Memory Virtualization

Questions answered in this lecture:

What is in the address space of a process (review)?

What are the different ways that that OS can virtualize memory?

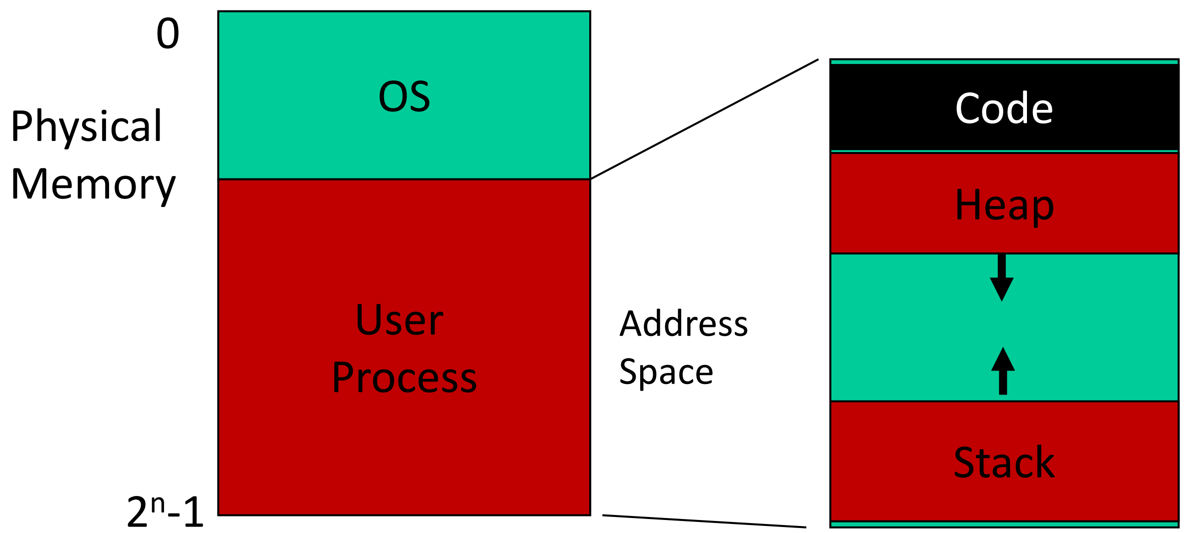
Time sharing, static relocation, dynamic relocation

(base, base + bounds, segmentation)

What hardware support is needed for dynamic relocation?

Motivation for Virtualization

- **Uniprogramming: One process runs at a time**



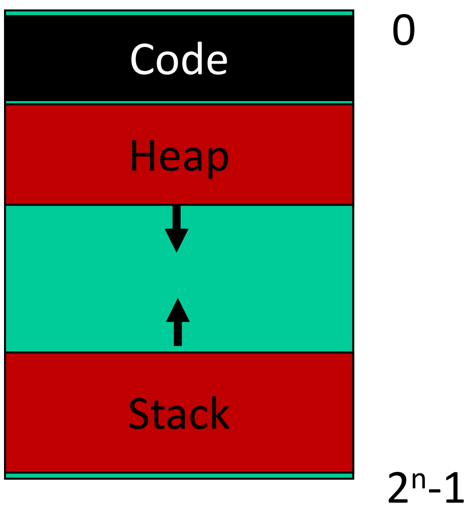
- Disadvantages:
  - Only one process runs at a time
  - Process can destroy OS

Multiprogramming Goals

- **Transparency**
  - Processes are not aware that memory is shared
  - Works regardless of number and/or location of processes
- **Protection**
  - Cannot corrupt OS or other processes
  - Privacy: Cannot read data of other processes
- **Efficiency**
  - Do not waste memory resources (minimize fragmentation)
- **Sharing**
  - Cooperating processes can share portions of address space

Abstraction: Address Space

- Address space: Each process has set of addresses that map to bytes
- Review: What is in an address space?
- Address space has static and dynamic components
  - Static: Code and some global variables
  - Dynamic: Stack and Heap



Motivation for Dynamic Memory

- **Why do processes need dynamic allocation of memory?**
  - Do not know amount of memory needed at compile time
  - Must be pessimistic when allocate memory statically
    - Allocate enough for worst possible case; Storage is used inefficiently
- **Recursive procedures**
  - Do not know how many times procedure will be nested
- **Complex data structures: lists and trees**
  - ```
    struct my_t *p = (struct my_t *)
      malloc(sizeof(struct my_t));
    ```
- **Two types of dynamic allocation**
  - Stack
  - Heap
    ```

Stack Organization

- **Definition: Memory is freed in opposite order from allocation**

```
alloc(A);
alloc(B);
alloc(C);
free(C);
alloc(D);
free(D);
free(B);
free(A);
```

- **Simple and efficient implementation:**
  Pointer separates allocated and freed space
  - Allocate: Increment pointer
  - Free: Decrement pointer
- **No fragmentation**

Where Are Stacks Used?

- **OS uses stack for procedure call frames (local variables and parameters)**

