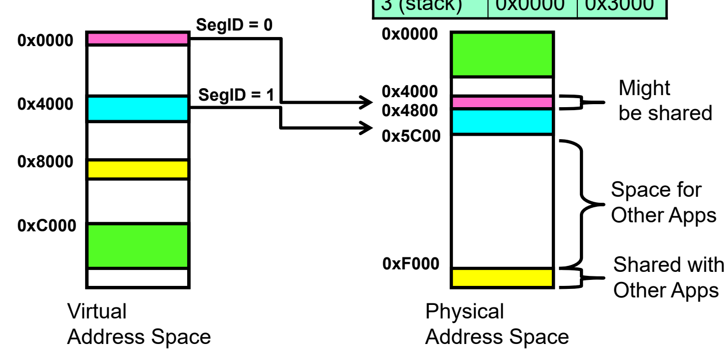

## Example of Segment Translation (16bit address)

```
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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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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2. Fetch 0x0244. Translated to Physical=0x4244. Get "jal strlen"
   Move 0x0248 → $ra (return address!), Move 0x0360 → PC



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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



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0x0368           beq  $r0,$t0, done
  …                …
0x4050  varx     dw   0x314159
```

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

Let's simulate a bit of this code to see what happens (PC=0x0240):

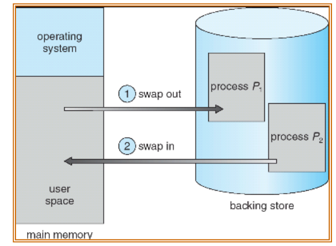
1. Fetch 0x0240 (0000 0010 0100 0000). Virtual segment #? 0; Offset? 0x240
   Physical address? Base=0x4000, so physical addr=0x4240
   Fetch instruction at 0x4240. Get "la $a0, varx"
   Move 0x4050 → $a0, Move PC+4→PC
2. Fetch 0x0244. Translated to Physical=0x4244. Get "jal strlen"
   Move 0x0248 → $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

- Translation on every instruction fetch, load or store
- Virtual address space has holes
  – Segmentation efficient for sparse address spaces
- When it is OK to address outside valid range?
  – This is how the stack (and heap?) 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)
- 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 in memory?




- Extreme form of Context Switch: Swapping
  – 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

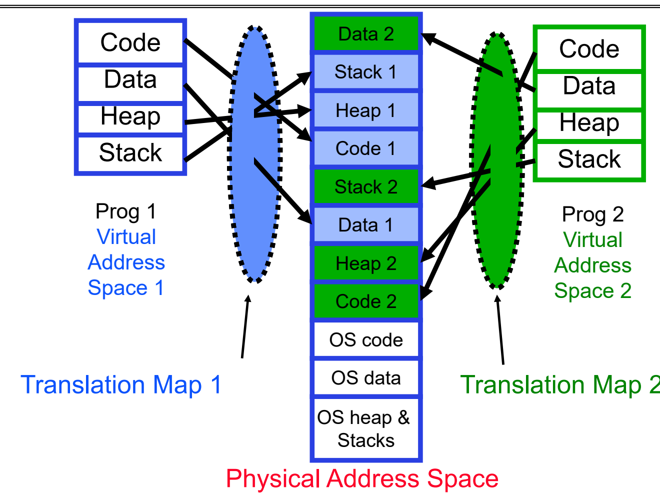


## Problems with Segmentation

- 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

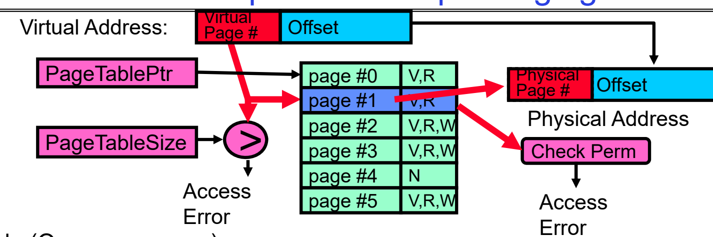


## Paging: Physical Memory in Fixed Size Chunks

- 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 Simple Paging?

