Lecture 7
Address Translation

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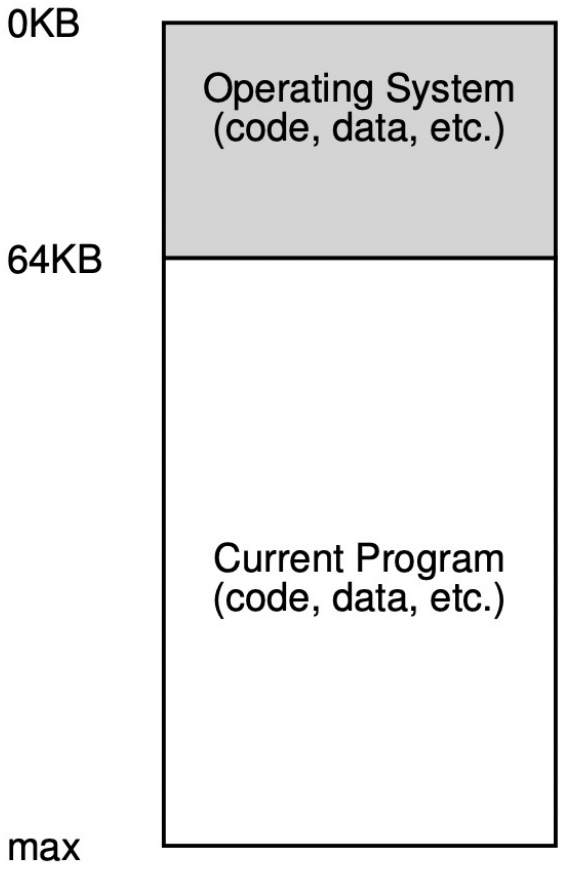
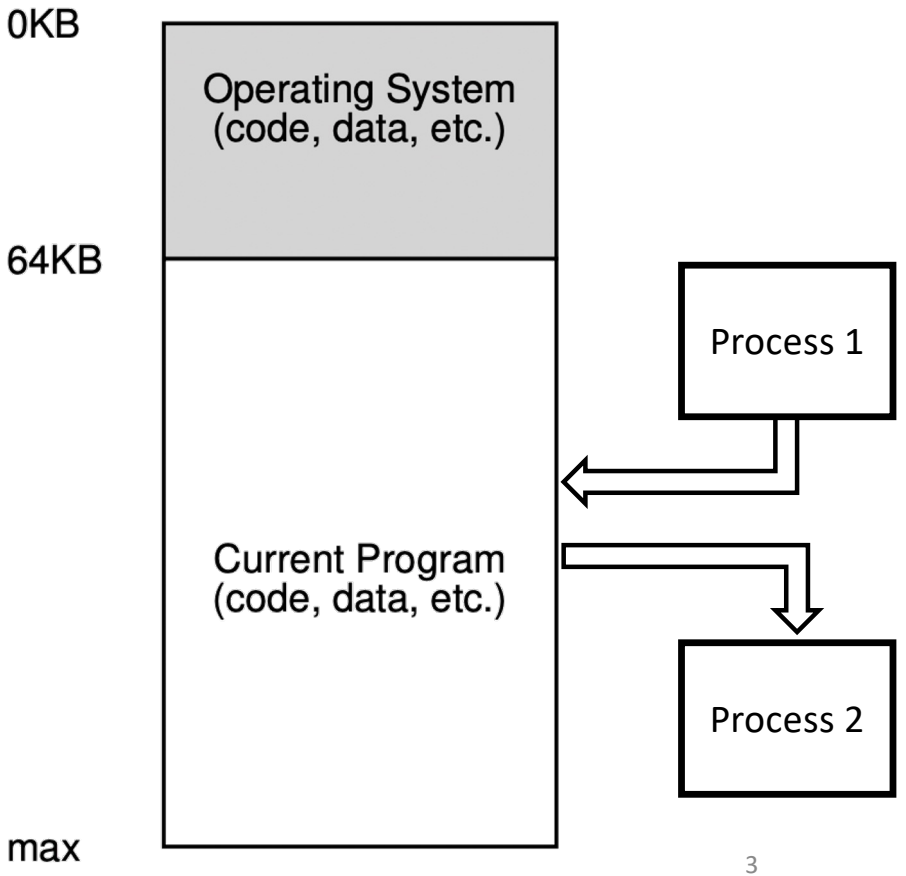
Operating System in Early Days

- The OS is a set of routines (a library) that uses lower memory
  - Starting at physical address 0 in this example
- One running program uses the rest of memory
  - Starting at physical address 64k in this example



Multiprogramming and Time Sharing

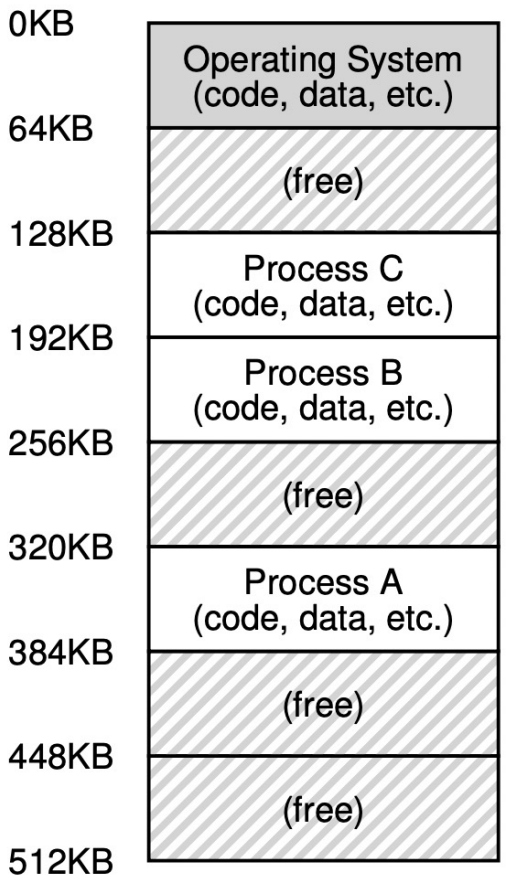
- Multiprogramming [DV66]
  - Multiple processes ready to run at a given time
  - OS switches between them, e.g., when one decided to perform I/O.
- Benefit of multiprogramming
  - Time sharing of computer resources
  - More effective use of CPU
- What about physical memory?
  - Moving data in/out of memory is slow



[DV66] Jack B. Dennis, Earl C. Van Horn. "Programming Semantics for Multiprogrammed Computations". 1966

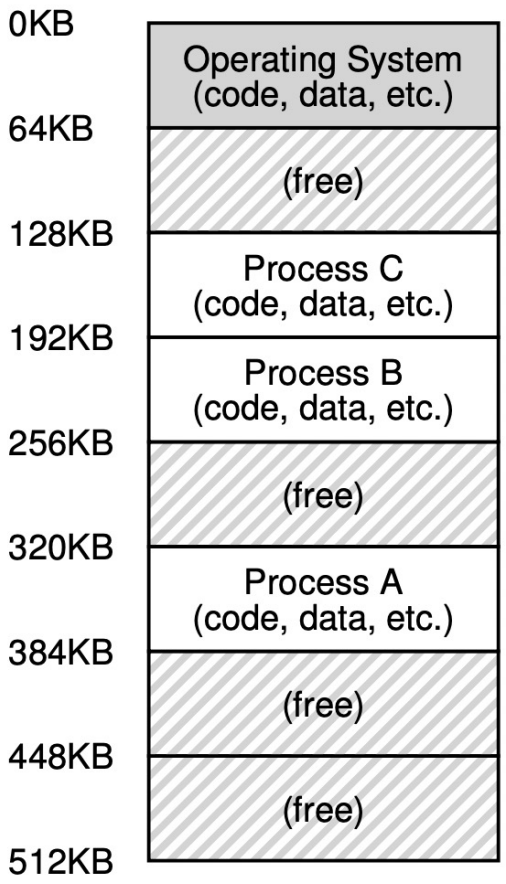
Multiprogramming with Memory Partition

- Solution:
  - Leave processes in memory when switching
  - Each process owns a small part of the physical memory that is carved out for them.
- New demand for complex memory management