```
main () {
      int A = 0;
      foo (A);
      printf(“A: %d\n”, A);
}

void foo (int Z) {
      int A = 2;
      Z = 5;
      printf(“A: %d Z: %d\n”, A, Z);
}
```

Heap Organization

- **Definition: Allocate from any random location: malloc(), new()**
  - Heap memory consists of allocated areas and free areas (holes)
  - Order of allocation and free is unpredictable

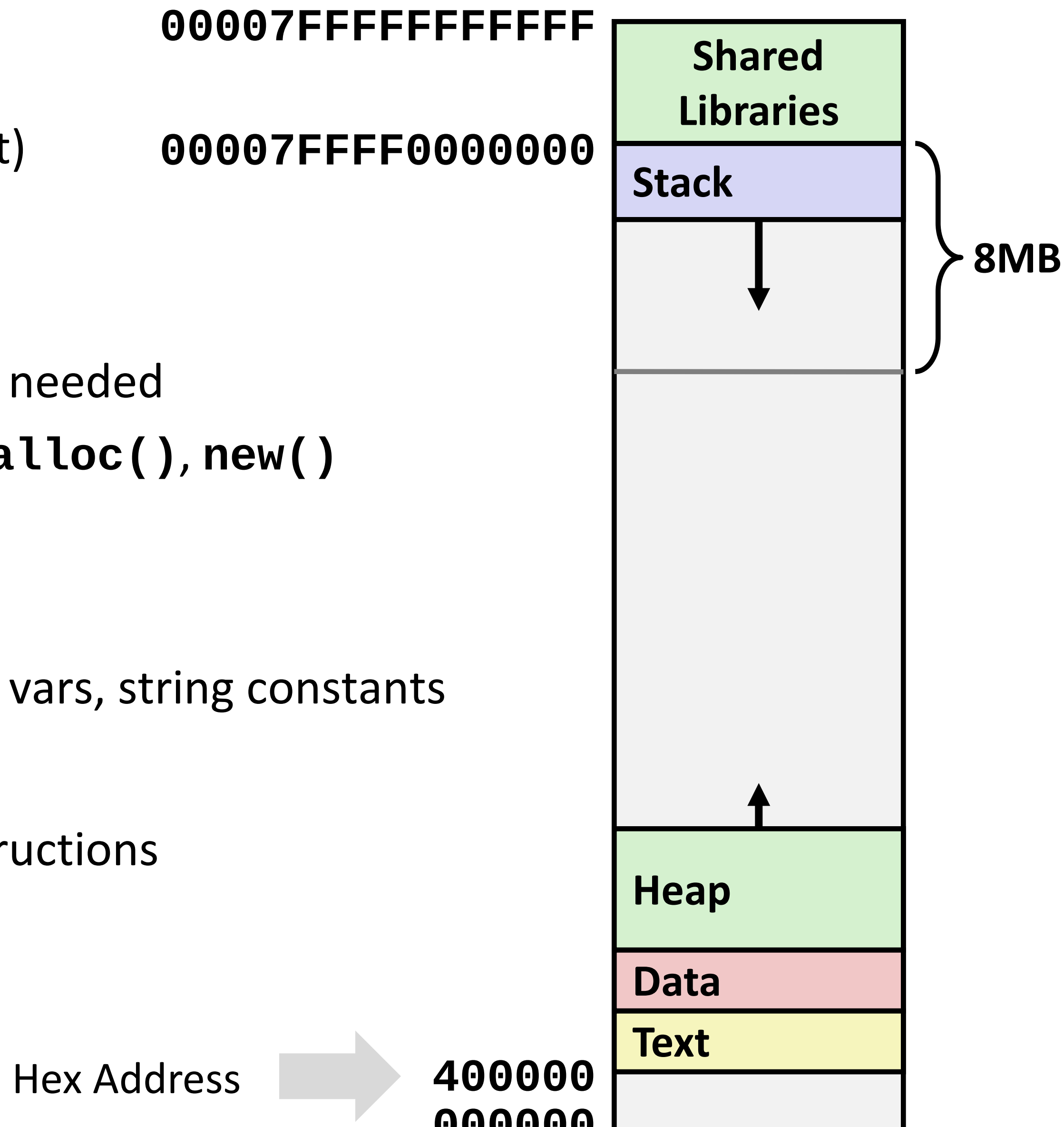
- **Advantage**
  - Works for all data structures
- **Disadvantages**
  - Allocation can be slow
  - End up with small chunks of free space - fragmentation
  - Where to allocate 12 bytes? 16 bytes? 24 bytes??

- **What is OS's role in managing heap?**
  - OS gives big chunk of free memory to process; library manages individual allocations

x86-64 Linux Memory Layout

not drawn to scale

- **Stack**
  - Runtime stack (8MB limit)
  - E. g., local variables
- **Heap**
  - Dynamically allocated as needed
  - When call **`malloc()`**, **`calloc()`**, **`new()`**
- **Data**
  - Statically allocated data
  - E.g., global vars, **`static`** vars, string constants
- **Text / Shared Libraries**
  - Executable machine instructions
  - Read-only



Memory Access

```
int function(int len, char* src) {
 char buffer[100];
 process(buffer, src, len);
 return 0;
}

