CS162
Operating Systems and Systems Programming
Lecture 13

Memory 1: Address Translation and Virtual Memory

March 4th, 2021

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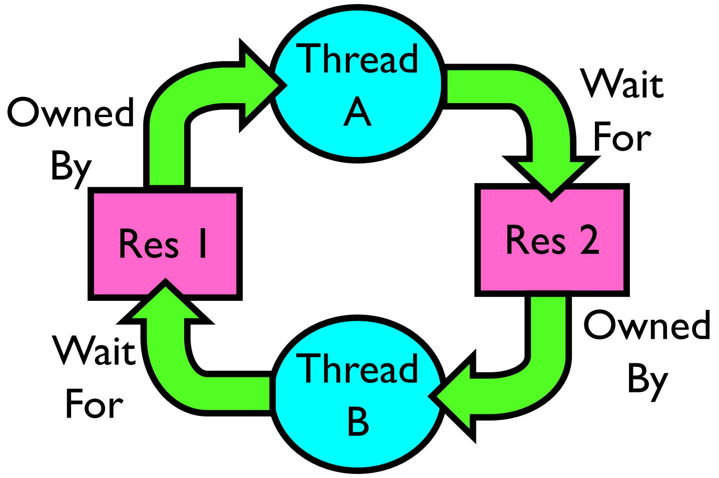
Recall: Deadlock is A Deadly type of Starvation

- 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 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

- Banker's algorithm assumptions:
  - Every thread pre-specifies is *maximum* need for resources
    - » However, it doesn't have to ask for the all at once… (key advantage)
  - Threads may now request and hold dynamically up to the maximum specified number of each resources
- Simple use of the deadlock detection algorithm
  - For each request for resources from a thread:
    - » 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 $\{T_1, T_2, \ldots T_n\}$ with T_1 requesting all remaining resources, finishing, then T_2 requesting all remaining resources, etc..
- Banker's algorithm prevents deadlocks involving threads and resources by stalling requests that would lead to deadlock
  - Can't fix all issues – e.g., thread going into an infinite loop!

Revisit: Deadlock Avoidance using Banker's Algorithm

- Idea: When a thread requests a resource, OS checks if it would result in ~~deadlock~~ an unsafe state
  - If not, it grants the resource right away
  - If so, it waits for other threads to release resources
- Example:

Thread A:

```
x.Acquire();
y.Acquire();
…
y.Release();
x.Release();
```

Thread B:

```
y.Acquire();
x.Acquire();
…
x.Release();
y.Release();
```

Thread B Waits until Thread A releases resources…

- At point that Thread B attempts `y.Acquire()`:
  - Banker's algorithm: Pretend to give y mutex to B
  - Try to run deadlock detection algorithm
    - » Neither A nor B can get enough resources to complete
  - Stall B by putting it to sleep.

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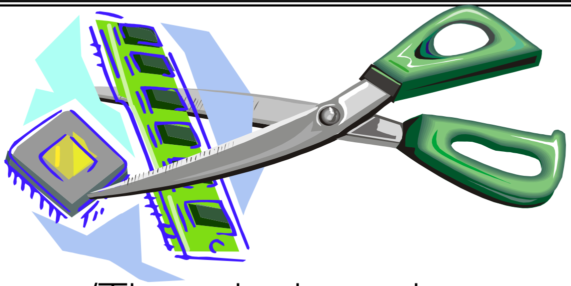
Virtualizing Resources

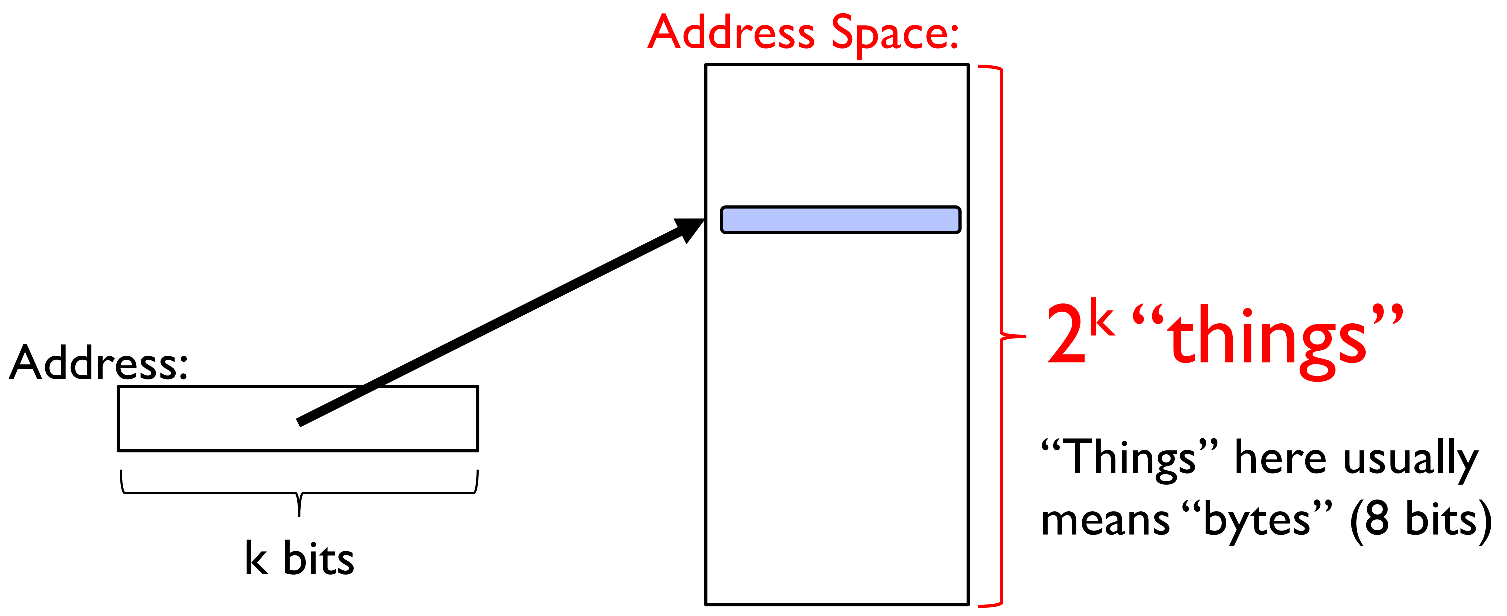


- Physical Reality: Different Processes/Threads share the same hardware
  - Need to multiplex CPU (Just finished: scheduling)
  - Need to multiplex use of Memory (starting today)
  - Need to multiplex disk and devices (later in term)
- Why worry about memory sharing?
  - The complete working state of 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: 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

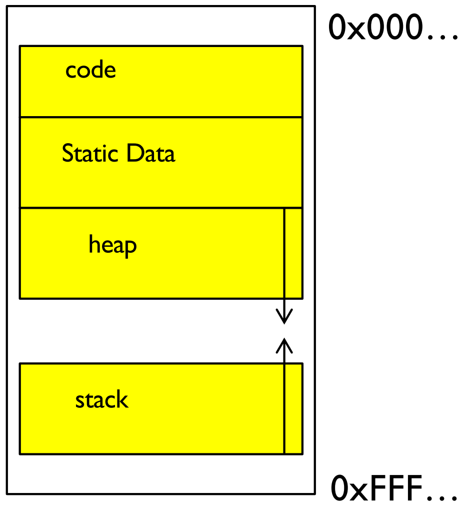
THE BASICS: Address/Address Space



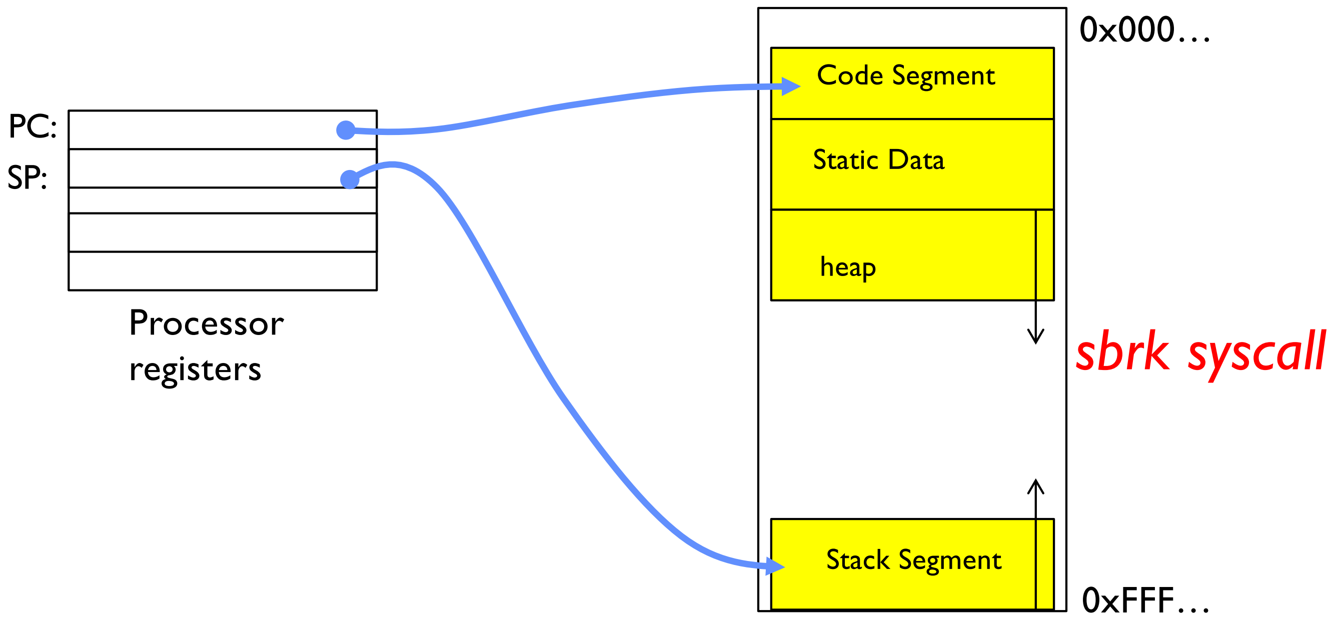
- What is 2^{10} bytes (where a byte is appreviated as "B")?
  - 2^{10} B = 1024B = 1 KB (for memory, 1K = 1024, *not* 1000)
- How many bits to address each byte of 4KB page?
  - 4KB = 4× 1KB = 4× 2^{10}= 2^{12} $\Rightarrow$ 12 bits
- How much memory can be addressed with 20 bits? 32 bits? 64 bits?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

Address Space, Process Virtual Address Space

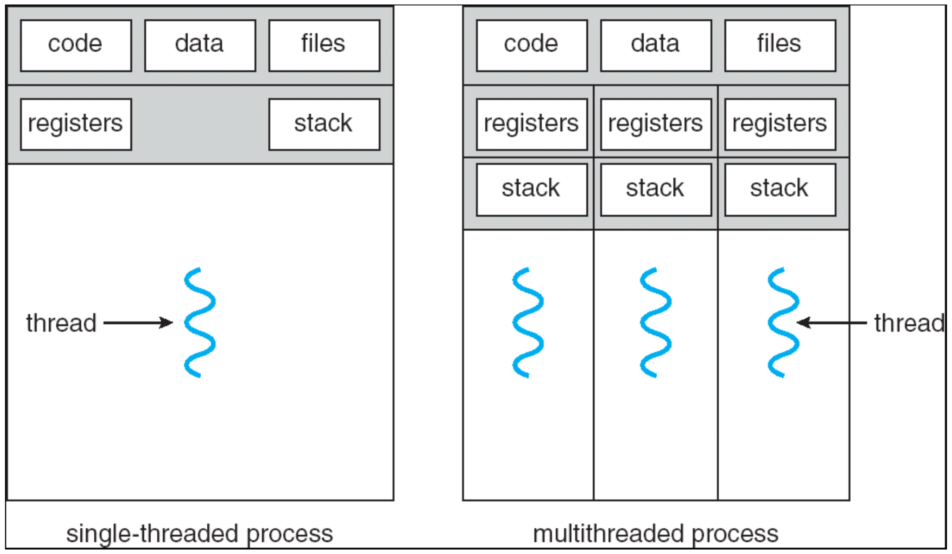
- Definition: **Set of accessible addresses and the state associated with them**
  - 2^{32} = ~4 billion ***bytes*** on a 32-bit machine
- How many 32-bit numbers fit in this address space?
  - 32-bits = 4 bytes, so $2^{32}/4 = 2^{30}$=~1billion
- What happens when processor reads or writes to an address?
  - 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: Single and Multithreaded Processes



- Threads encapsulate concurrency
  - "Active" component
- Address space encapsulate protection:
  - "Passive" component
  - Keeps bugs from crashing the entire system
- Why have multiple threads per address space?