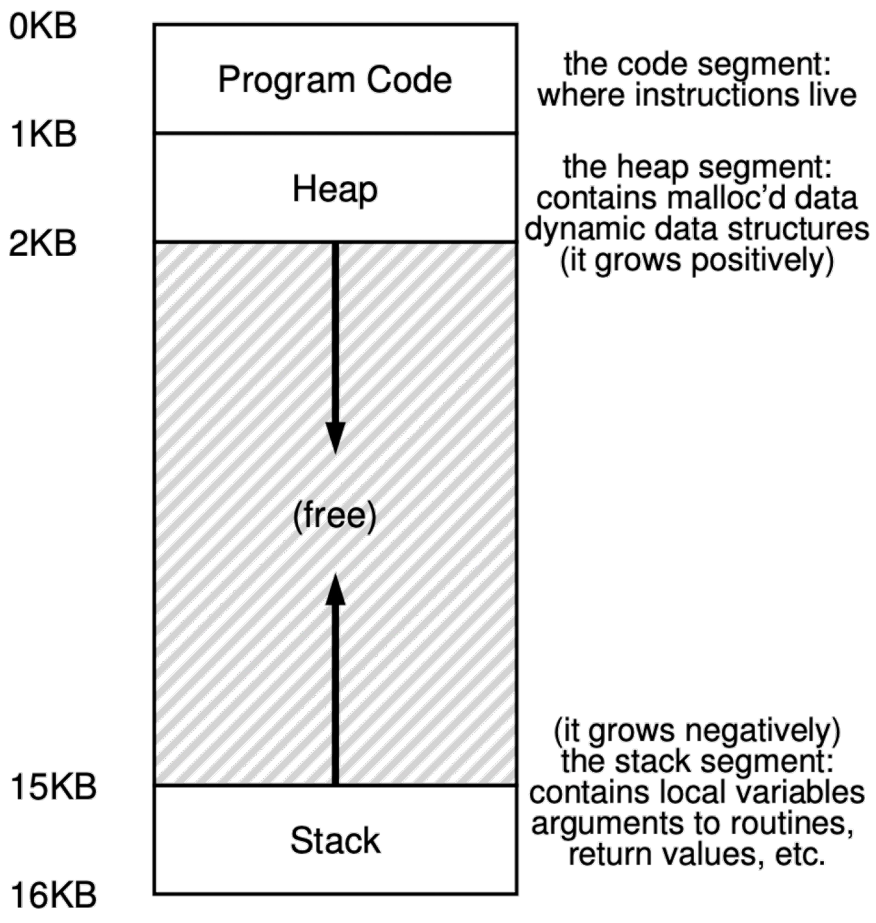
Multiprogramming with Memory Partition

- Potential issues:
  - What happens when Process C needs more memory?
  - How to compile Program B so that it knows it will run at 192KB?
  - What if Process C has an error and writes to address at 1KB or 330KB?



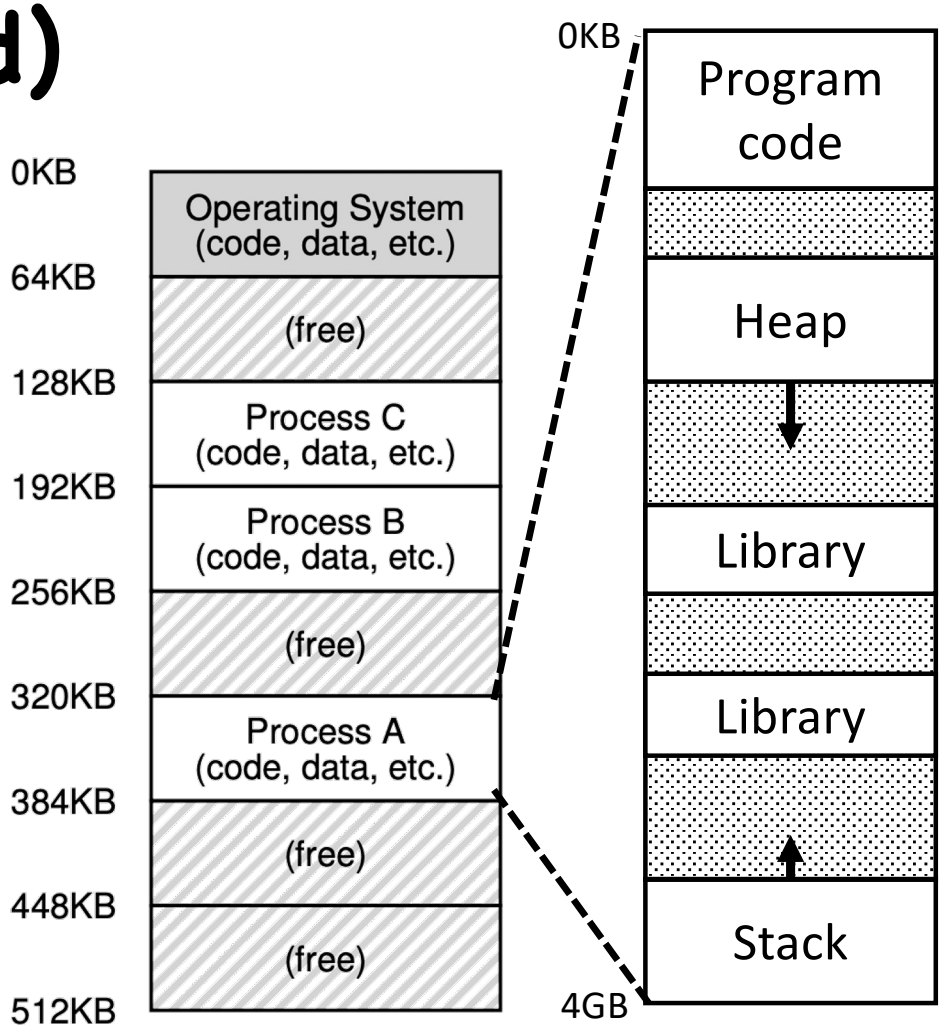
Address Space

- Address space is an important OS abstraction
  - Address space is a process' **view** of memory in the computer system
- Segments in an address space
  - Code segment: instructions at the bottom
  - Stack segment: local variables, arguments, return values
  - Heap: malloc
  - Stack and Heap need to grow



Address Space (Cont'd)

- This 16KB address space is just an abstraction
  - 0KB in the address space is not 0KB of physical memory
- This 16KB address space is just an illustration
  - 32-bit CPU supports up to 2^32 Byte (4GB) address space
  - 64-bit CPU supports up to 2^64 (4EB) Byte
    - But most CPU would reserve higher address bits
    - x86-64 supports only 2^48 Bytes (256TB) address space



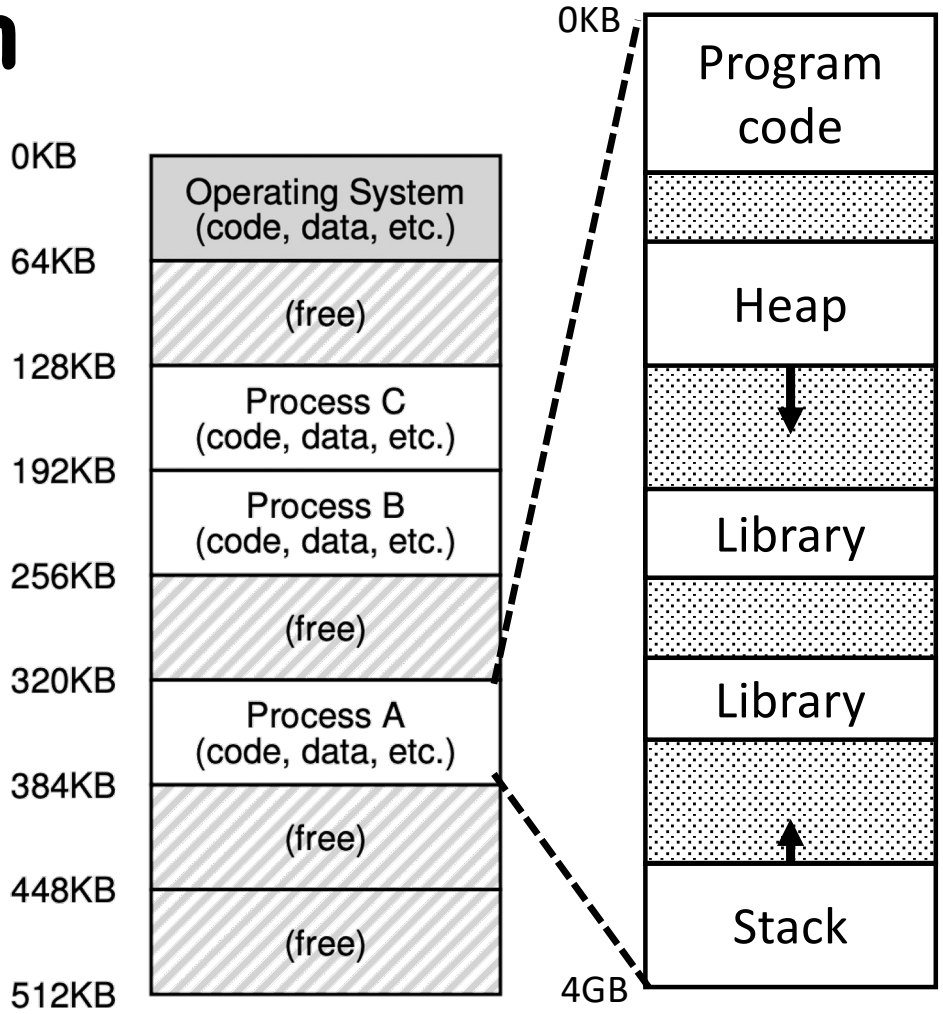
Memory Virtualization

- An abstraction of a private, large address space for multiple running processes on top of a single, physical memory