void main() {
  function(50, "Hello\n");
}
```

```
Calling Convention:
function(%rdi, %rsi, %rdx)
```

```
sub    $0x64, %rsp
movq   %rdi, %rdx
movq   %rsp, %rdi
callq  < process >
xor    %rax,%rax
add    $0x64, %rsp
retq
```

How to Virtualize Memory?

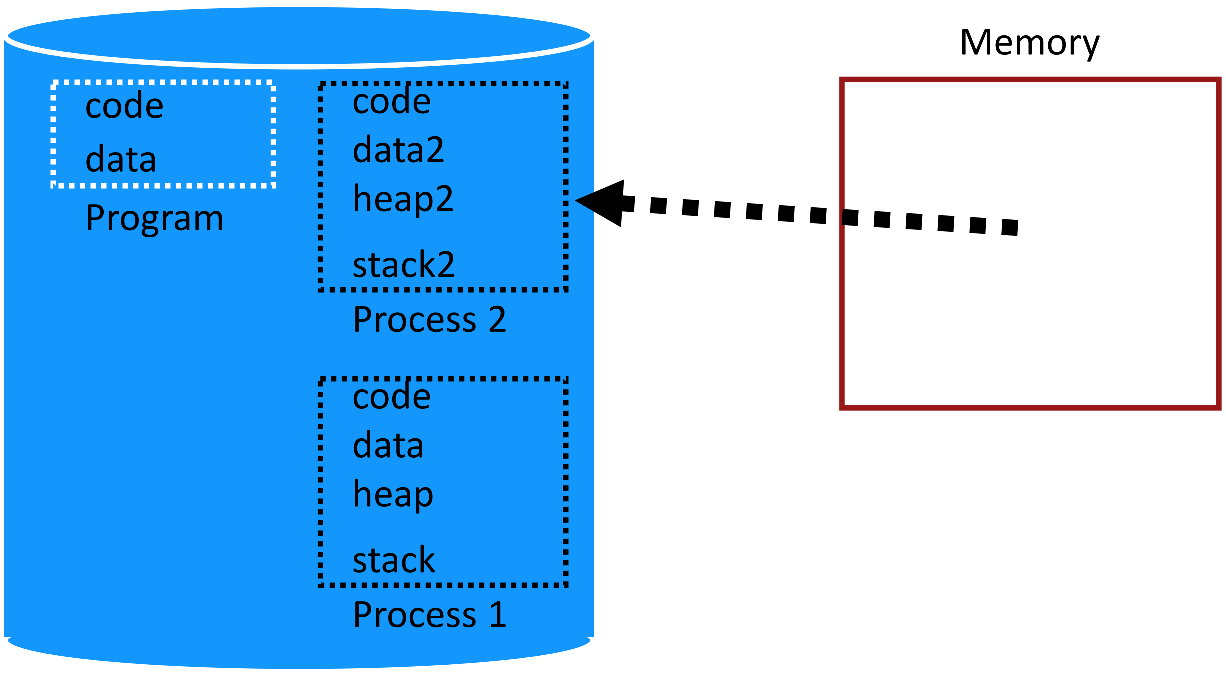
- **Problem: How to run multiple processes simultaneously?**

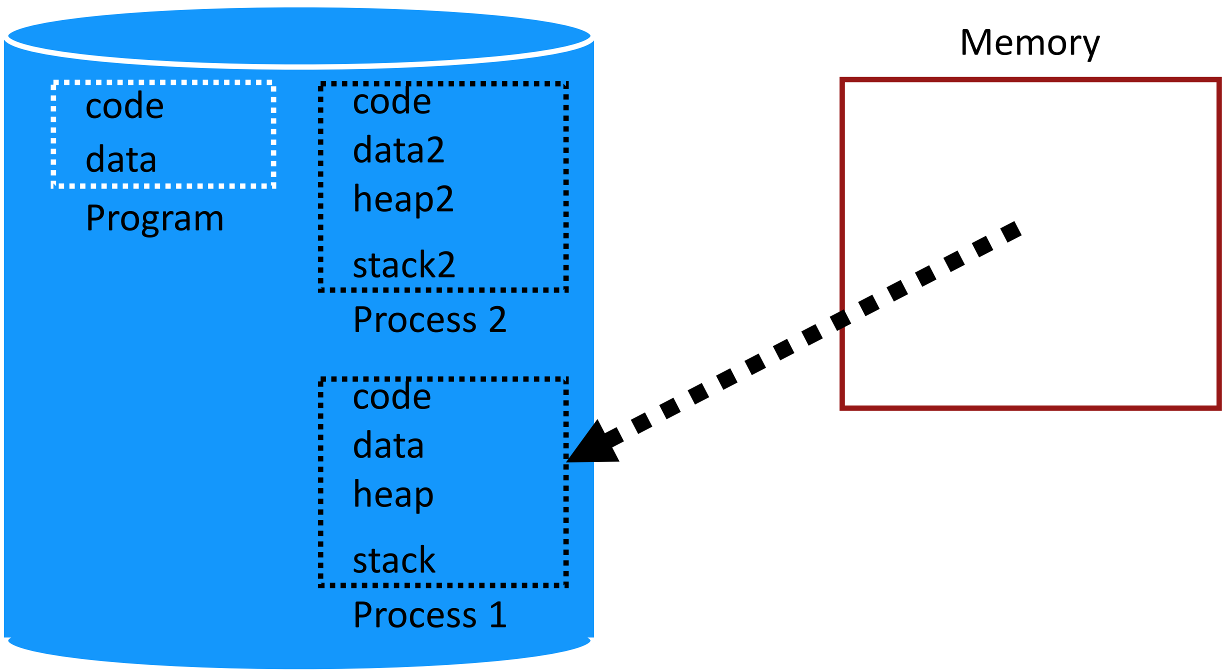
- **Addresses are "hardcoded" into process binaries**
- **How to avoid collisions?**
- **Possible Solutions for Mechanisms (covered today):**
  1. Time Sharing
  2. Static Relocation
  3. Base
  4. Base+Bounds
  5. Segmentation

1) Time Sharing of Memory

- **Try similar approach to how OS virtualizes CPU**
- **Observation:**
  OS gives illusion of many virtual CPUs by saving CPU registers to memory when a process isn't running

- Could give illusion of many virtual memories by saving memory to disk when process isn't running


Memory
code
data
Program
code
data2
heap2
stack2
Process 2
code
data
heap
stack
Process 1


code
data
Program
code
data2
heap2
stack2
Process 2
code
data
heap
stack
Process 1
Memory

Problems with Time Sharing Memory

- **Problem**
  - Ridiculously poor performance

- **Better Alternative: space sharing**
  - At same time, space of memory is divided across processes
- **Remainder of solutions all use space sharing**