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

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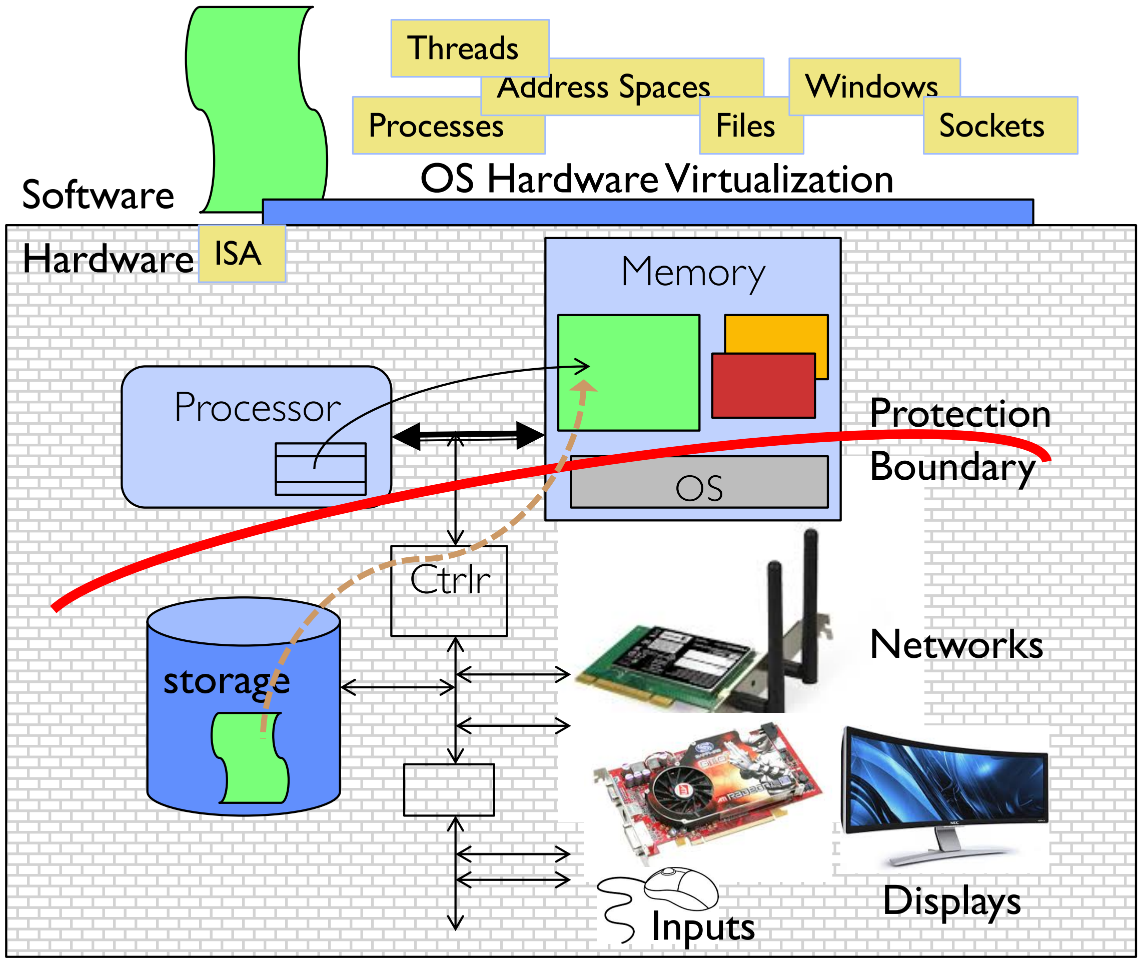
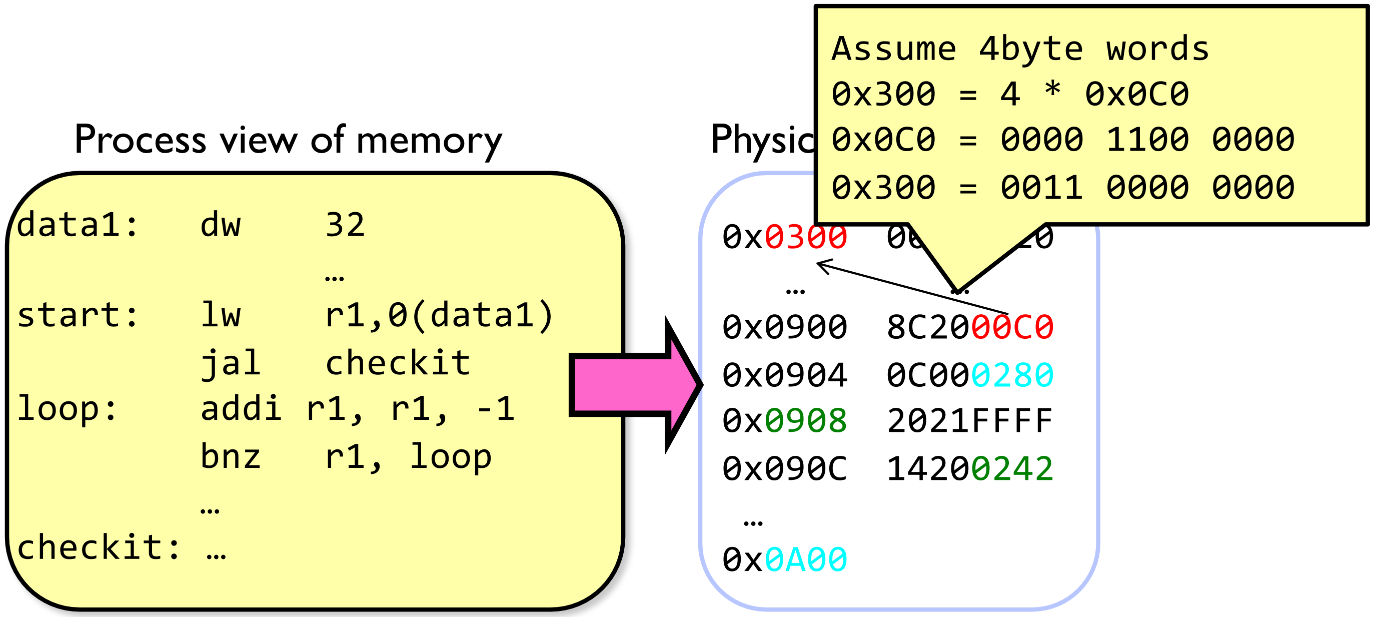
Recall: Loading



Binding of Instructions and Data to Memory



Process view of memory

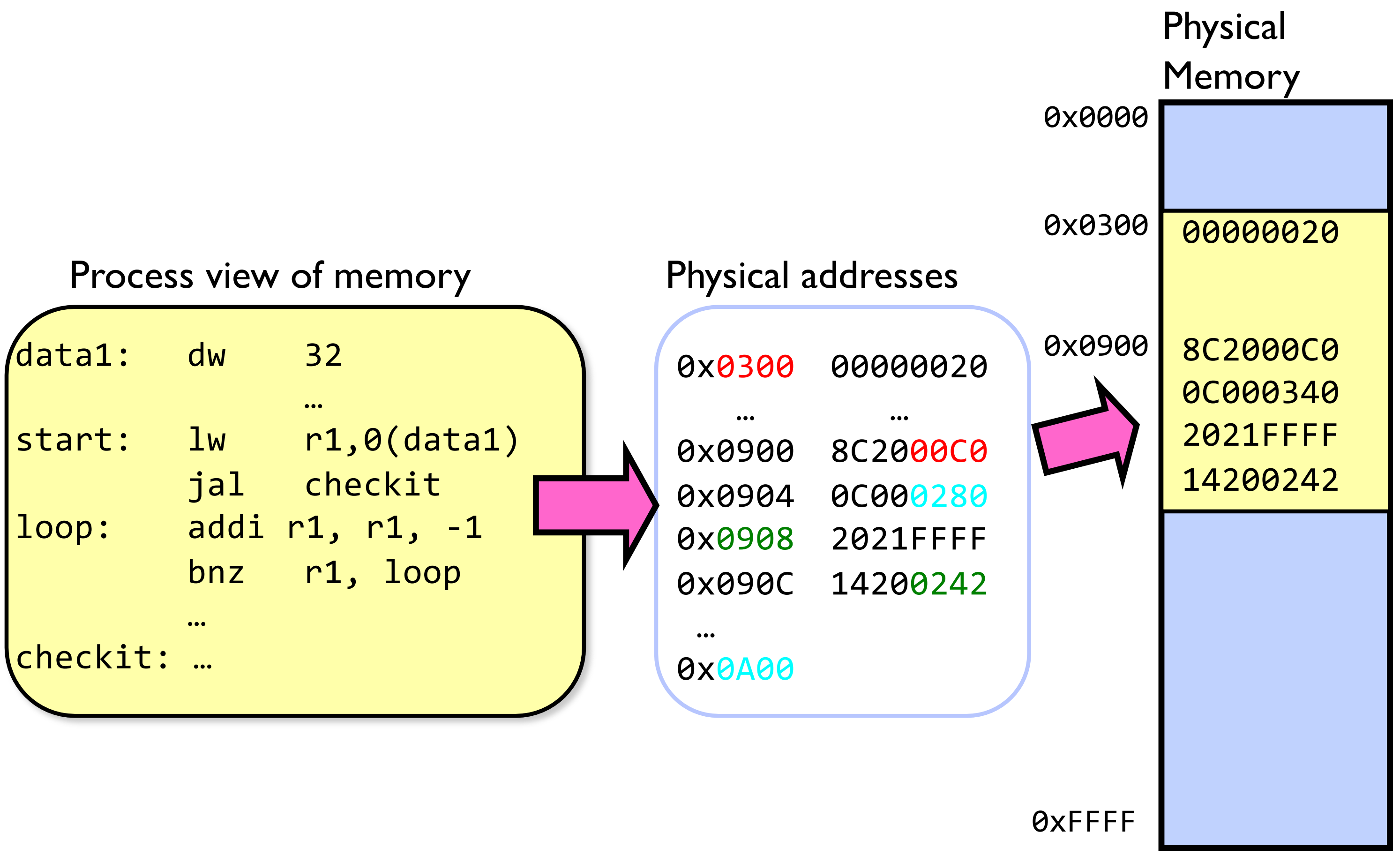
```
data1:   dw    32
               …
start:   lw    r1,0(data1)
         jal   checkit
loop:    addi r1, r1, -1
         bnz   r1, loop
         …
checkit: …
```