内存虚拟化是操作系统提供的一种抽象，使得多个正在运行的进程可以在一个单一的物理内存上拥有各自独立的、私有的大地址空间。

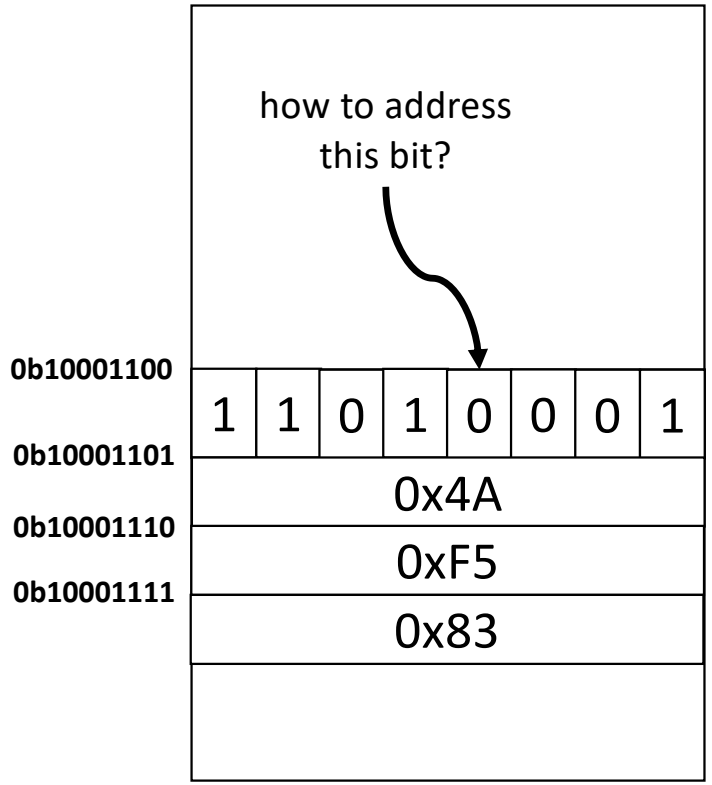
- Virtual address
  - Address in a process' own address space
- Physical address
  - Address of the physical memory
- Address translation
  - Virtual to physical address translation
  - example: 0KB -> 320KB

操作系统通过内存管理单元（MMU）将虚拟地址转换为物理地址。



Aside: Addressing Memory

- Memory address is the address of a BYTE
  - 1 byte = 8 bit
  - how to address a bit?
- Address representation
  - hexidecimal: 0x8c
  - decimal: 140
  - binary: 0b10001100
- Big endian or little endian
  - 32-bit int at 0x8c
  - big endian: 0x d1 4a f5 83
  - little endian: 0x 83 f5 4a d1



Memory Virtualization (Cont'd)

- A mechanism that virtualize memory should
  - Be **transparent**
    - Memory virtualization should be invisible to processes
    - Processes run as if on a single private memory
  - Be **efficient**
    - Time: translation is fast
    - Space: not too space consuming
  - Provide **protection**
    - Enable **memory isolation**
    - One process may not access memory of another process or the OS kernel
    - Isolation is a key principle in building reliable systems

内存虚拟化对进程是透明的。也就是说，进程不需要知道它们的内存实际上是虚拟的，它们只需要使用自己的虚拟地址空间，操作系统负责地址转换。

进程就像在独立的私有内存中运行。

Virtual Address v.s. Physical Address

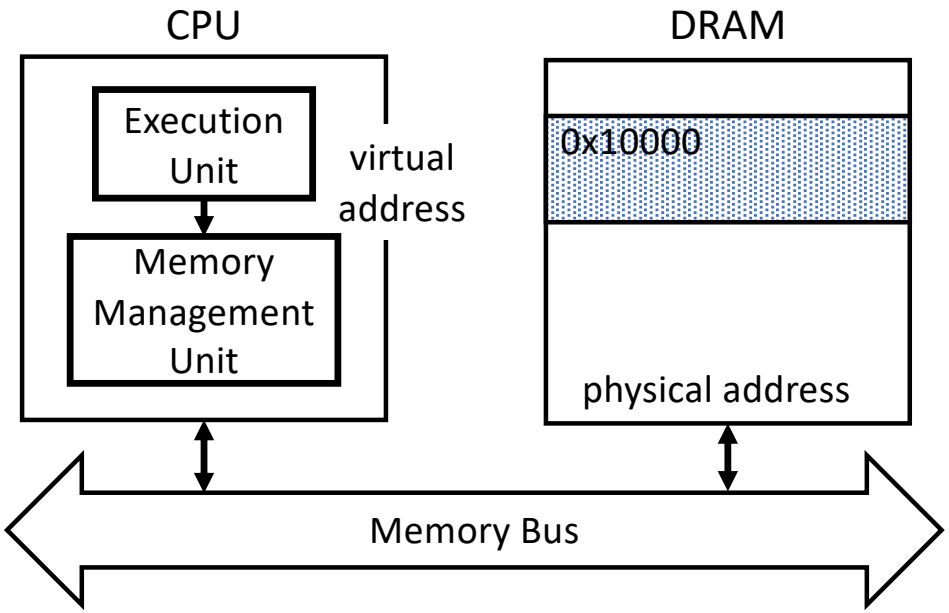
- Process uses virtual addresses

```
1.  #include <stdio.h>
2   #include <stdlib.h>
3   int main(int argc, char *argv[]) {
4       printf("code : %p\n", main);
5       printf("heap : %p\n", malloc(100e6));
6       int x = 3;
7       printf("stack: %p\n", &x);
8       return x;
9   }
```

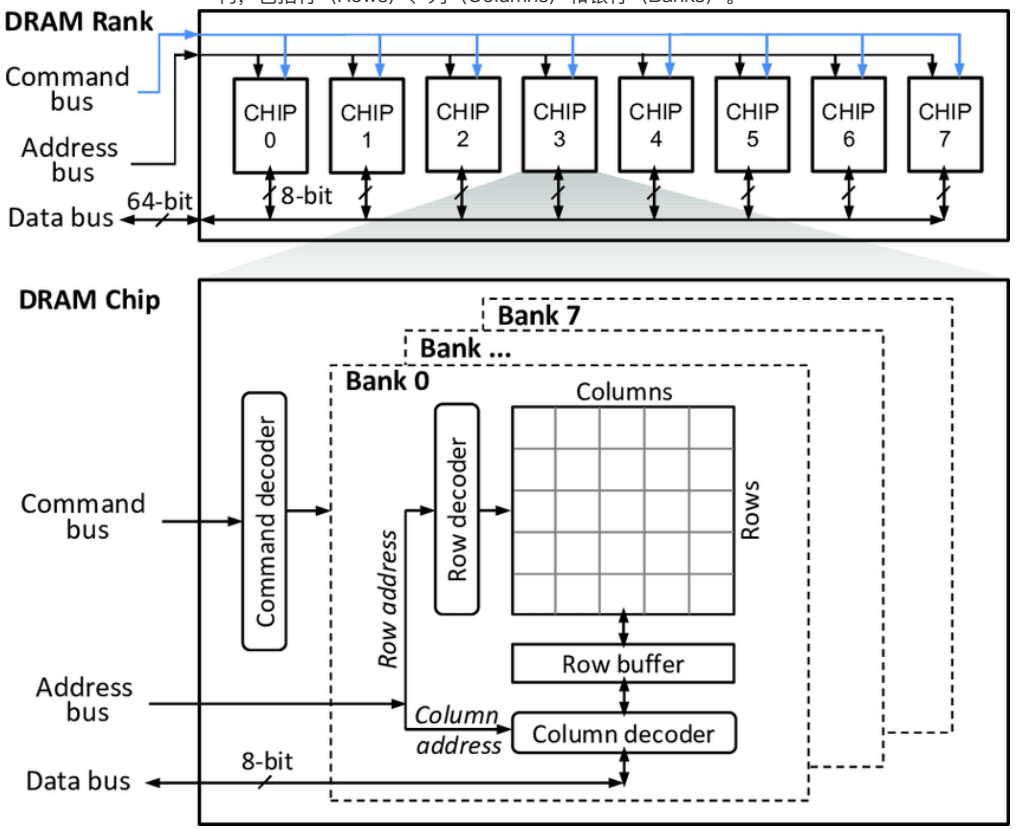
```
$ ./mem_layout
code : 0x1095afe50
heap : 0x1096008c0
stack: 0x7fff691aea64
```

Virtual Address v.s. Physical Address

- CPU uses physical addresses to access DRAM



DRAM（动态随机存取内存）被划分成多个内存芯片（DRAM Chip），每个芯片内部有不同的存储结构，包括行（Rows）、列（Columns）和银行（Banks）。