2) Static Relocation

- Idea: OS rewrites each program before loading it as a process in memory
- Each rewrite for different process uses different addresses and pointers
- Change jumps, loads of static data

rewrite

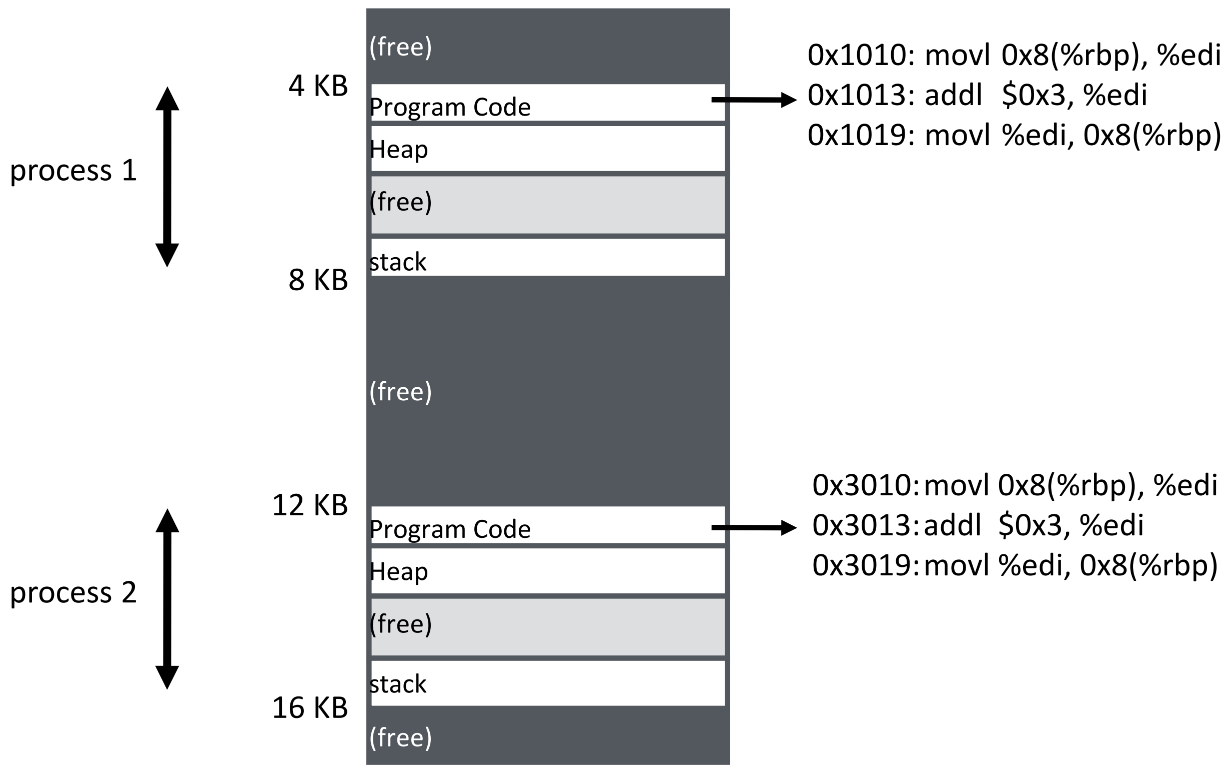
0x1010: movl 0x8(%rbp), %edi
0x1013: addl $0x3, %edi
0x1019: movl %edi, 0x8(%rbp)

- 0x10: movl 0x8(%rbp), %edi
- 0x13: addl $0x3, %edi
- 0x19: movl %edi, 0x8(%rbp)

rewrite

0x3010: movl 0x8(%rbp), %edi
0x3013: addl $0x3, %edi
0x3019: movl %edi, 0x8(%rbp)

Static: Layout in Memory

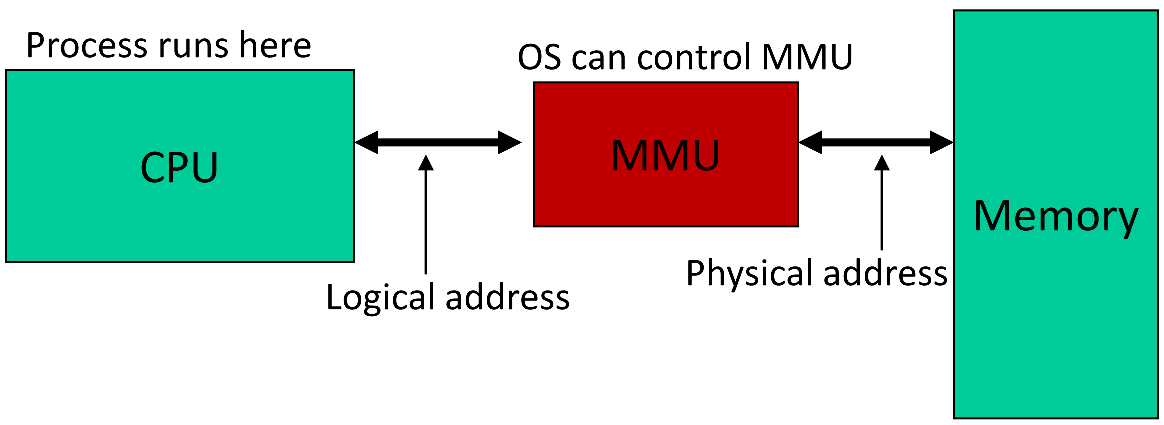


Static Relocation: Disadvantages

- **No protection**
  - Process can destroy OS or other processes
  - No privacy
- **Cannot move address space after it has been placed**
  - May not be able to allocate new process
  - Need to be the same place for being switched back

3) Dynamic Relocation

- **Goal: Protect processes from one another**
- **Requires hardware support**
  - Memory Management Unit (MMU)
- **MMU dynamically changes process address at every memory reference**
  - Process generates logical or virtual addresses (in their address space)
  - Memory hardware uses physical or real addresses



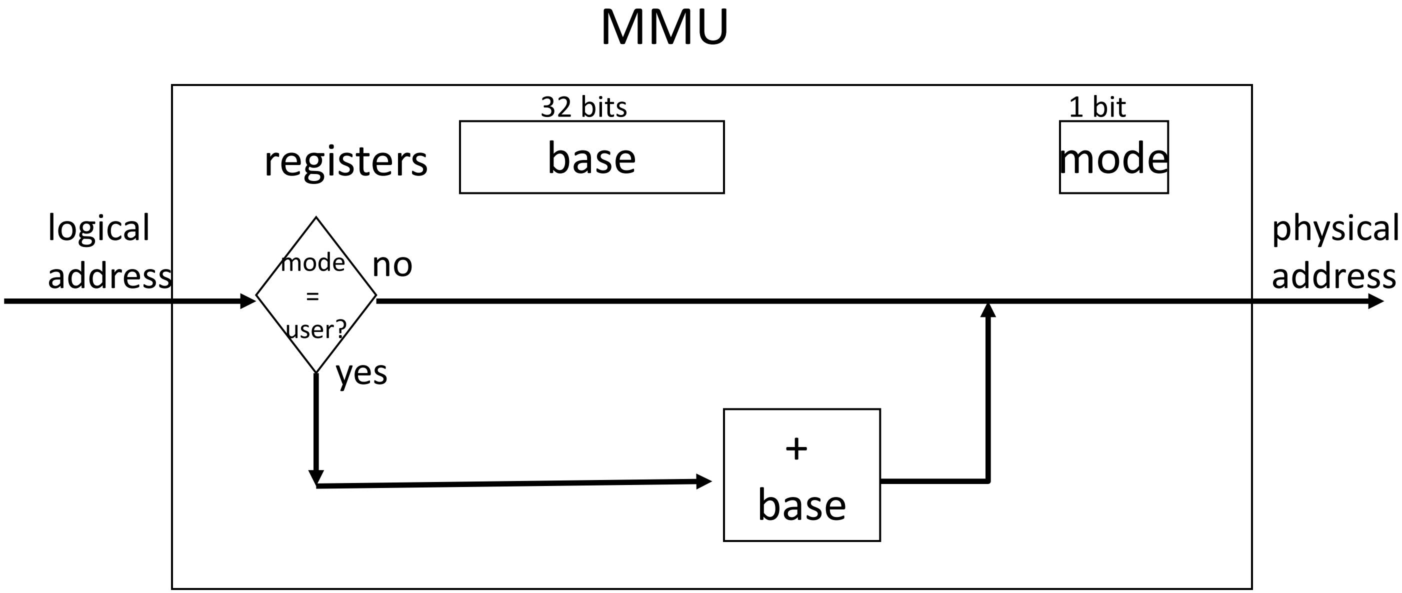
Hardware Support for Dynamic Relocation

- **Two operating modes**
  - **Privileged (protected, kernel) mode: OS runs**