Physic

```
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



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```

Second copy of program from previous example

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```

Physical addresses

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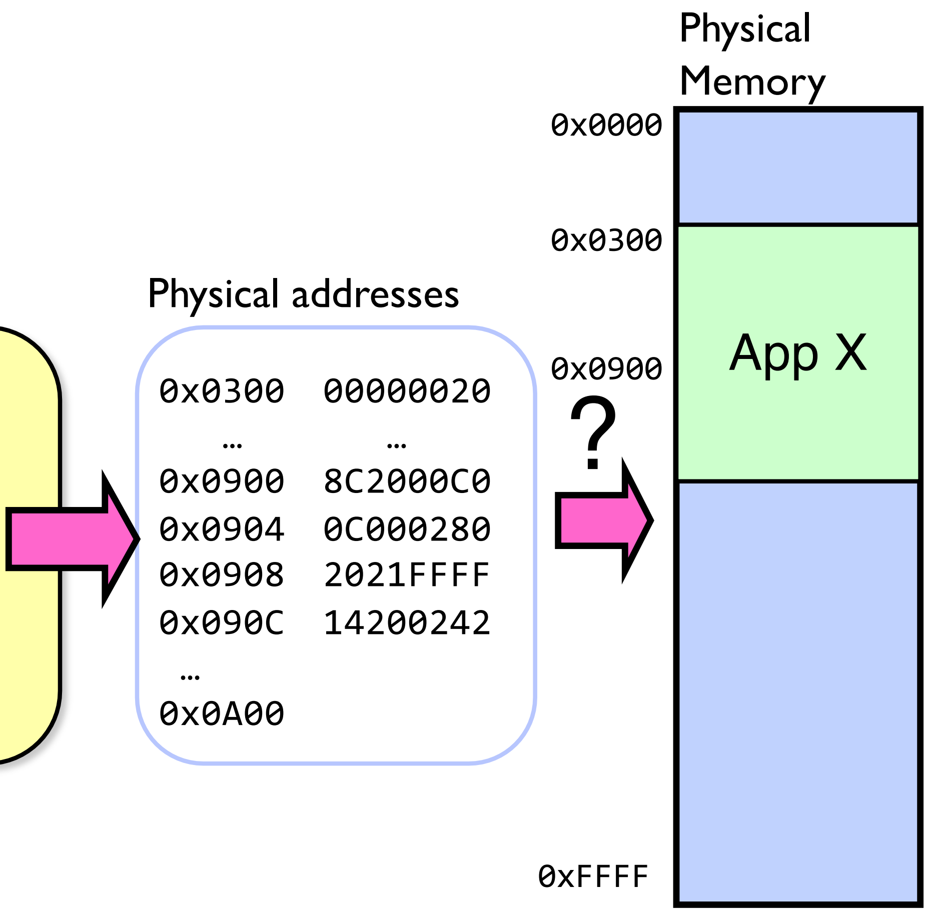
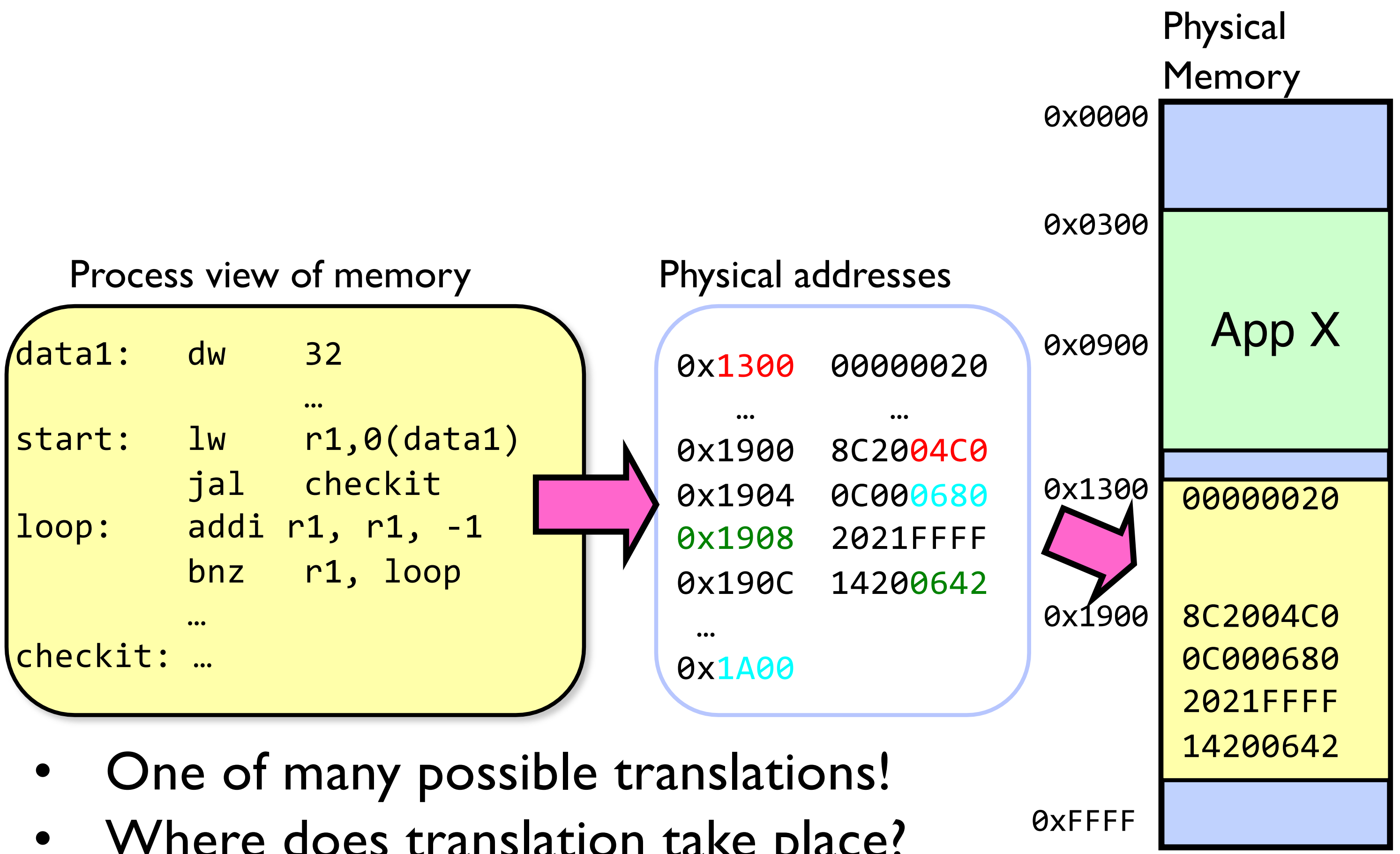


Need address translation!

Second copy of program from previous example



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         jal   checkit
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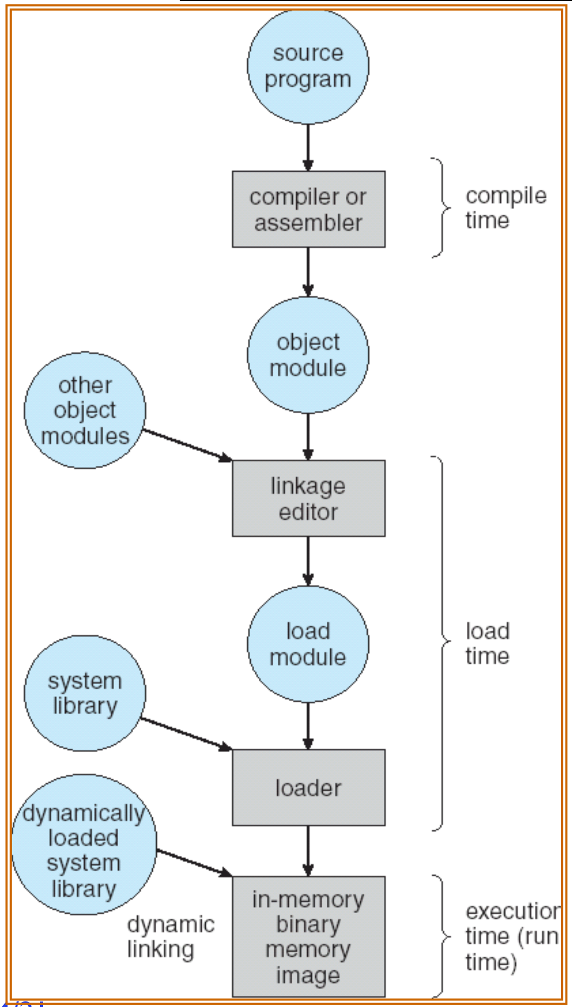
         bnz   r1, loop
         …
checkit: …
```

```
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?

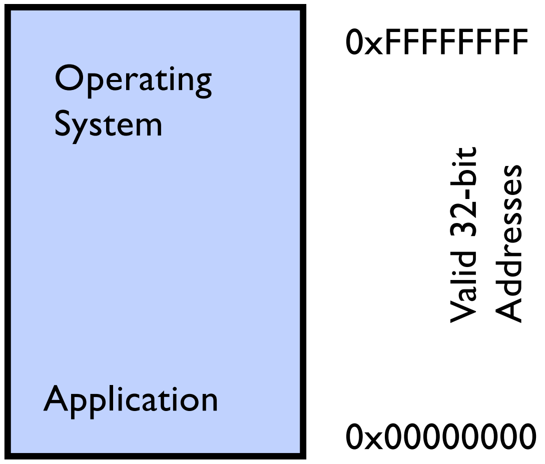
From Program to Process



- 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

Recall: Uniprogramming

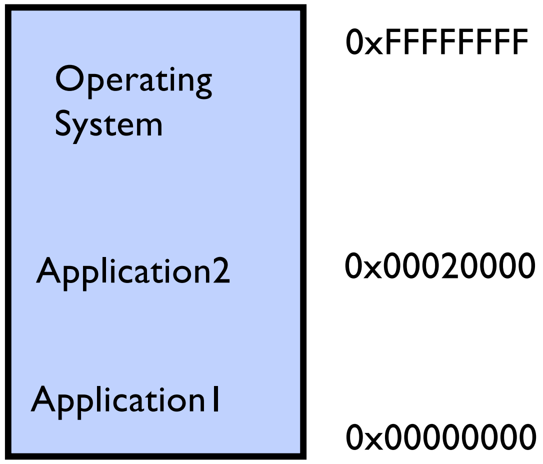
- Uniprogramming (no Translation or Protection)
  - Application always runs at same place in physical memory since only one application at a time
  - Application can access any physical address

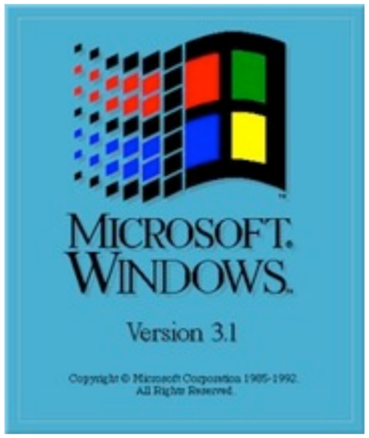


  - Application given illusion of dedicated machine by giving it reality of a dedicated machine

Primitive Multiprogramming

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

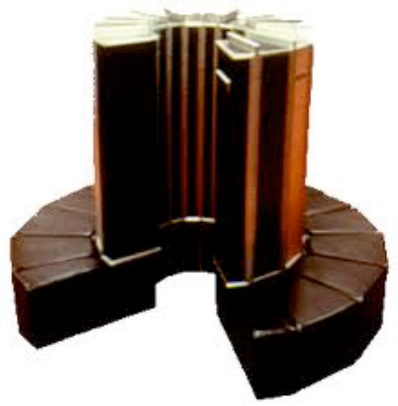


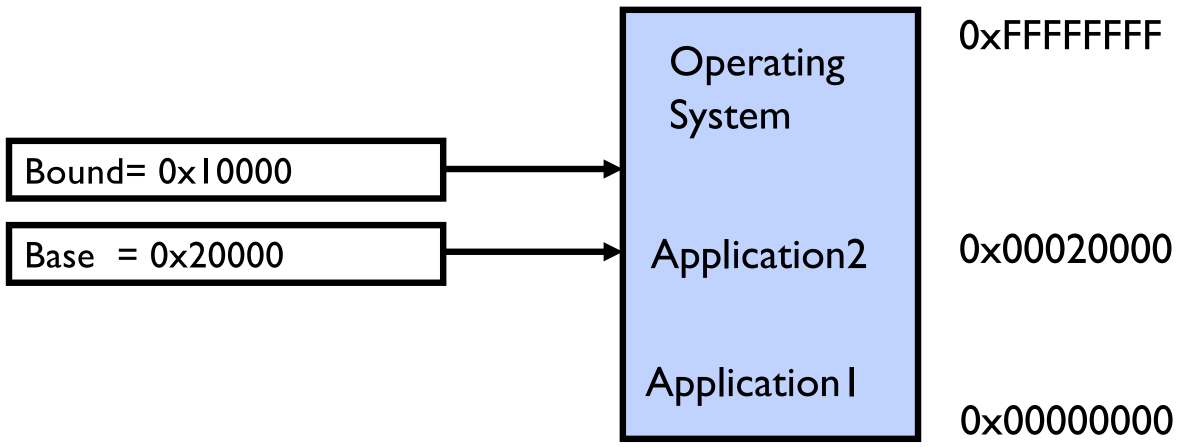


  - Use Loader/Linker: Adjust addresses while program loaded into memory (loads, stores, jumps)