Address Translation

MMU is usually on the CPU chip, but may also be off-chip or pure software

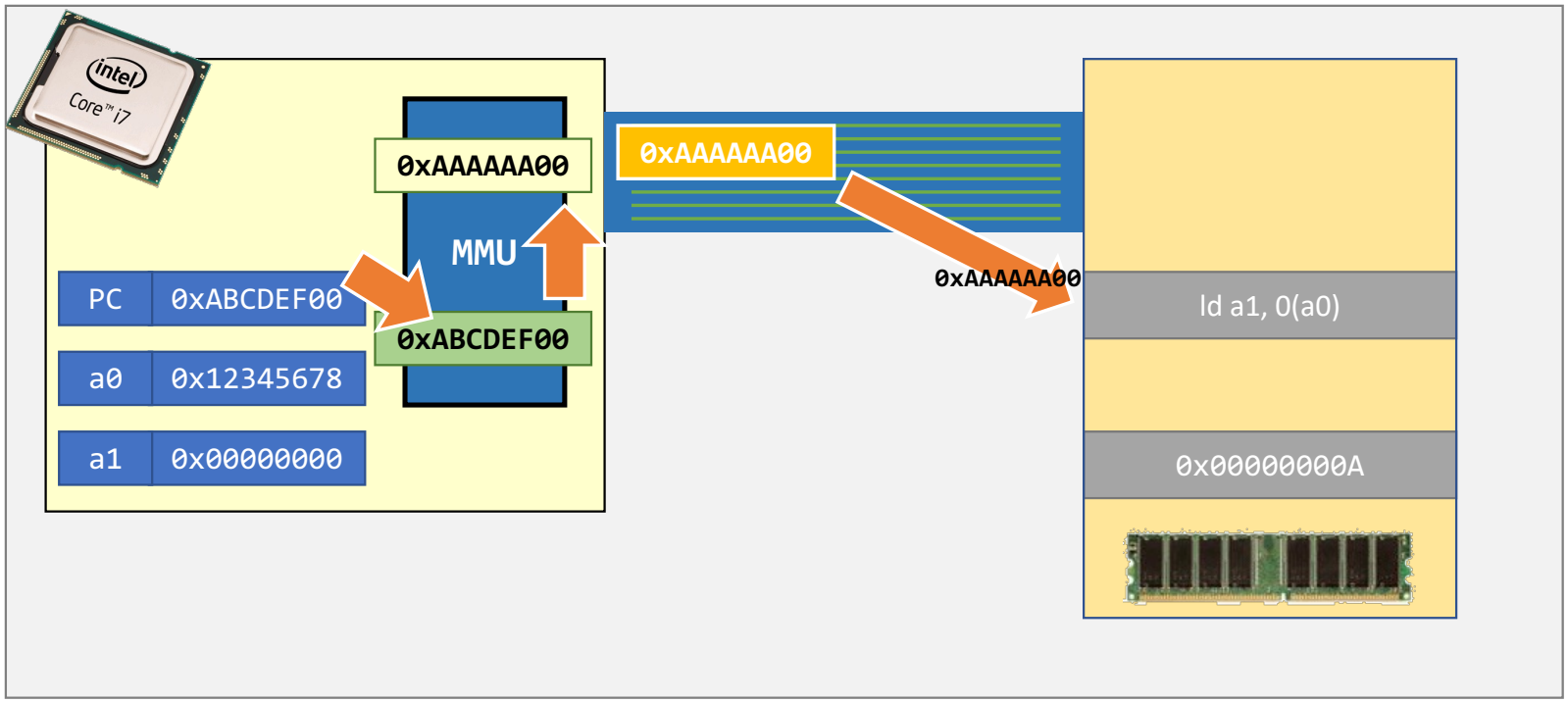
- Coordination between CPU hardware and OS software
- Memory management unit (MMU) in CPU
  - Translate virtual address used by instruction to physical address understood by DRAM
  - CPU interposes every memory access
    - Interposition: a generic and powerful technique used in computer systems for better tranparency

CPU拦截每次内存访问：每次内存访问都经过MMU进行地址转换，以确保程序访问到正确的内存位置。

- Operating system
  - Set up hardware for correct translation
  - Keep track of which locations are free and which are in use
  - Maintain control of how memory is used