    - When enter OS (trap, system calls, interrupts, exceptions)
    - Allows certain instructions to be executed
      - Can manipulate contents of MMU
    - Allows OS to access all of physical memory
  - **User mode: User processes run**
    - Perform translation of logical address to physical address

- **Minimal MMU contains base register for translation**
  - base: start location for address space

Implementation of Dynamic Relocation: BASE REG

- **Translation on every memory access of user process**
  - MMU adds base register to logical address to form physical address

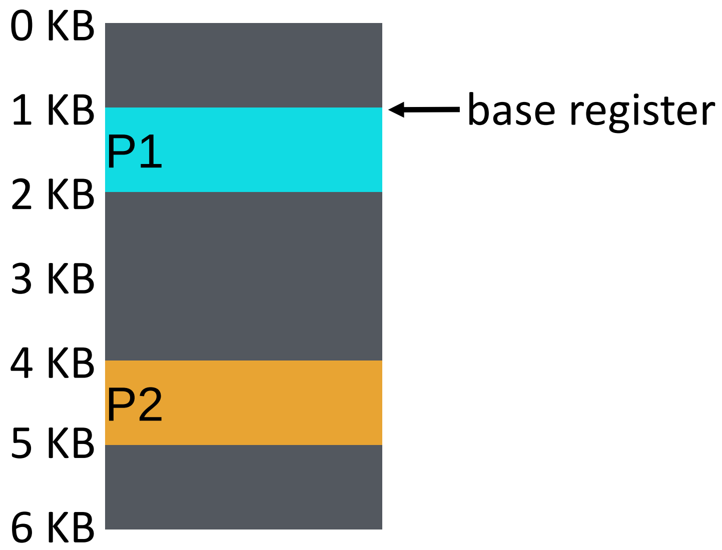


Dynamic Relocation with Base Register

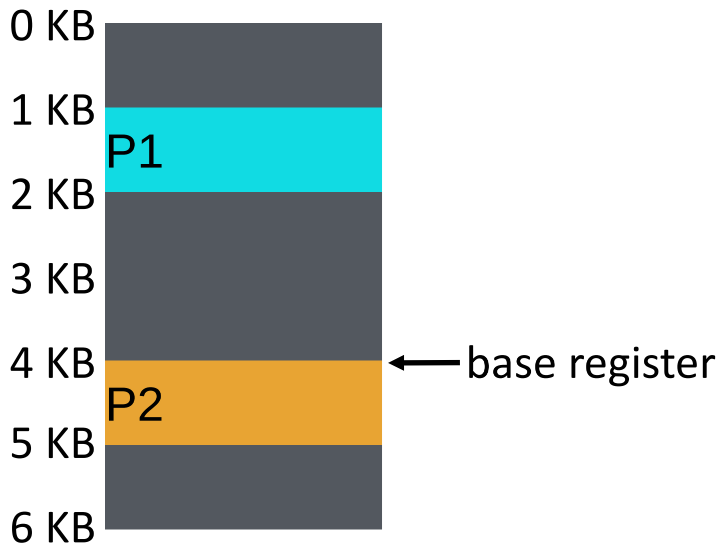
- Idea: translate virtual addresses to physical by adding a fixed offset each time.

- Store offset in base register

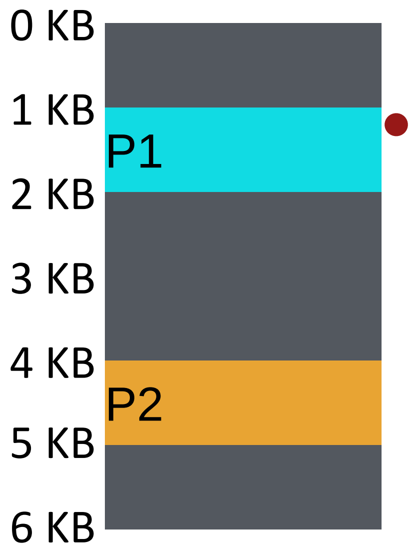
- Each process has different value in base register



P1 is running

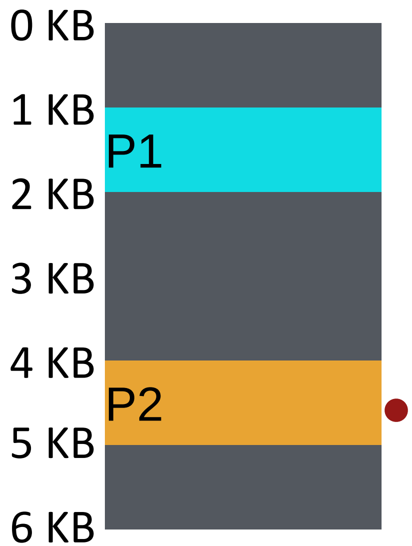


P2 is running



Virtual	Physical
P1: mov [100], R10	load 1124, R10

(1024 + 100)



Virtual	Physical
P1: mov [100], R10	load 1124, R10
P2: mov [100], R10	load 4196, R10

Virtual	Physical

Can P2 hurt P1?

Can P1 hurt P2?

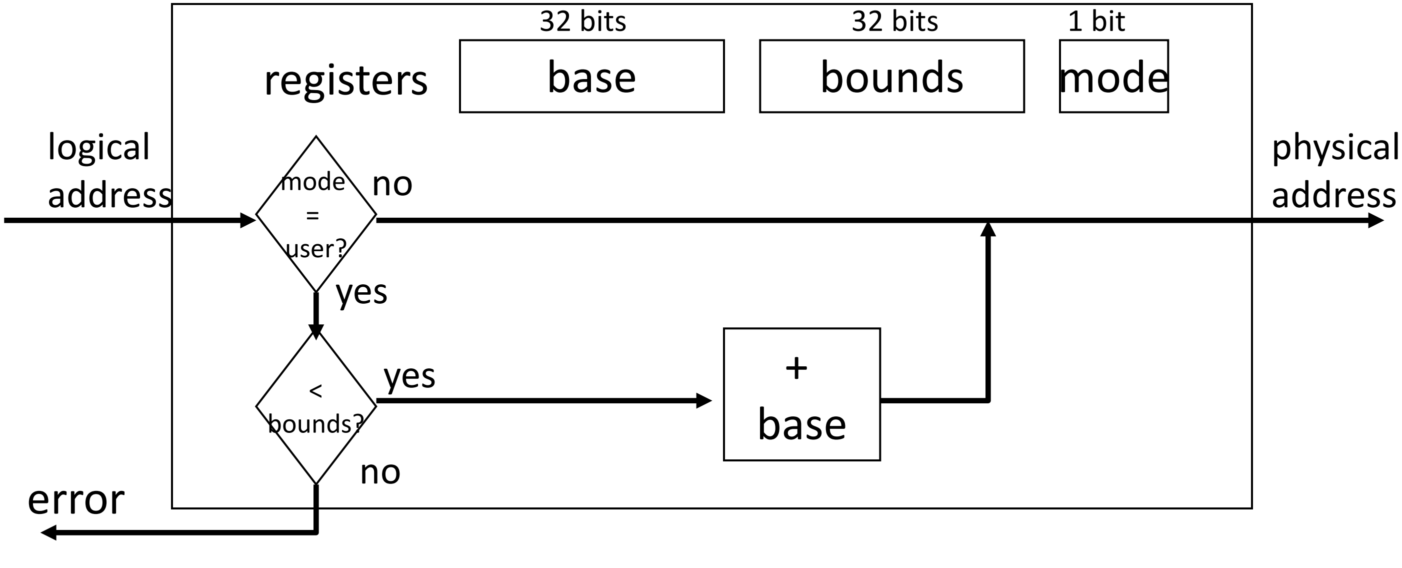
How well does dynamic relocation do with base register for protection?