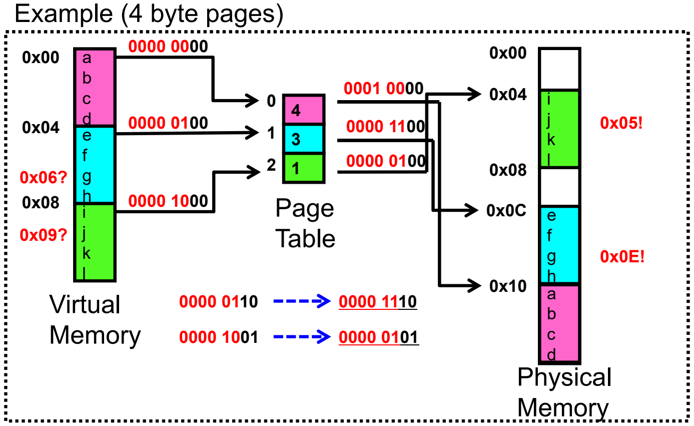



- Page Table (One per process)
  - Resides in physical memory
  - Contains physical page and permission for each virtual page (e.g. Valid bits, Read, Write, etc)
- Virtual address mapping
  - Offset from Virtual address copied to Physical Address
    - » Example: 10 bit offset ⇒ 1024-byte pages
  - Virtual 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



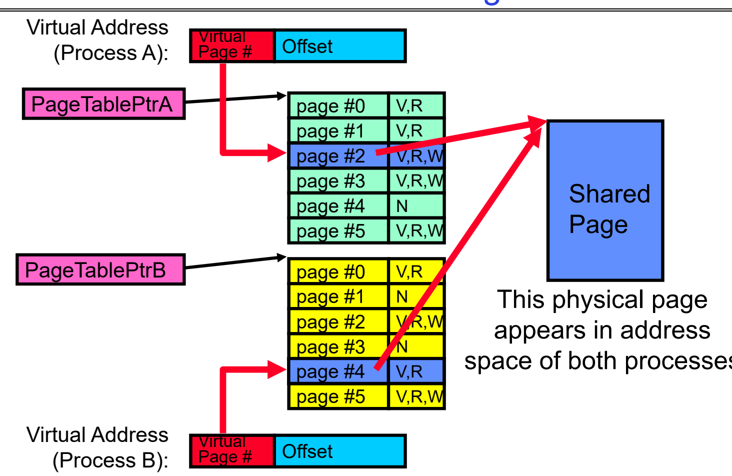
## Simple Page Table Example

Example (4 byte pages)






## What about Sharing?

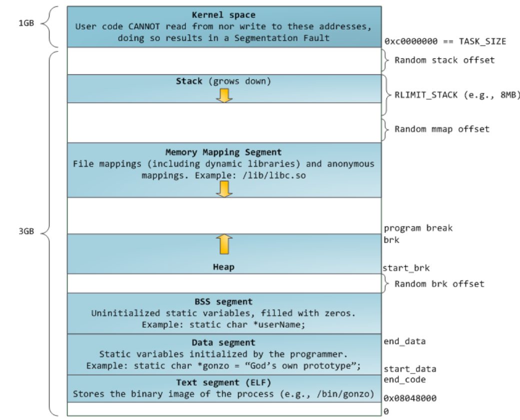


# Where is page sharing used ?

- The "kernel region" of every process has the same page table entries
  - The process cannot access it at user level
  - But on U->K switch, kernel code can access it AS WELL AS the region for THIS user
    - » What does the kernel need to do to access other user processes?
- Different processes running same binary!
  - Execute-only, but do not need to duplicate code segments
- User-level system libraries (execute only)
- Shared-memory segments between different processes
  - Can actually share objects directly between processes
    - » Must map page into same place in address space!
  - This is a limited form of the sharing that threads have within a single process