    - » Everything adjusted to memory location of program
    - » Translation done by a linker-loader (relocation)
    - » Common in early days (… till Windows 3.x, 95?)
- With this solution, no protection: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

Multiprogramming with Protection

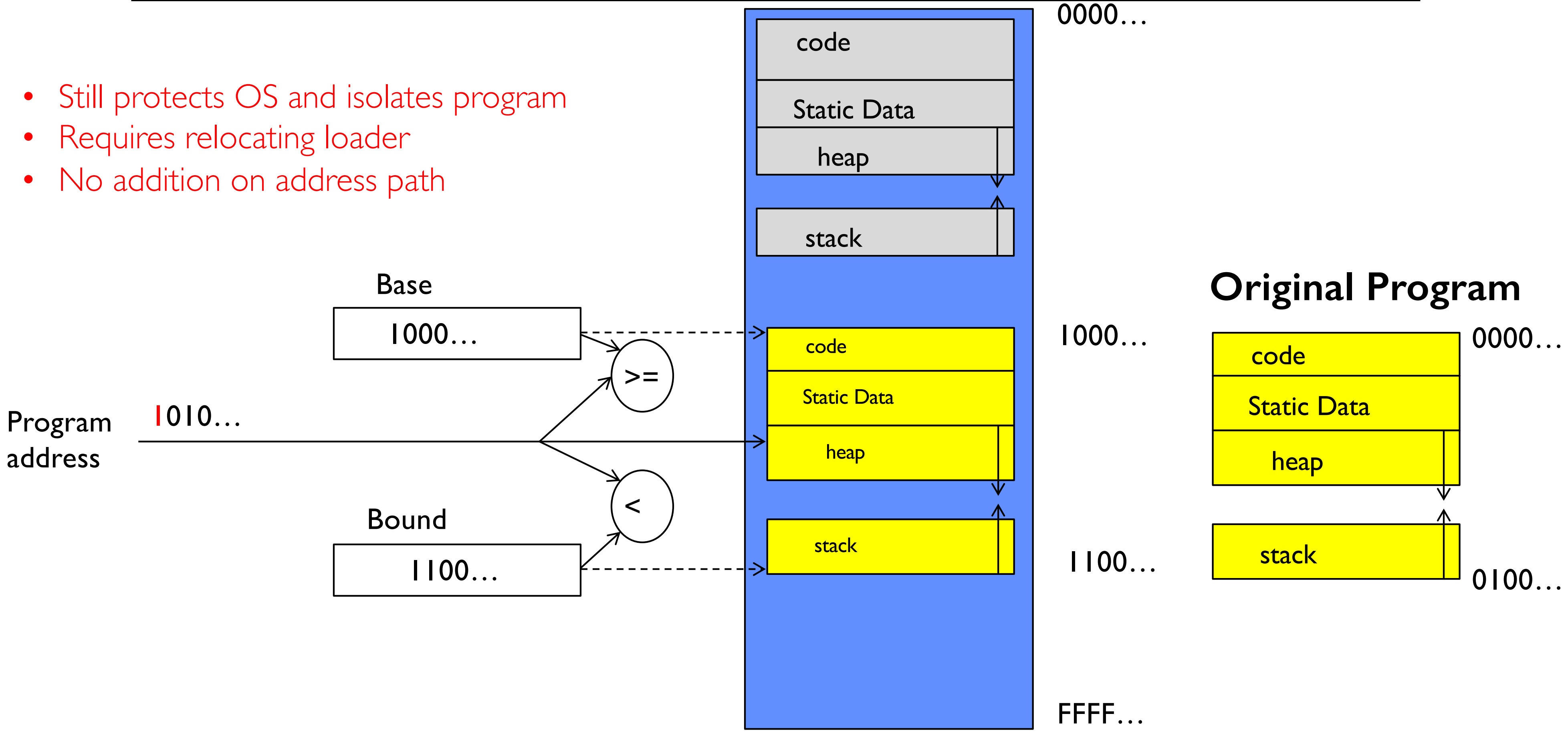
- Can we protect programs from each other without translation?
  - Yes: Base and Bound!
  - Used by, e.g., Cray-1 supercomputer



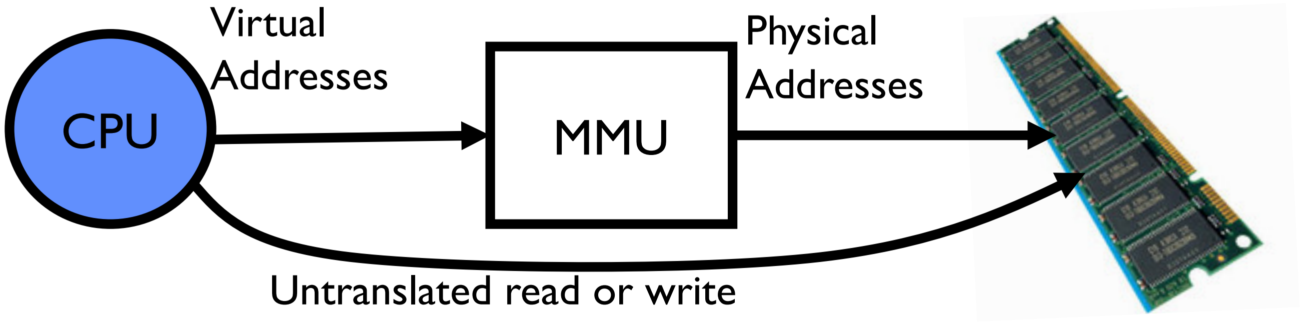


Recall: Base and Bound (No Translation)

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

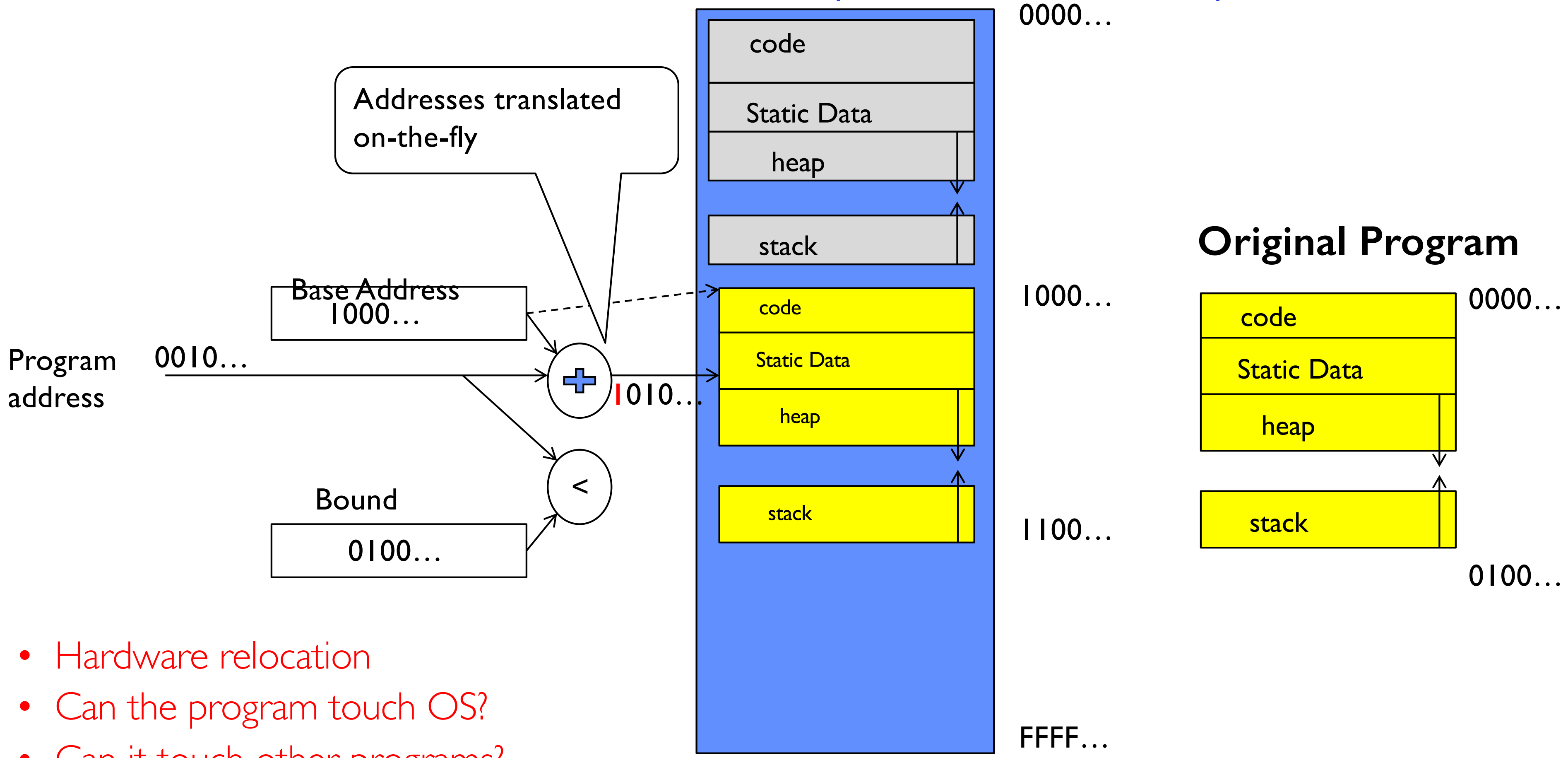


Recall: General Address translation



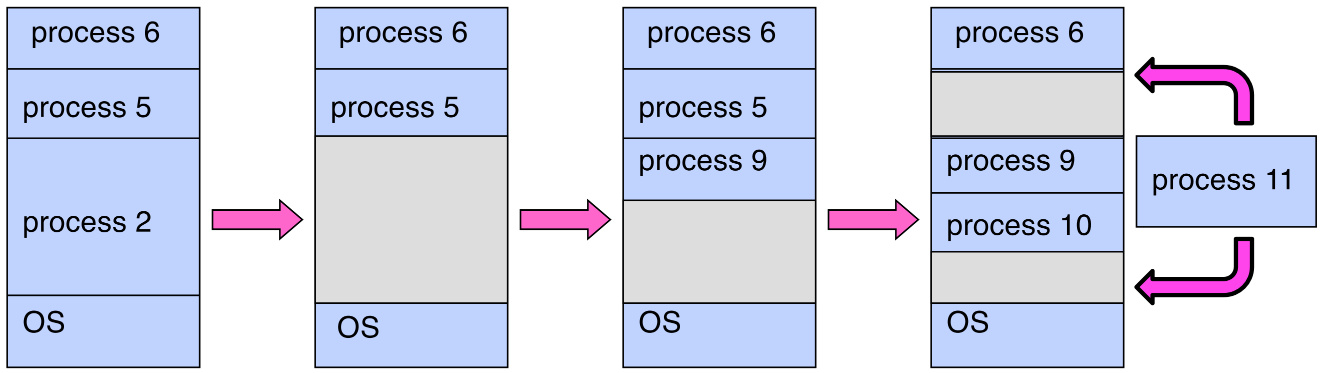
- Consequently, two views of memory:
  - View from the CPU (what program sees, virtual memory)
  - View from memory (physical memory)
  - Translation box (Memory Management Unit or MMU) converts between the two views
- Translation ⇒ much easier to implement protection!
  - If task A cannot even gain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



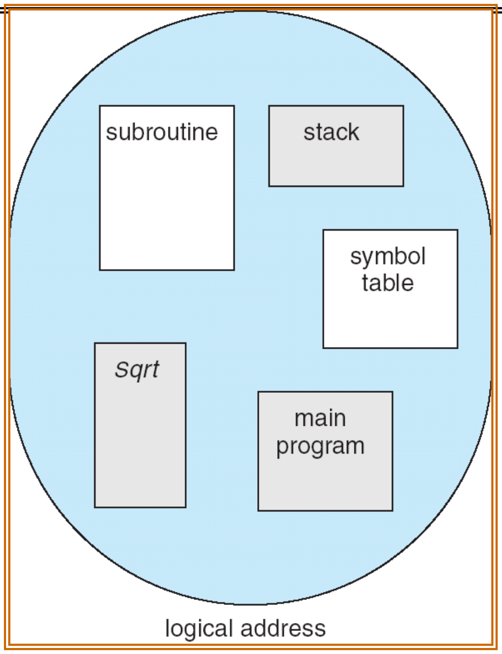
- Hardware relocation
- Can the program touch OS?
- Can it touch other programs?

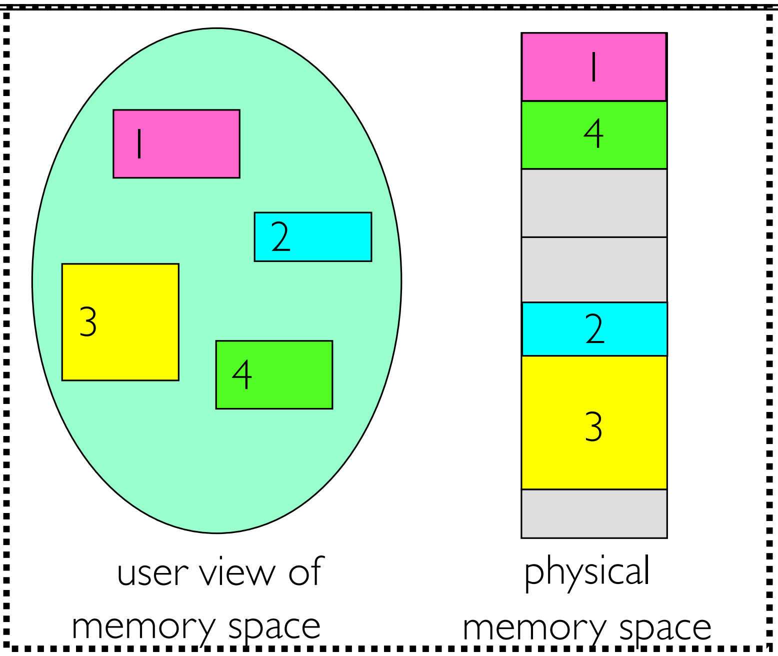
Issues with Simple B&B Method



- Fragmentation problem over time
  - Not every process is same size ⇒ memory becomes fragmented over time
- 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

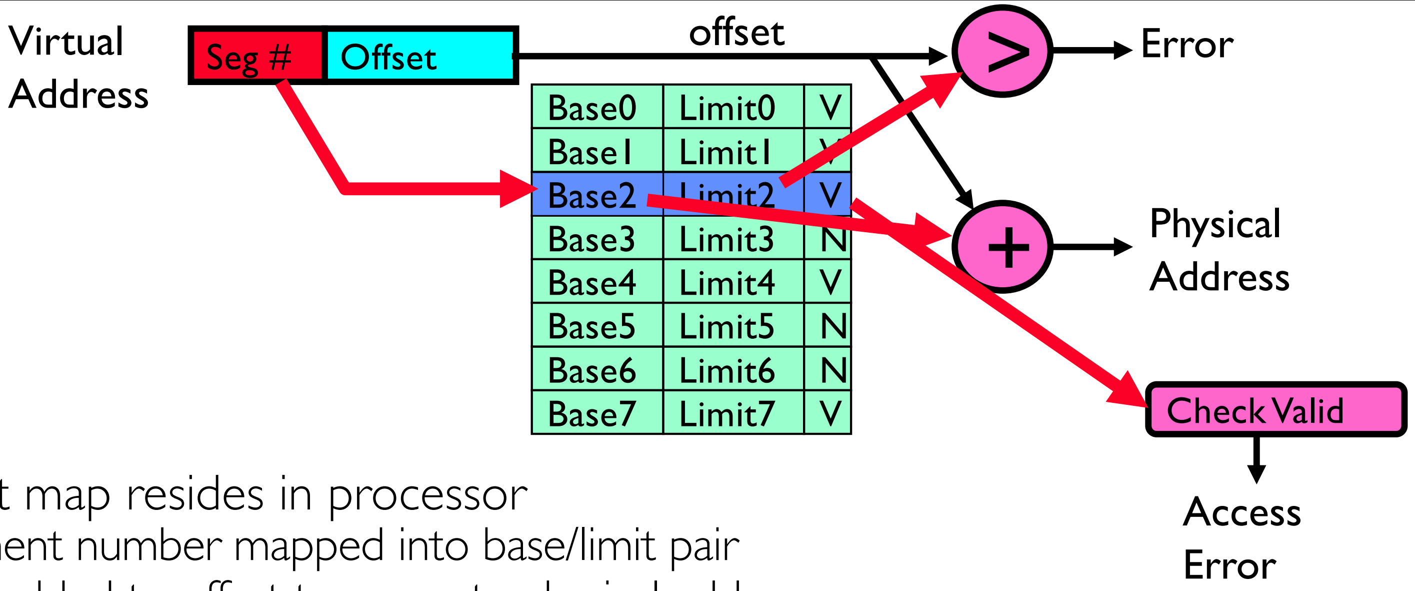
More Flexible Segmentation





- 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