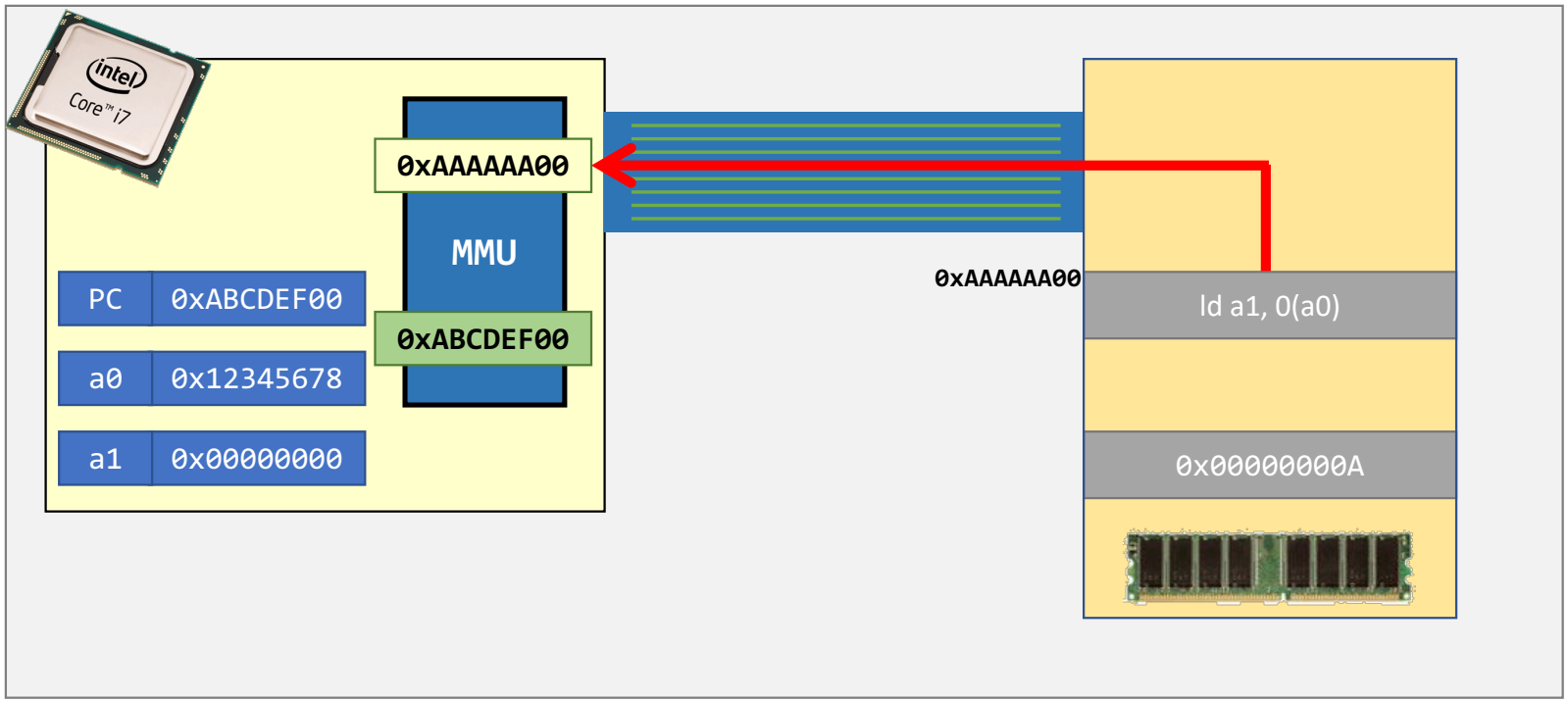
Address Translation in Action

- Step 1: Fetch instruction at virtual address 0xabcdef00



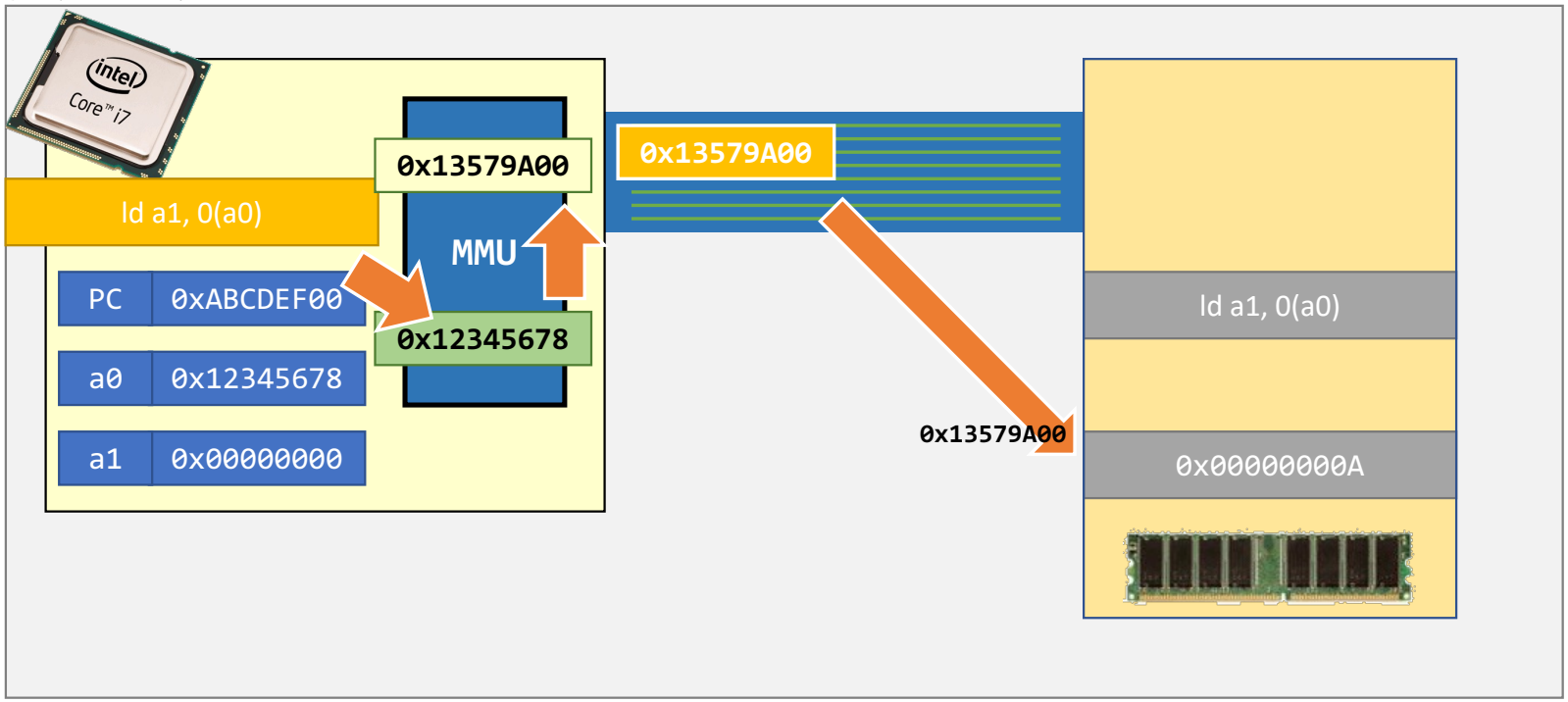
Address Translation in Action

- Step 2: Instruction fetched from physical address 0xaaaaaa00



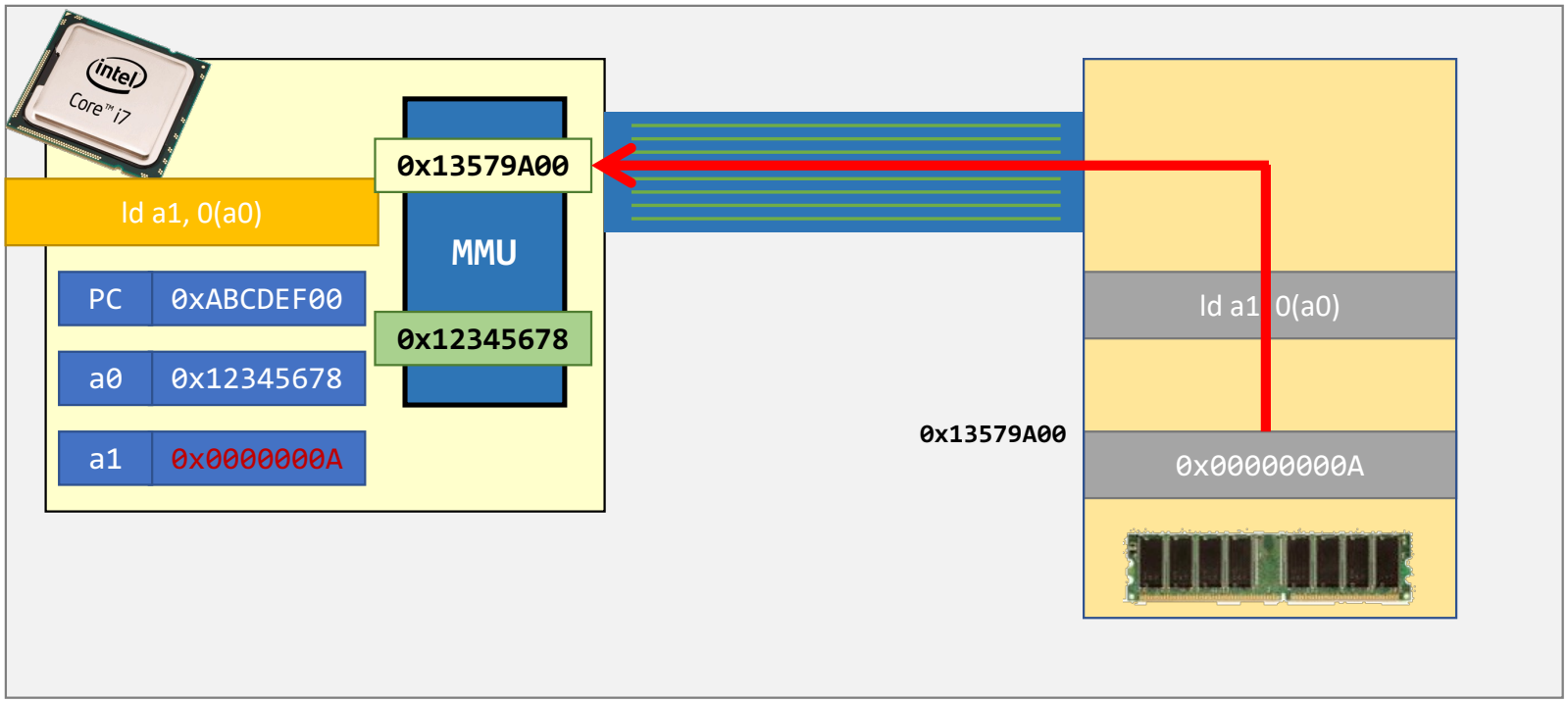
Address Translation in Action

- Step 3. CPU executes the instruction and access virtual address at 0x12345678



Address Translation in Action

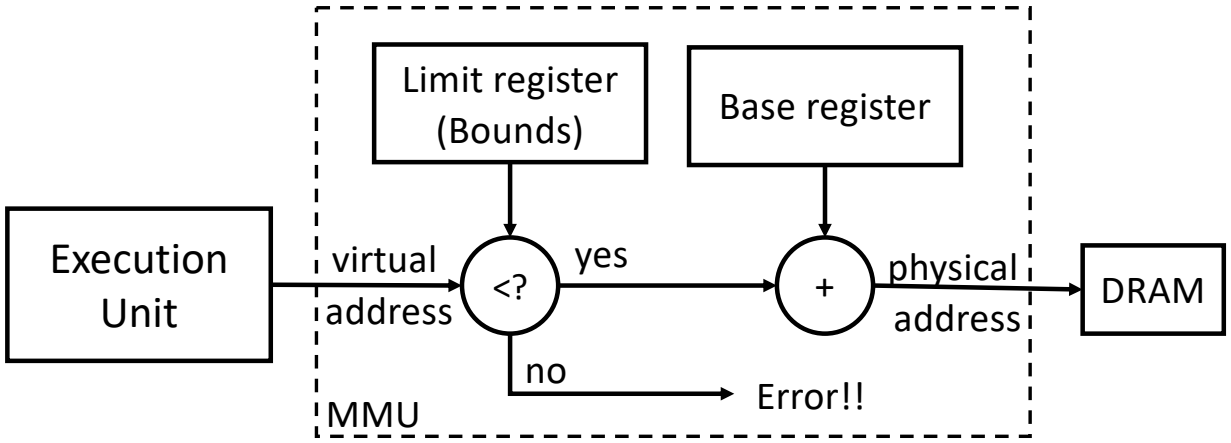
- Step 4. Data retrieved from physical address 0x13579a00 into EAX

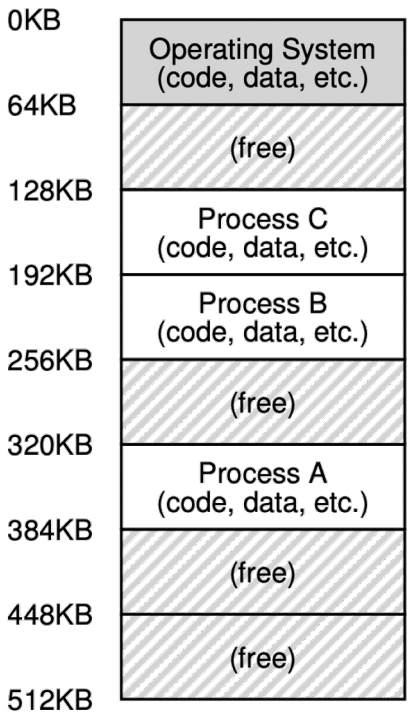


How to Translation Virtual Address to Physical Address

Base & Bounds: Dynamic Relocation

- Two hardware registers [SS74]
  - base register
  - bounds register (also called a limit register).
  - Process A, e.g., base 320KB, bounds 64KB





[SS74] "The Protection of Information in Computer Systems" by J. Saltzer and M. Schroeder. CACM, July 1974.