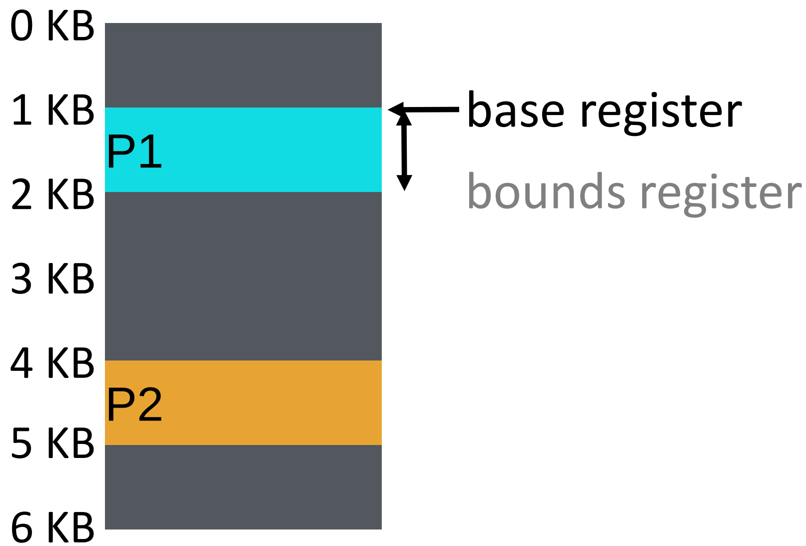
4) Dynamic with Base+Bounds

- **Idea: limit the address space with a bounds register**
- **Base register: smallest physical addr (or starting location)**
- **Bounds register: size of this process's virtual address space**
  - Sometimes defined as largest physical address (base + size)
- **OS kills process if process loads/stores beyond bounds**

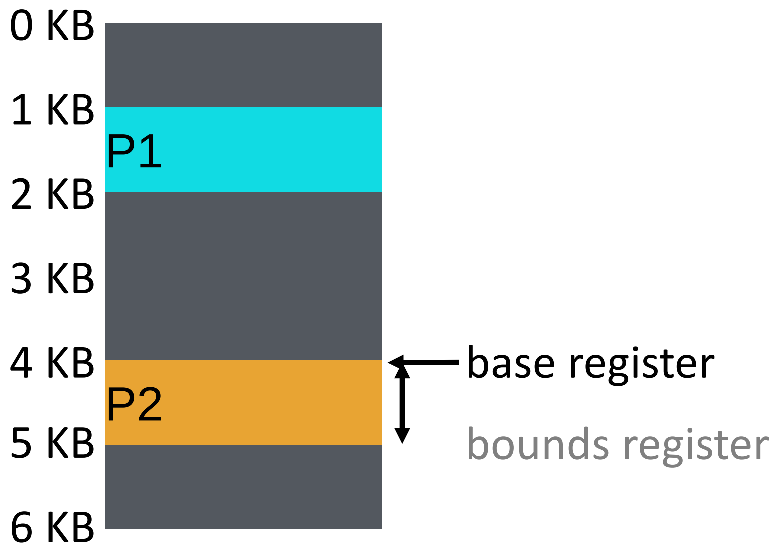
Implementation of BASE+BOUNDS

- **Translation on every memory access of user process**
  - MMU compares logical address to bounds register
    - if logical address is greater, then generate error
  - MMU adds base register to logical address to form physical address





P1 is running



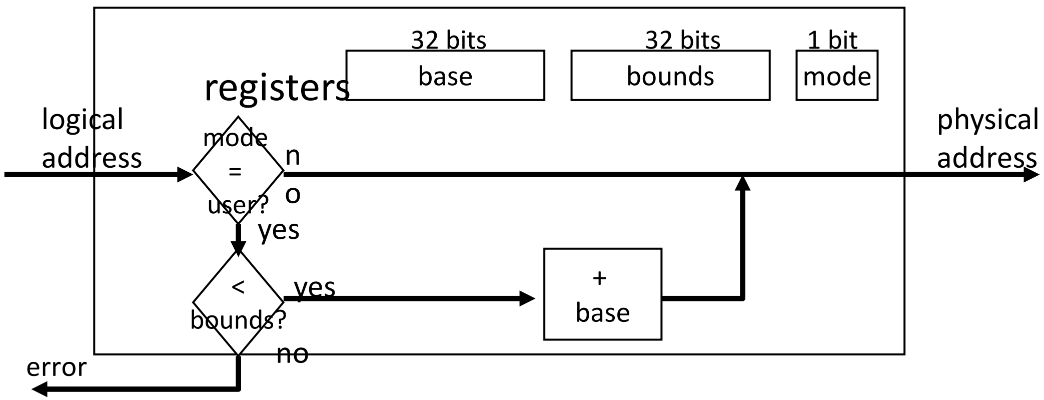
P2 is running

Managing Processes with Base and Bounds

- **Context-switch**
  - Add base and bounds registers to PCB
  - Steps
    - Change to privileged mode
    - Save base and bounds registers of old process
    - Load base and bounds registers of new process
    - Change to user mode and jump to new process
- **Protection requirement**
  - User process cannot change base and bounds registers
  - User process cannot change to privileged mode

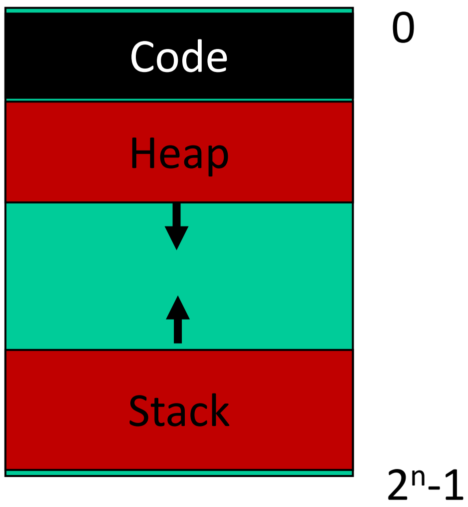
Base and Bounds Advantages

- **Advantages**
  - Provides protection (both read and write) across address spaces