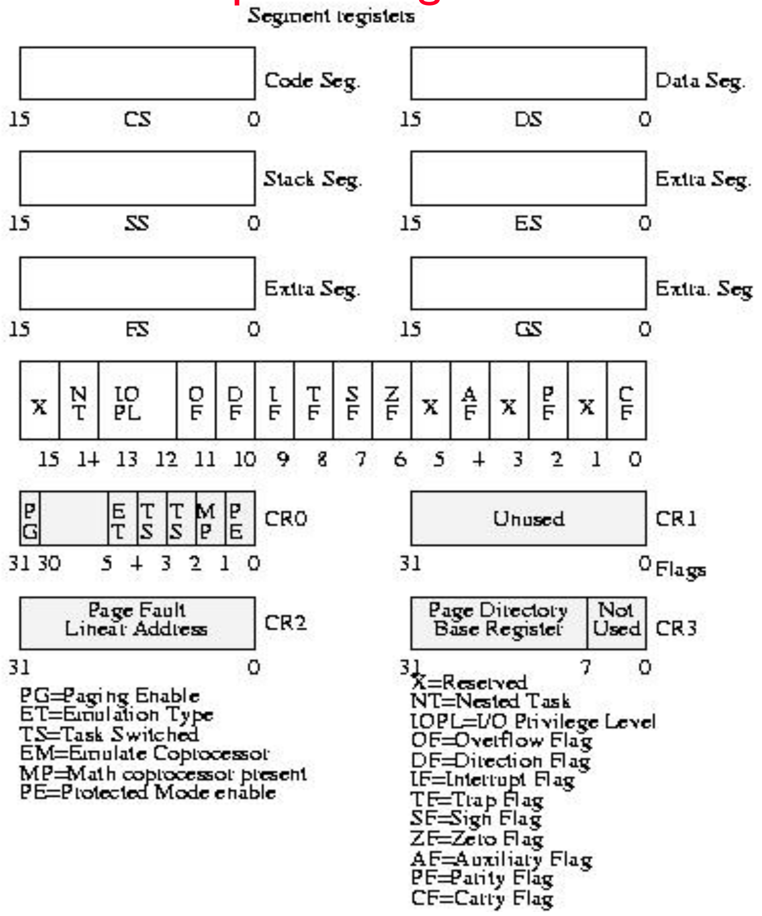
Implementation of Multi-Segment Model

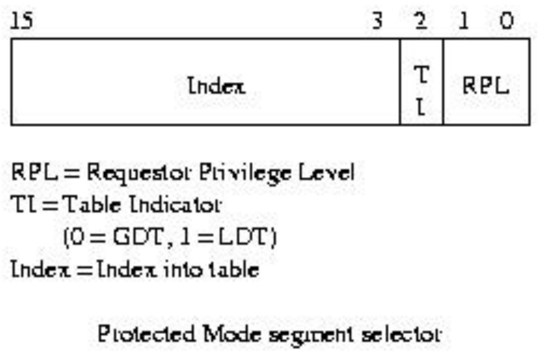


- Segment map resides in processor
  - Segment number mapped into base/limit pair
  - Base added to offset to generate physical address
  - Error check catches offset out of range
- As many chunks of physical memory as entries
  - Segment addressed by portion of virtual address
  - However, could be 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

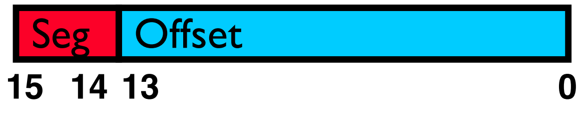
80386 Special Registers





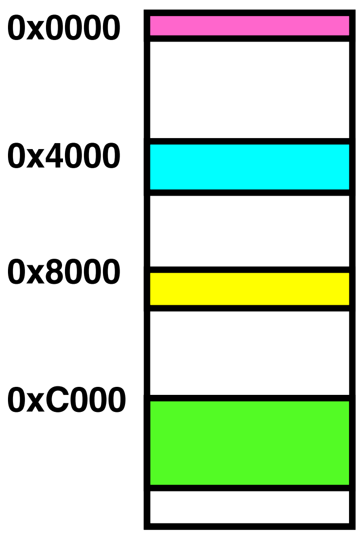
- Typical Segment Register
  - Current Priority is RPL of Code Segment (CS)
- Segmentation can't be just "turned off"
  - What if we just want to use paging?
  - Set base and bound to all of memory, in all segments

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



Virtual
Address Space

Physical
Address Space

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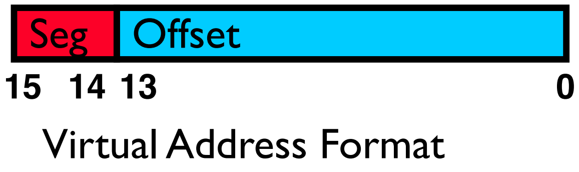

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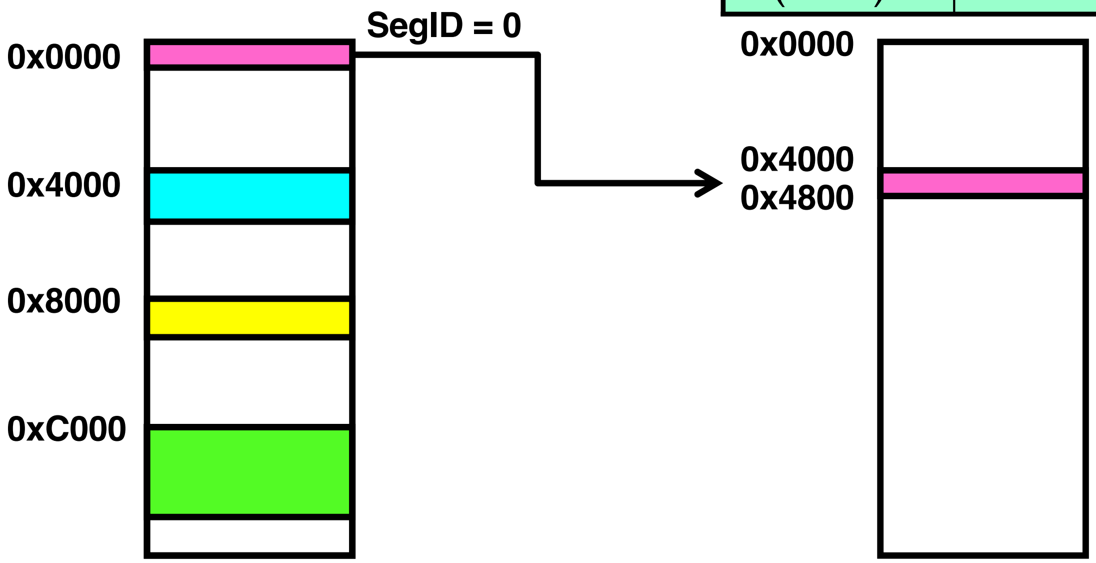

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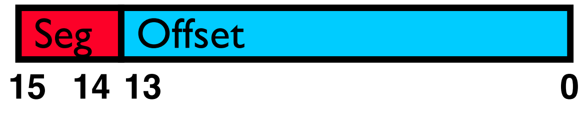

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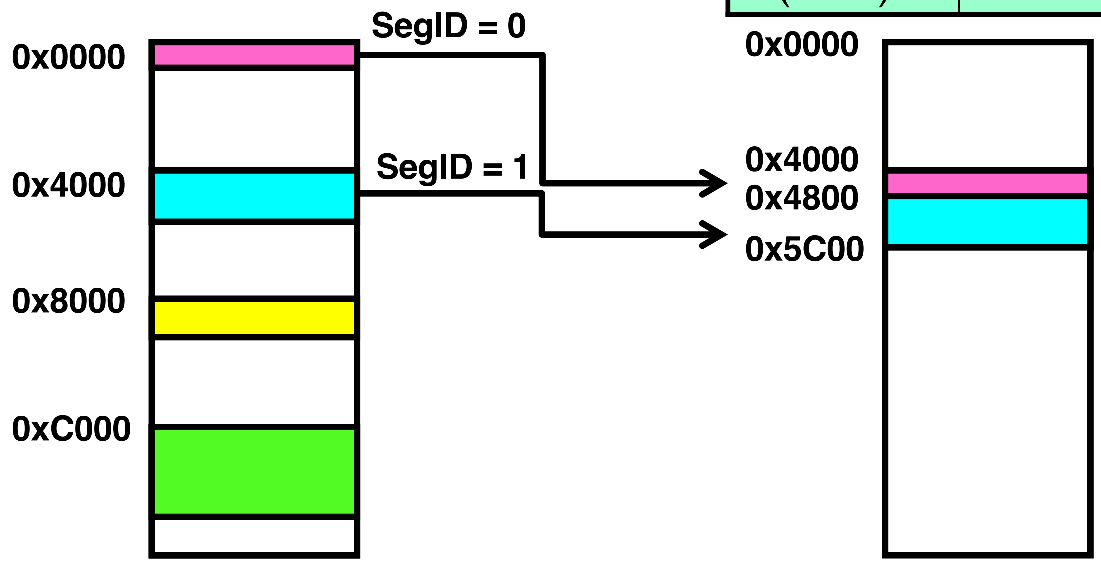

Virtual Address Space

Physical Address Space

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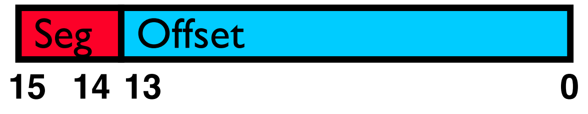

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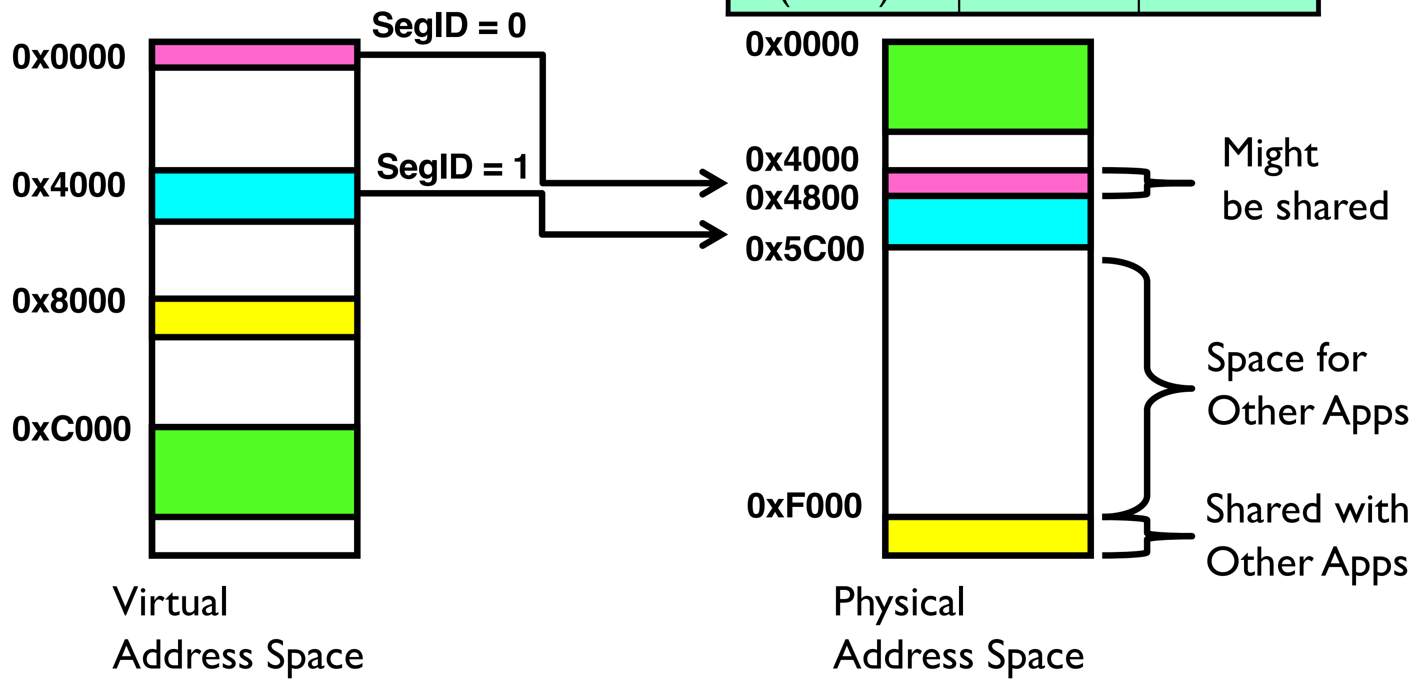

Example of Segment Translation (16-bit address)