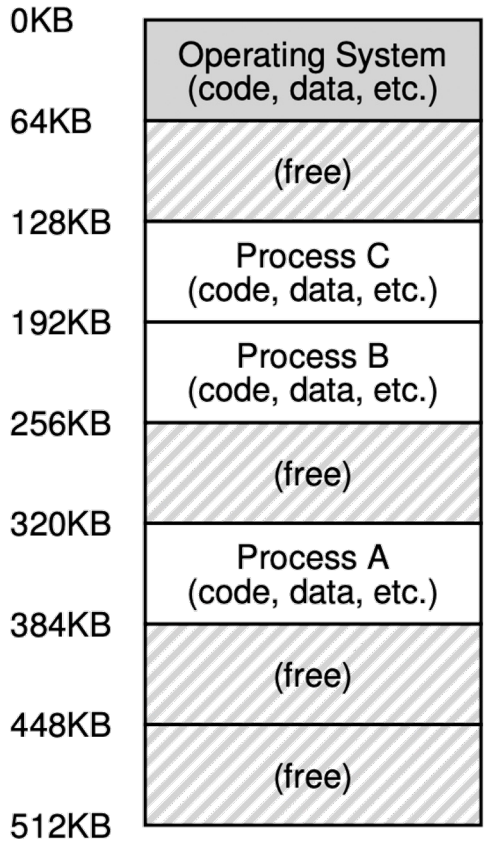
Hardware & OS Coordination

Hardware Support	Explanation
Privileged mode to update base/bounds	Needed to prevent user-mode processes from executing privileged operations to update base/bounds
Base/bounds registers	Need pair of registers per CPU to support address translation and bounds checks
Privileged instruction(s) to register exception handlers	Need to allow OS, but not the processes, to tell hardware what exception handlers code to run if exception occurs

OS Support	Explanation
Memory management	Need to allocate memory for new processes; Reclaim memory from terminated processes; manage memory via free list
Base/bounds management	Must set base/bounds properly upon context switch
Exception handling	Code to run when exceptions arise; likely action is to terminate offending process

Limitations of Base & Bounds

- Internal fragmentation
  - wasted memory between heap and stack
- Cannot support larger address space
  - Address space equals the allocated slot in memory
  - example: Process C's address space is at most 64KB
- Hard to do inter-process sharing
  - Want to share code segments when possible
  - Want to share memory between processes
  - example: Process A & C cannot share memory

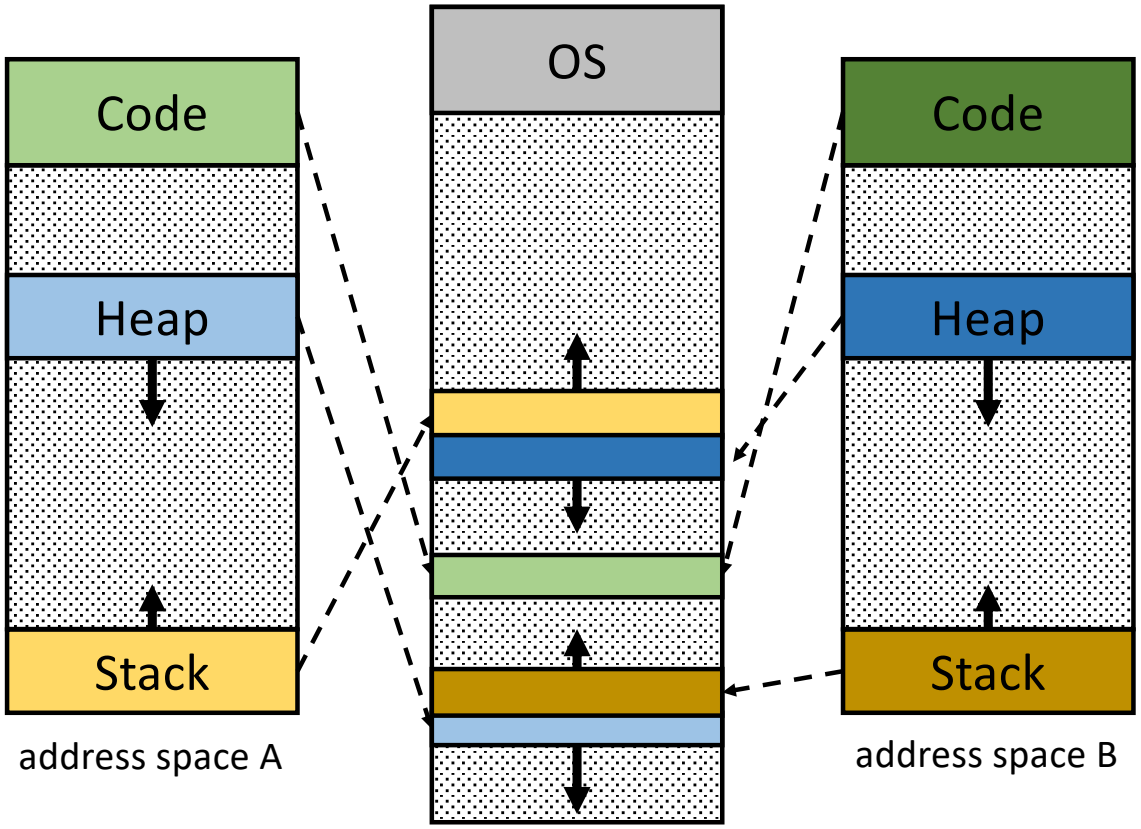


Segmentation: Generalized Base/Bounds

- A pair of base/bounds registers for each segment
  - code, stack, heap

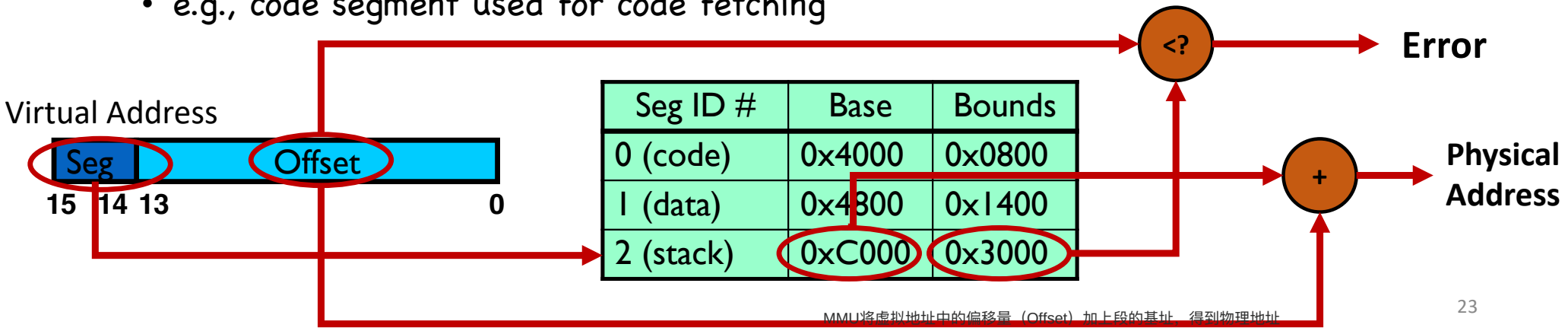
代码段（Code）、堆段（Heap）和栈段（Stack）都有各自的基址寄存器和界限寄存器

- Each segment mapped to a different region of the physical memory
  - internal fragmentation?
  - larger address space?
  - inter-process sharing?