  - Supports dynamic relocation
    - Can place process at different locations initially and also move address spaces
  - Simple, inexpensive implementation
    - Few registers, little logic in MMU
  - Fast
    - Add and compare in parallel



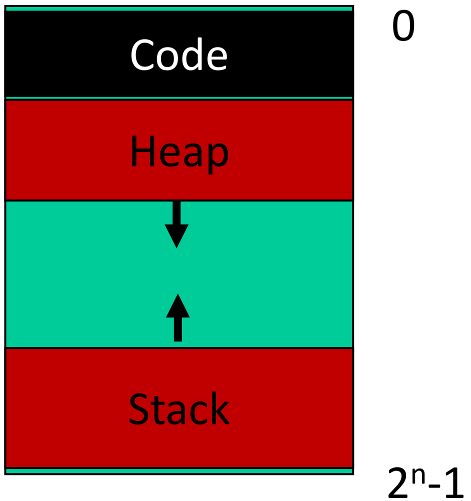
Base and Bounds DISADVANTAGES

- **Disadvantages**
  - Each process must be allocated contiguously in physical memory
    - Must allocate memory that may not be used by process
  - No partial sharing: Cannot share limited parts of address space



5) Segmentation

- **Divide address space into logical segments**
  - Each segment corresponds to logical entity in address space
    - code, stack, heap
- **Each segment can independently:**
  - be placed separately in physical memory
  - grow and shrink
  - be protected (separate read/write/execute protection bits)



Segmented Addressing

- **Process now specifies base and offset within segment**
- **How does process designate a particular segment?**
  - Use part of logical address
    - Top bits of logical address select segment
    - Low bits of logical address select offset within segment
- **What if small address space, not enough bits?**
  - Implicitly by type of memory reference
  - Special registers

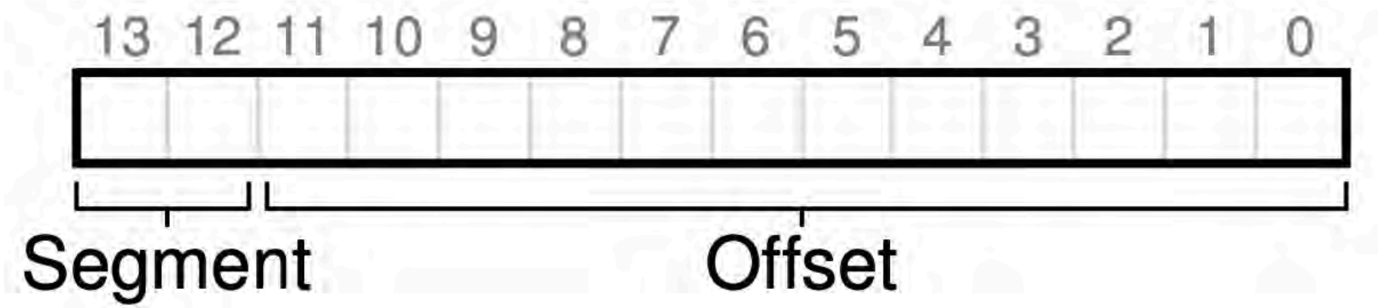
Segmentation Implementation