```
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
```

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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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   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

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
2 (shared)	0xF000	0x1000
3 (stack)	0x0000	0x3000

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
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
```

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

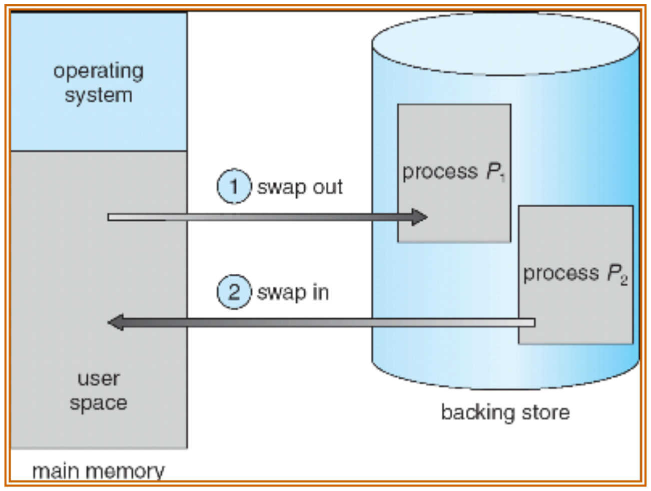
Let's simulate a bit of this code to see what happens (PC=0x0240):

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?



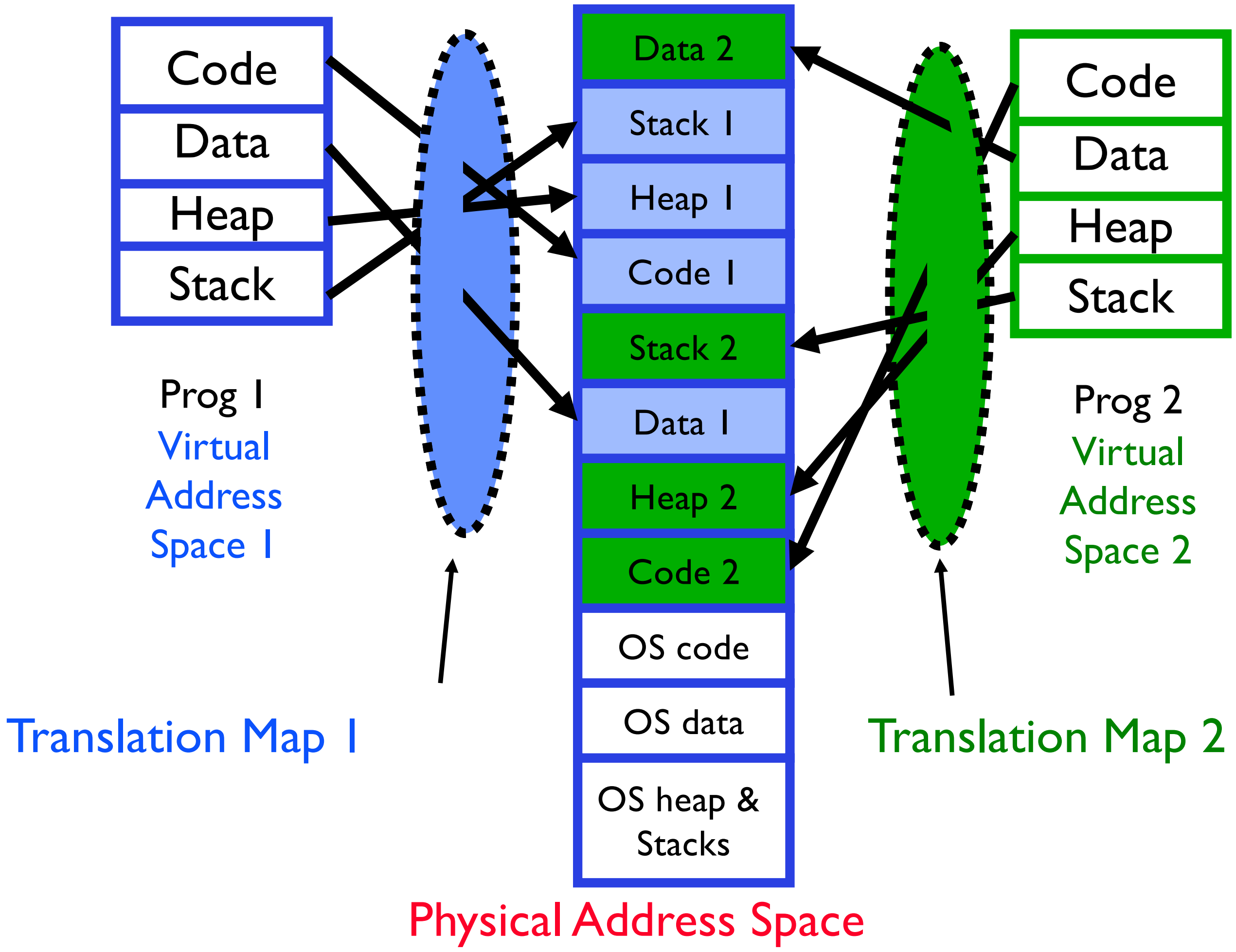
- Extreme form of Context Switch: Swapping
  - To make room for next process, some or all of the previous process is moved to disk
    - » Likely need to send out complete segments
  - This greatly increases the cost of context-switching
- What might be a desirable alternative?
  - Some way to keep only 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

[redacted]