Segmentation: Implementation

- Base/bounds registers organized as a table
  - Segment ID used to index the base/bounds pair
  - Base added to offset (of virtual address) to generate physical address
  - Error check catches offset (of virtual address) out of range
- Use segments explicitly
  - **Segment addressed by top bits of virtual address**
  - or, x86-32 mov [es:bx],ax.
- Use segments implicitly
  - e.g., code segment used for code fetching



MMU将虚拟地址中的偏移量（Offset）加上段的基址，得到物理地址

More about Segmentation

- Memory sharing with segmentation
  - Code sharing on modern OS is very common
  - If multiple processes use the same program code or library code
    - Their address space may overlap in the physical memory
    - The cooresponding segments have the same base/bounds
  - Memory sharing needs memory protection
- Memory protection with segmentation
  - Extend base/bounds register pair
  - Read/Write/Execute permission

当多个进程使用相同的程序代码或共享库时，它们的地址空间可能会在物理内存中重叠。尽管它们在虚拟地址空间中独立，但在物理内存中可以共享相同的代码段。

由于内存共享可能带来安全隐患，内存保护机制显得非常重要。操作系统可以使用扩展的基址/界限寄存器，为每个段设置读/写/执行权限，从而防止未经授权的访问。

Seg ID	Base	Bounds	protection
0 (code)	0x4000	0x0800	Read-Execute
1 (data)	0x4800	0x1400	Read-Write
2 (stack)	0xC000	0x3000	Read-Write

Problems with Segmentation

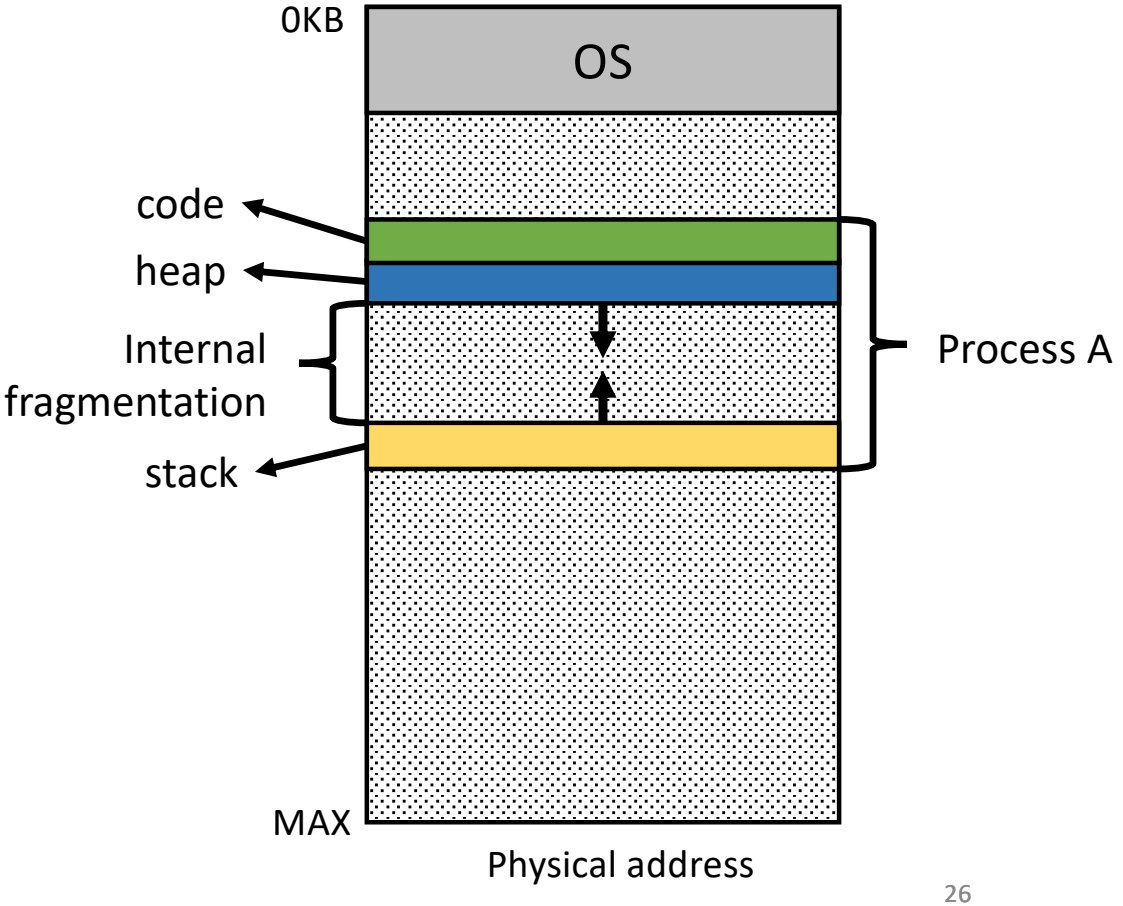
- OS context switch must also save and restore all pairs of segment registers
- A segment may grow, which may or may not be possible
- Management of free spaces of physical memory with variable-sized segments
- **External fragmentation**: free gaps between allocated segments
  - Segmentation may also have internal fragmentation if more space allocated than needed.

内存中会出现已分配段之间的空隙，这些空隙通常无法直接利用，导致内存利用率下降

即使分段方式能有效地管理内存，内部分配碎片依然存在。如果分配给一个段的内存比它实际需要的多，剩余的空闲空间就会被浪费。

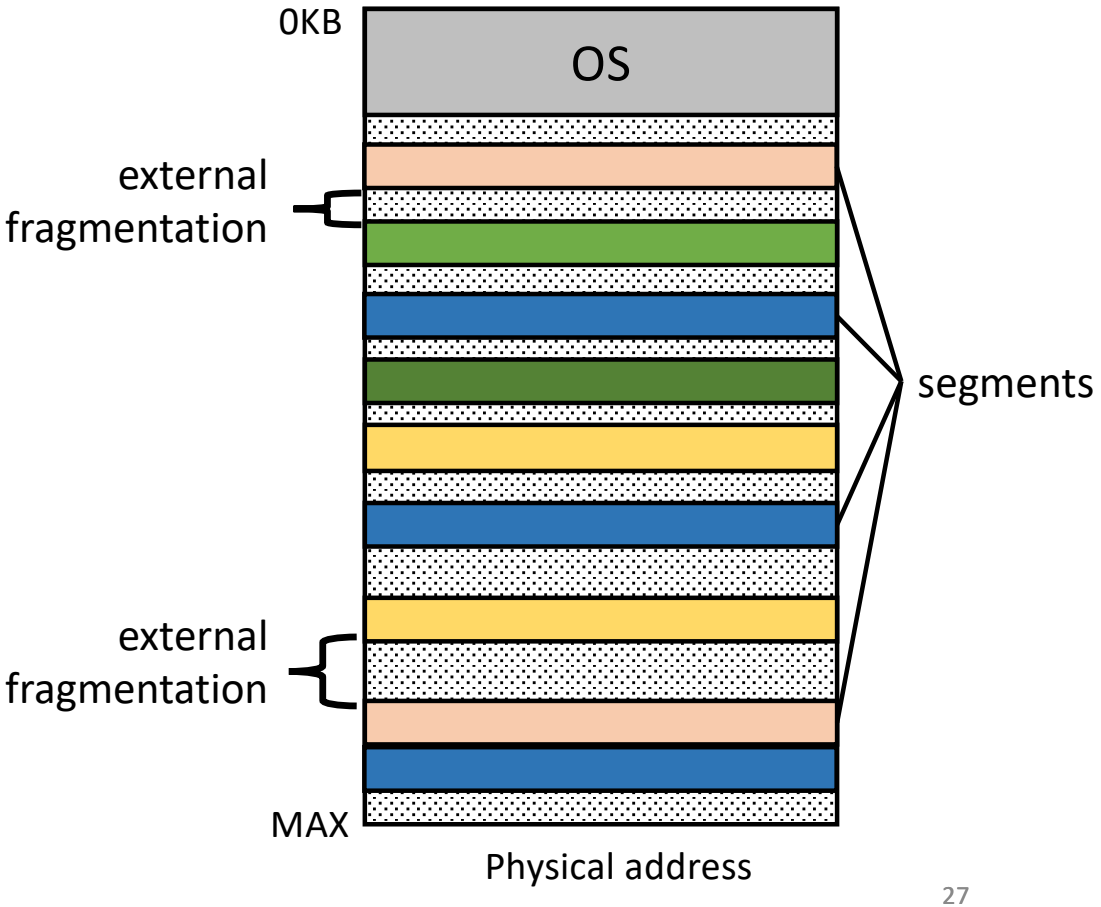
Fragmentation Illustrated

- Internal fragmentation with Base & Bounds
- Space between heap and stack may be wasted



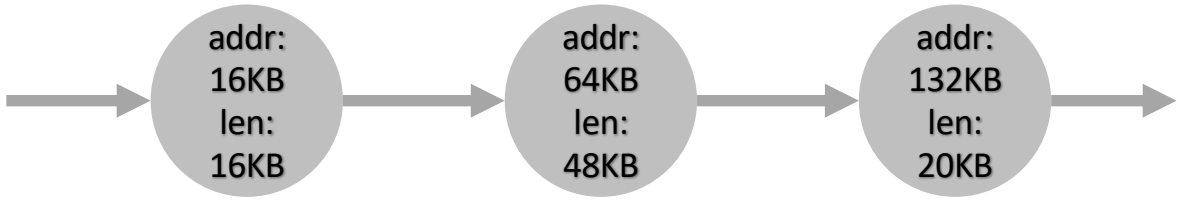
Fragmentation Illustrated (Cont'd)