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

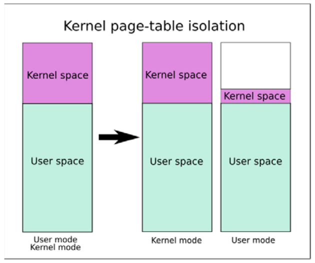



http://static.duartes.org/img/blogPosts/linuxFlexibleAddressSpaceLayout.png



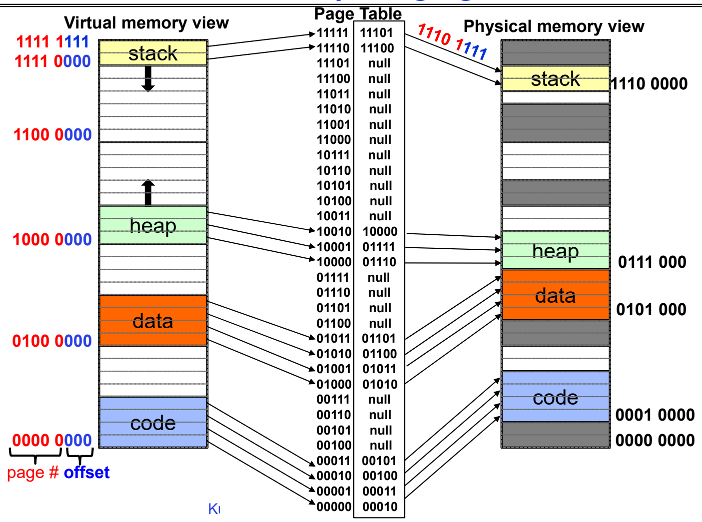
# Some simple security measures

- Address Space Randomization
  - Position-Independent Code ⇒ can place user code anywhere in address space
    - » Random start address makes much harder for attacker to cause jump to code that it seeks to take over
  - Stack & Heap can start anywhere, so randomize placement
- Kernel address space isolation
  - Don't map whole kernel space into each process, switch to kernel page table
  - Meltdown⇒map none of kernel into user mode!

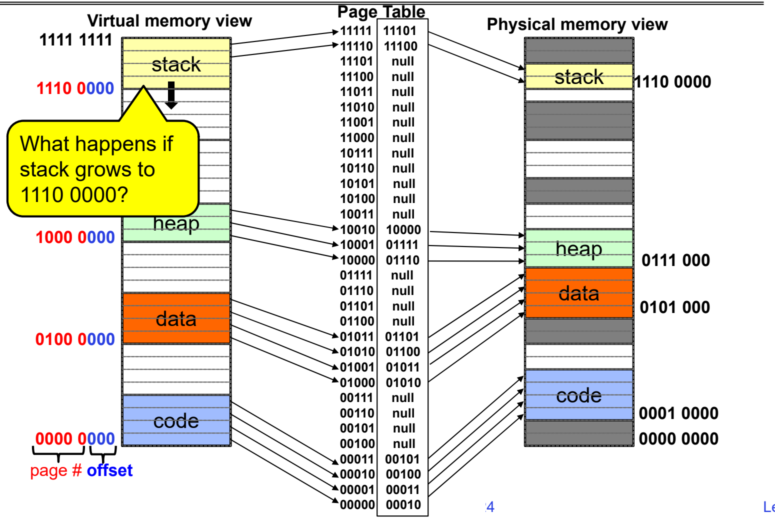





# Summary: Paging

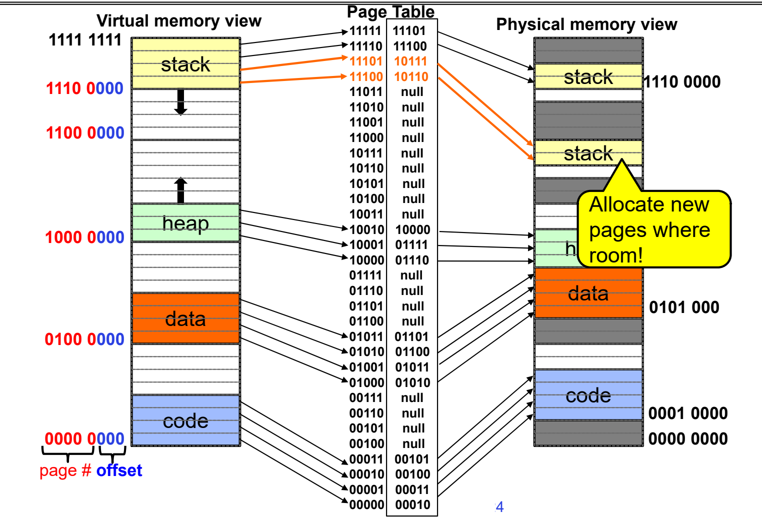


# Summary: Paging






# Summary: Paging






# Conclusion

- 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
- Next Time: Multi-Level Tables
  - Virtual address mapped to series of tables
  - Permit sparse population of address space