Recall: General Address Translation

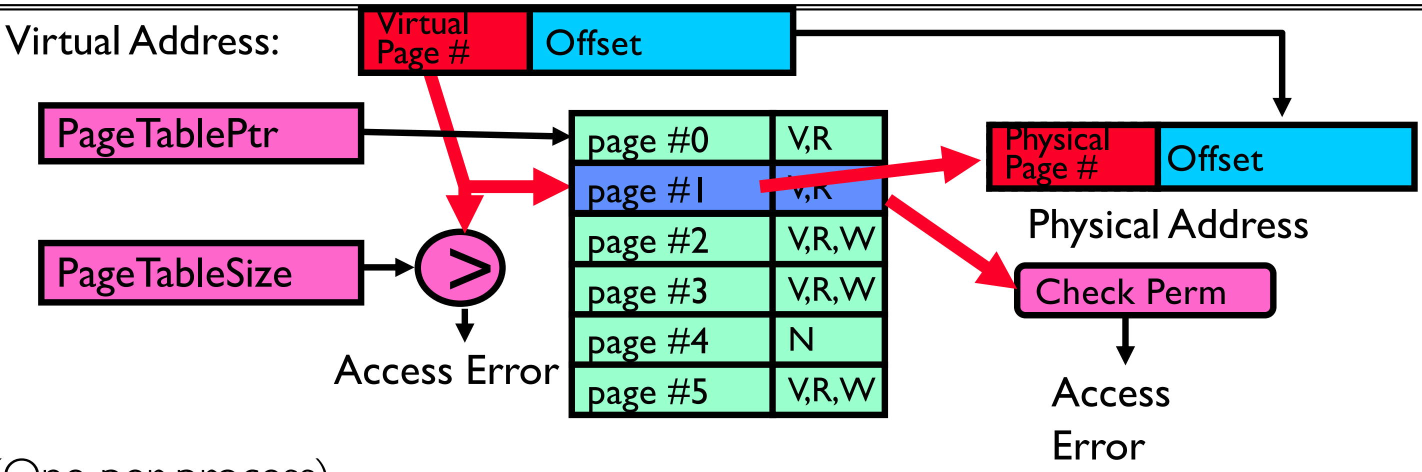


Paging: Physical Memory in Fixed Size Chunks

- 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

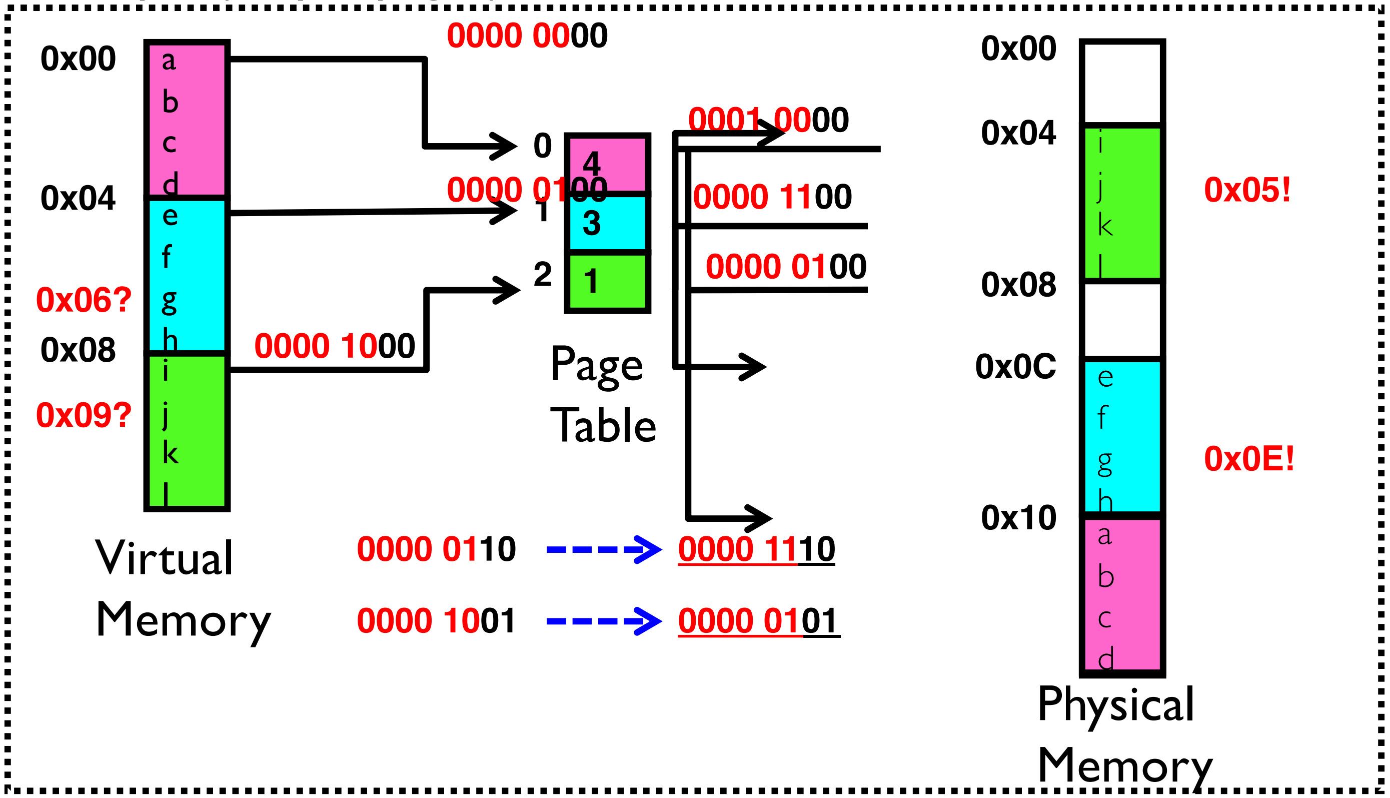
How to Implement Simple Paging?



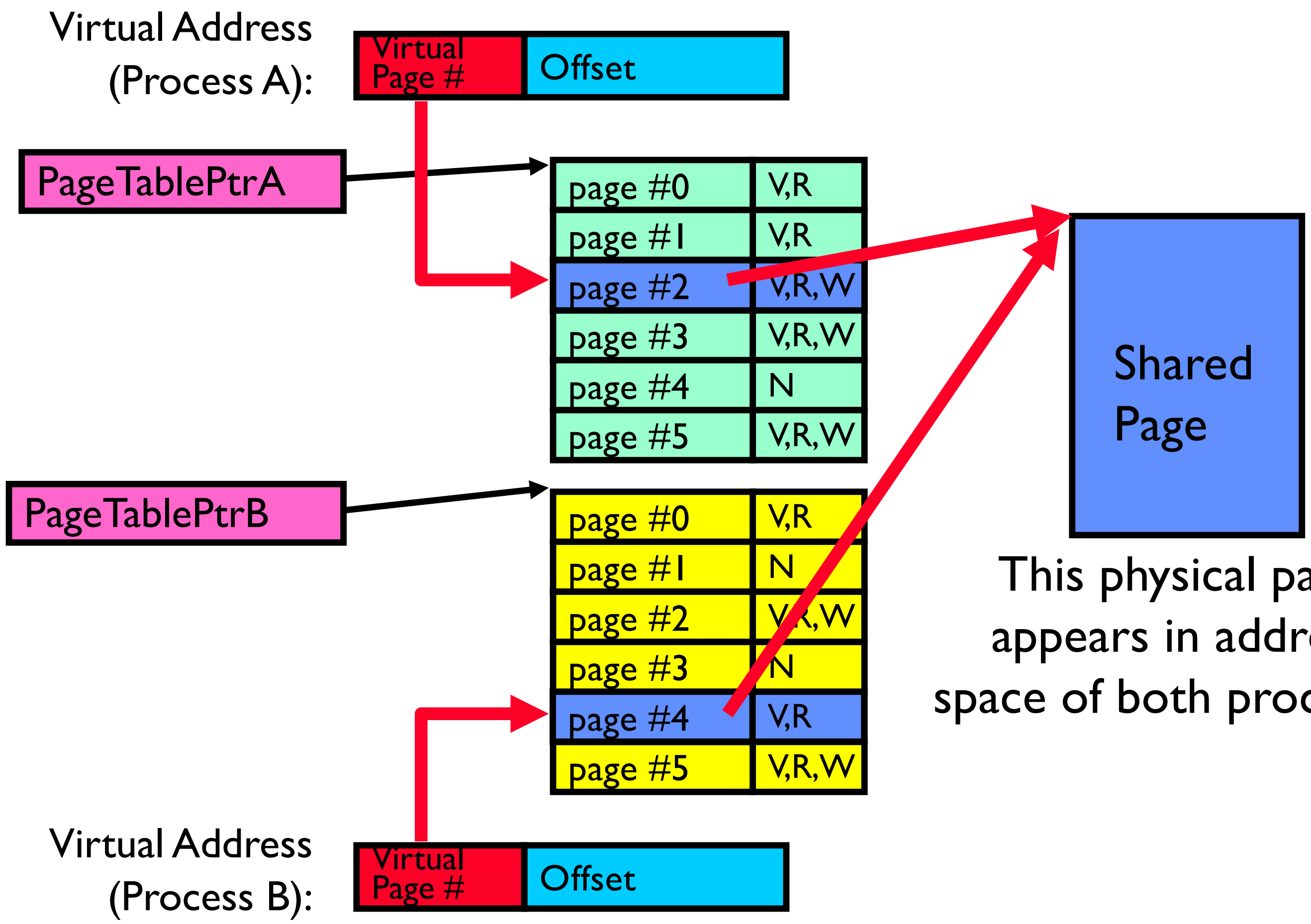
- Page Table (One per process)
  - Residesin physical memory
  - Contains physical page and permission for each virtual page (e.g., Valid bits, Read, Write, etc.)
- Virtual address mapping
  - Offset from Virtual address copied to Physical Address
    - » Example: 10 bit offset ⇒ 1024-byte pages
  -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

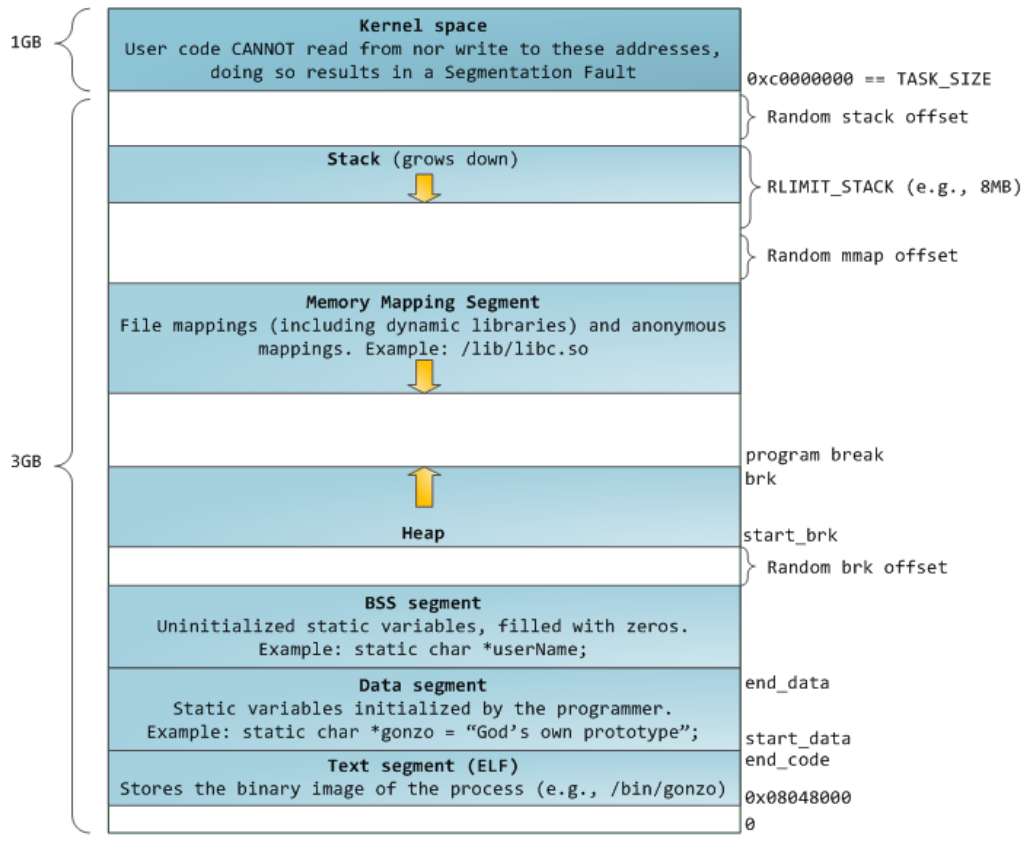


This physical page appears in address space of both processes

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

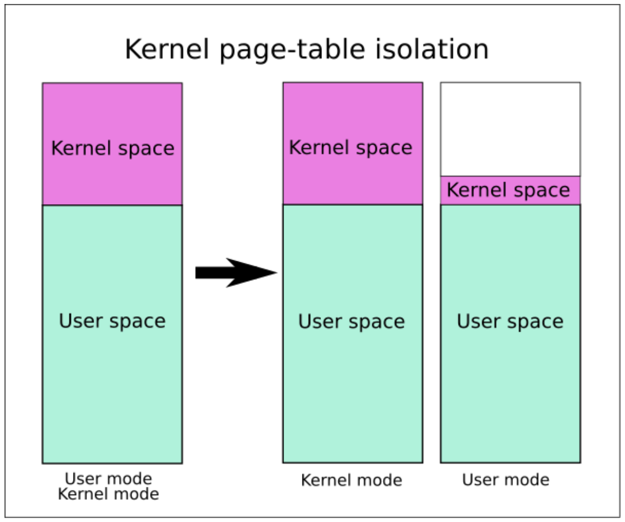
Memory Layout for Linux 32-bit (Pre-Meltdown patch!)