- **MMU contains Segment Table (per process)**
  - Each segment has own base and bounds, protection bits
  - Example: 14 bit logical address, 4 segments; how many bits for segment? How many bits for offset?

Segment	Base	Bounds	R W
0	0x2000	0x6ff	1 0
1	0x0000	0x4ff	1 1
2	0x3000	0xfff	1 1
3	0x0000	0x000	0 0

remember:
1 hex digit->4 bits

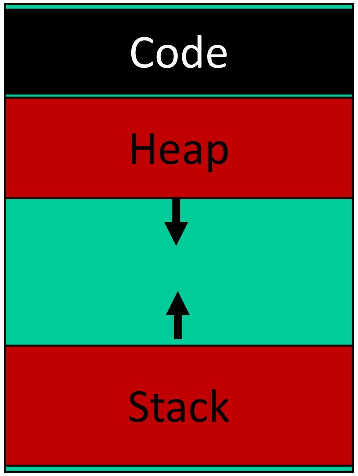
Segmentation Implementation




```
Segment = (VirtualAddress & SEG_MASK) >> SEG_SHIFT
Offset = VirtualAddress & OFFSET_MASK
if (Offset >= Bounds[Segment])
    RaiseException(PROTECTION_FAULT)
else
    PhysAddr = Base[Segment] + Offset
    Register = AccessMemory(PhysAddr)
```

Advantages of Segmentation

- **Enables sparse allocation of address space**
  - Stack and heap can grow independently
  - Heap: If no data on free list, dynamic memory allocator requests more from OS (e.g., UNIX: malloc calls sbrk())
  - Stack: OS recognizes reference outside legal segment, extends stack implicitly
- **Different protection for different segments**
  - Read-only status for code
- **Enables sharing of selected segments**
- **Supports dynamic relocation of each segment**



Disadvantages of Segmentation

- **Each segment must be allocated contiguously**
  - May not have sufficient physical memory for large segments

- **Fix in next lecture with paging…**