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

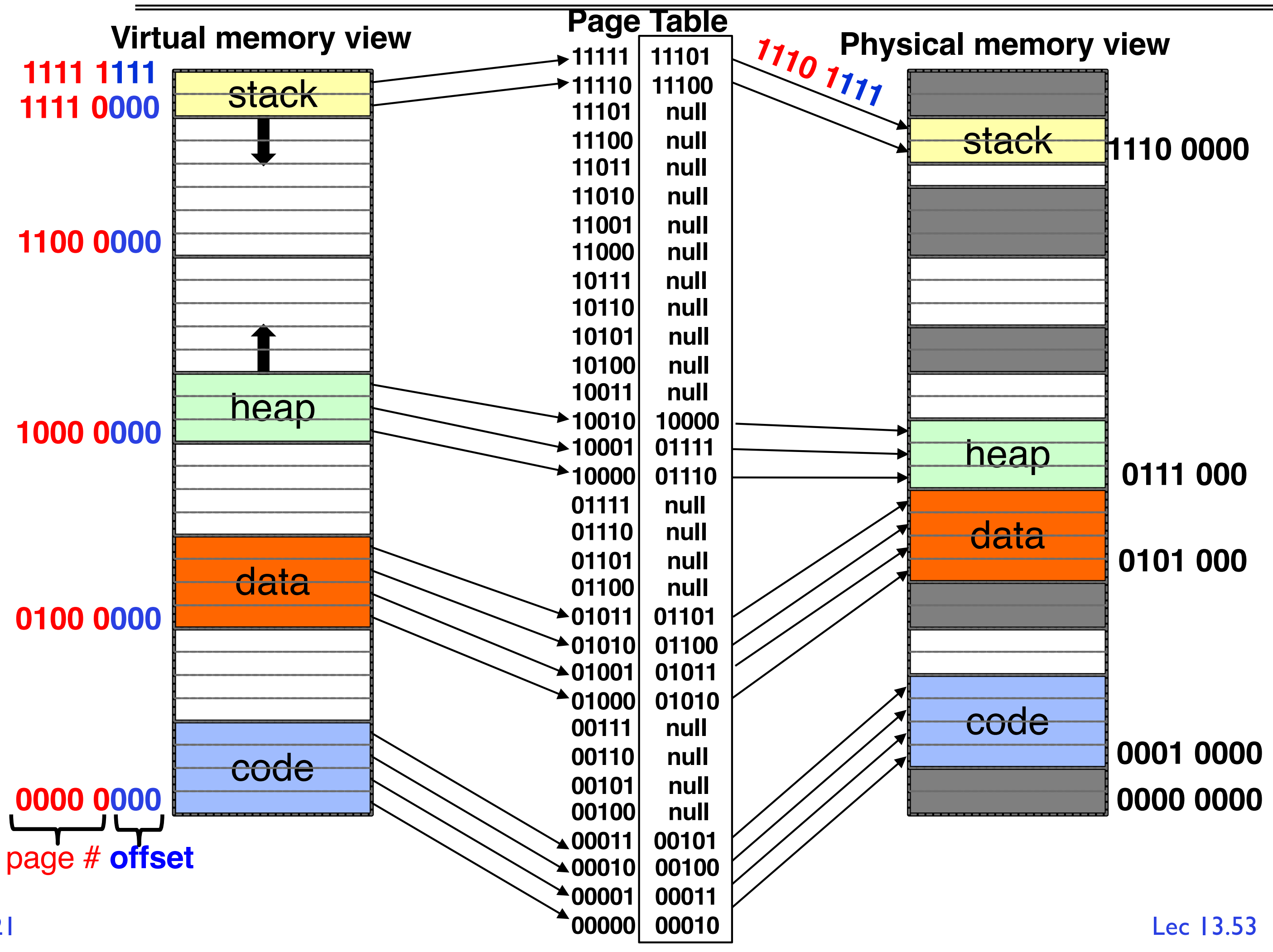
http://static.duartes.org/img/blogPosts/linuxFlexibleAddressSpaceLayout.png

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!

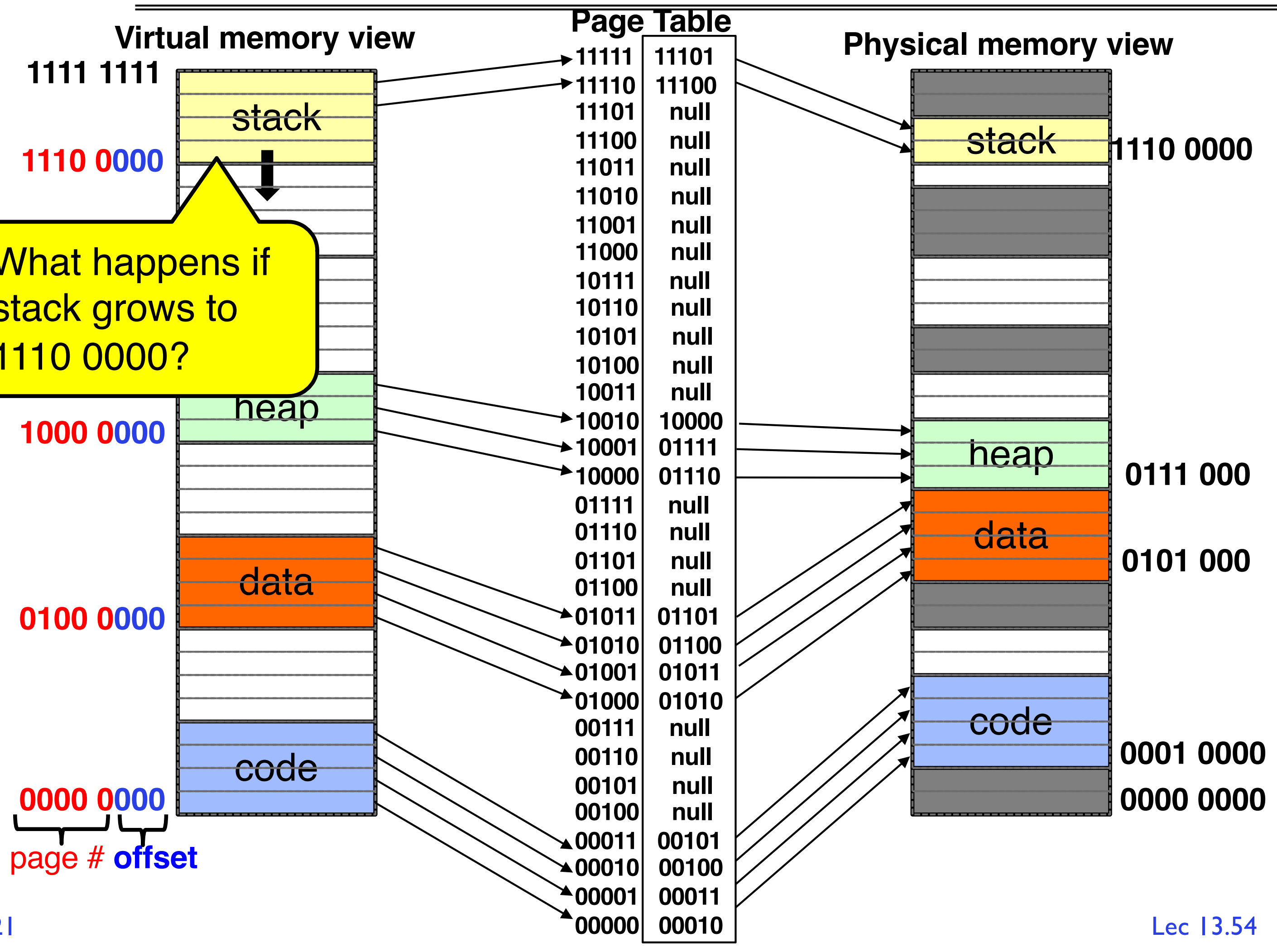


Summary: Paging

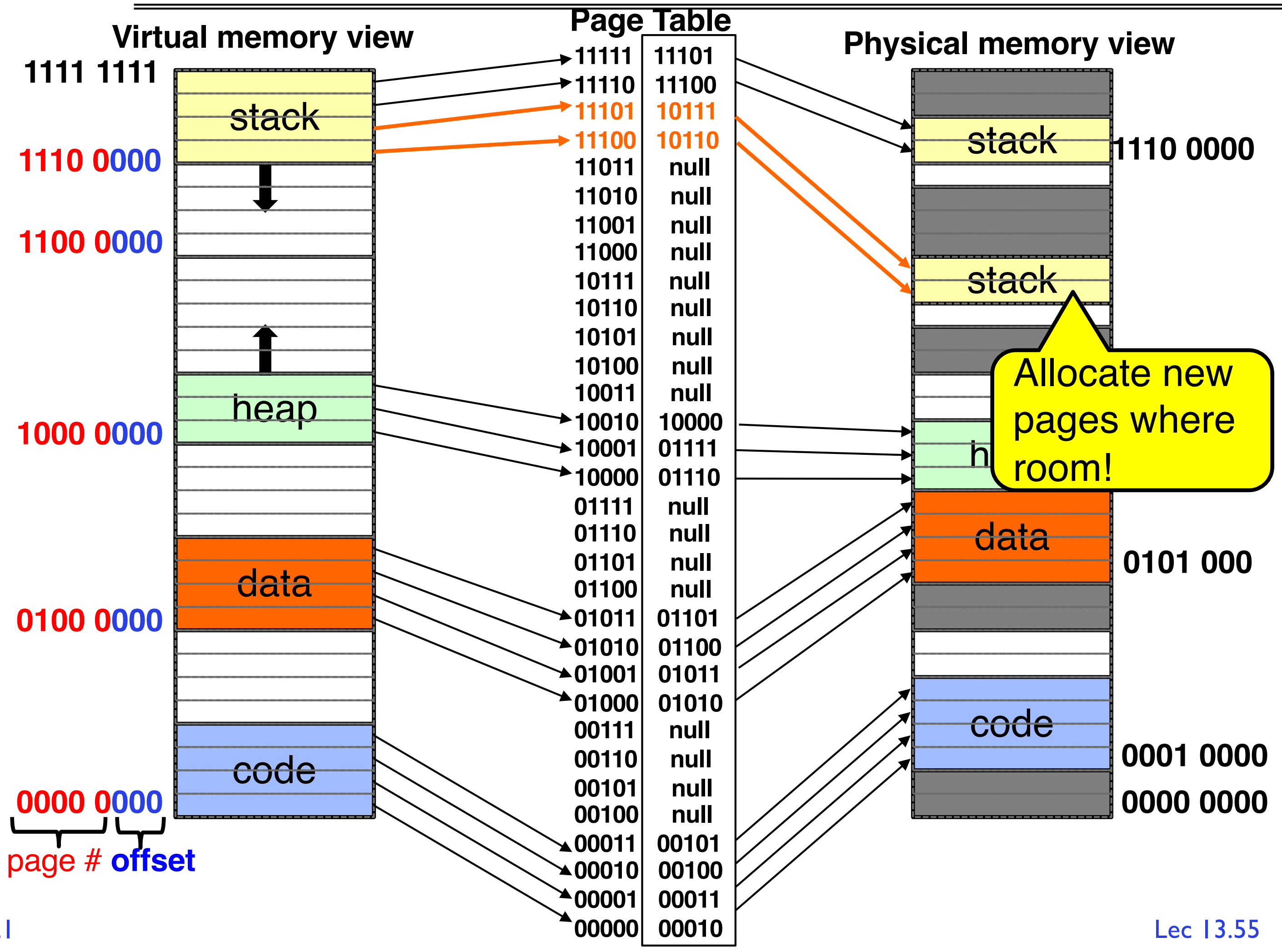


11111	11101
11110	11100
11101	null
11100	null
11011	null
11010	null
11001	null
11000	null
10111	null
10110	null
10101	null
10100	null
10011	null
10010	10000
10001	01111
10000	01110
01111	null
01110	null
01101	null
01100	null
01011	01101
01010	01100
01001	01011
01000	01010
00111	null
00110	null
00101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

Summary: Paging



Summary: Paging



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

How big do things get?

- 32-bit address space => 2^{32} bytes (4 GB)
  - Note: "b" = bit, and "B" = byte
  - And *for memory*:
    - » "K"(kilo) = 2^{10} = 1024 ≈ 10^3 (But not quite!): Sometimes called "Ki" (Kibi)
    - » "M"(mega) = 2^{20} = $(1024)^2$ = 1,048,576 ≈ 10^6 (But not quite!): Sometimes called "Mi" (Mibi)
    - » "G"(giga) = 2^{30} = $(1024)^3$ = 1,073,741,824 ≈ 10^9 (But not quite!): Sometimes called "Gi" (Gibi)
- Typical page size: 4 KB
  - how many bits of the address is that ? (remember 2^{10} = 1024)
  - Answer – 4KB = $4 \times 2^{10} = 2^{12} \Rightarrow$ 12 bits of the address
- So how big is the simple page table for *each* process?
  - $2^{32}/2^{12} = 2^{20}$ (that's about a million entries) x 4 bytes each => 4 MB
  - When 32-bit machines got started (vax 11/780, intel 80386), 16 MB was a LOT of memory
- How big is a simple page table on a 64-bit processor (x86_64)?
  - $2^{64}/2^{12} = 2^{52}$(that's 4.5×10^{15} or 4.5 exa-entries)×8 bytes each = 36×10^{15} bytes or 36 exa-bytes!!!! This is a ridiculous amount of memory!
  - This is really a lot of space – for only the page table!!!
- The address space is *sparse*, i.e., has holes that are not mapped to physical memory
  - So, most of this space is taken up by page tables mapped to nothing

Page Table Discussion

- What needs to be switched on a context switch?
  - Page table pointer and limit
- What provides protection here?
  - Translation (per process) *and* dual-mode!
  - Can’t let process alter its own page table!
- 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 is really big?
    - » Not all pages used all the time ⇒ would be nice to have working set of page table in memory
- Simple Page table is way too big!
  - Does it all need to be in memory?
  - How about multi-level paging?
  - or combining paging and segmentation

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