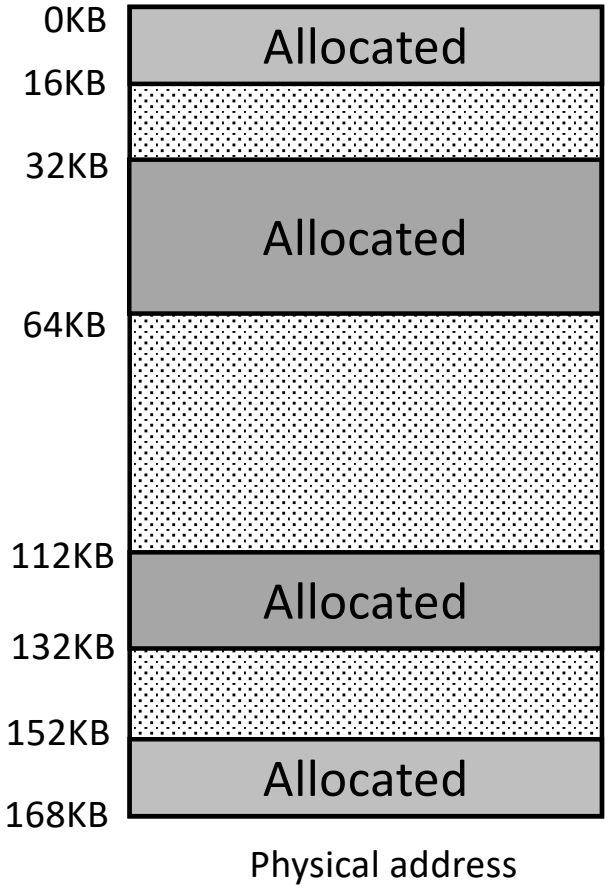
- External fragmentation with segmentation
- free spaces are curved into small chunks
  - each is too small for further allocation
  - added together could be a huge waste



Memory Allocation

- OS needs to manage all free physical memory regions
- A basic solution is to maintain a linked list of free slots
- An ideal allocation algorithm is both **fast** and **minimizes fragmentation**.



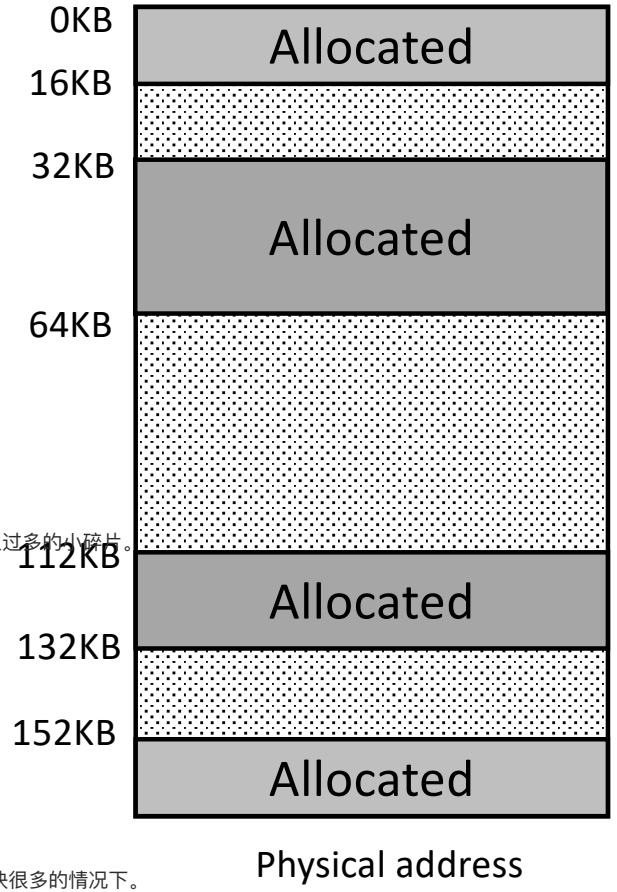


Basic Strategies: Best Fit

- Idea
  - search through the free list and find chunks of free memory that are as big or bigger than the requested size.
  - return the one that is the **smallest** in that group of candidates;
- Pros
  - Satisfy the request with minimal external fragmentation
- Cons
  - exhaustive search is slow

搜索空闲内存链表，找到所有大小大于或等于所请求内存大小的空闲内存块。

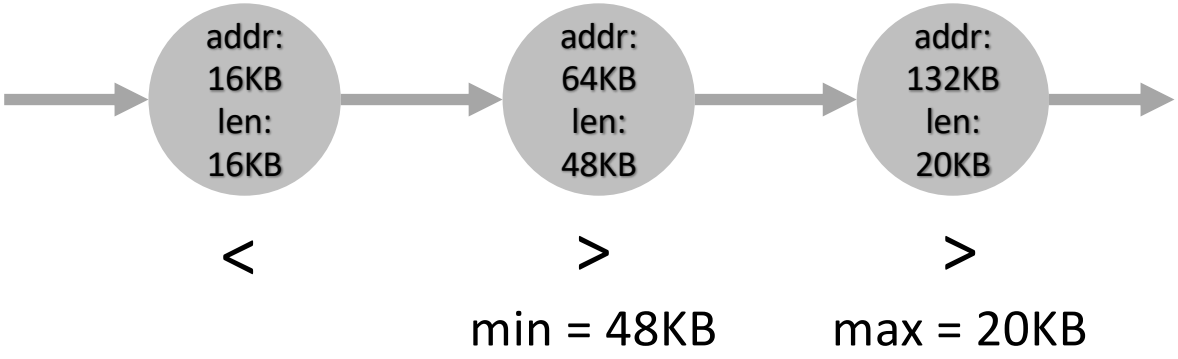
选择最小的空闲内存块，即在满足请求大小的所有内存块中，选择最小的那个。这可以减少内存的浪费，避免产生过多的小碎片。

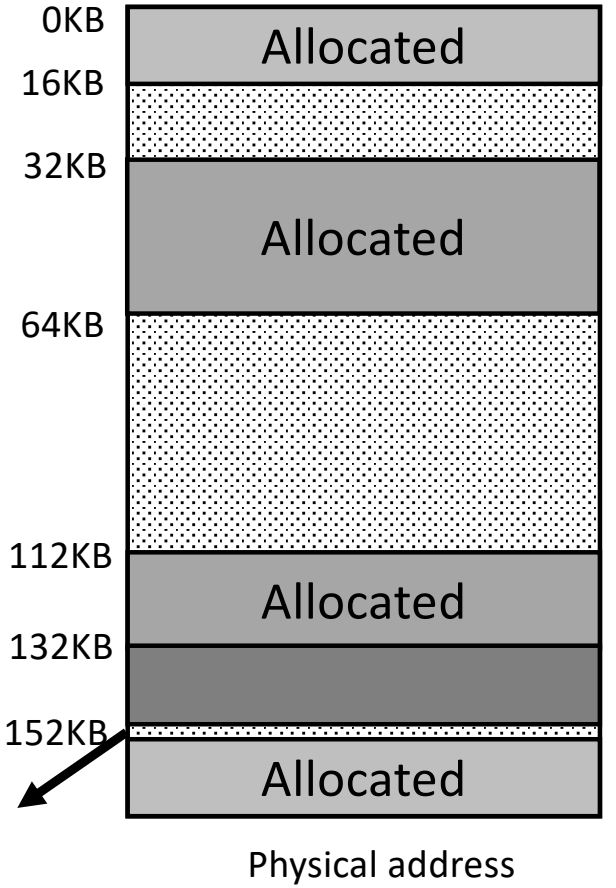


搜索开销大：由于需要对空闲链表进行全面搜索以找到最适合的内存块，这样的算法可能会导致较慢的内存分配过程，特别是在空闲内存块很多的情况下。

Basic Strategies: Best Fit (Cont'd)

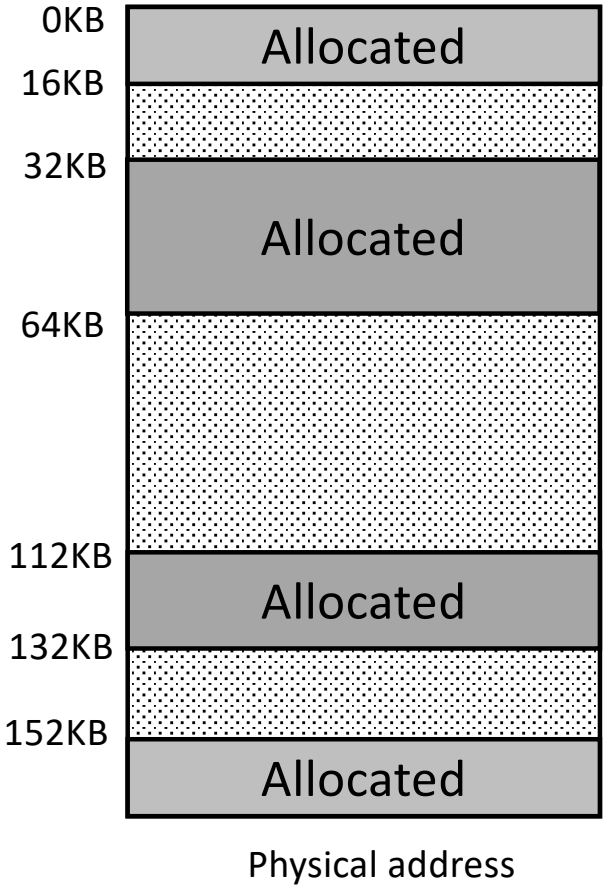
- Example
  - Requested space is 18KB
  - Allocated at 132KB





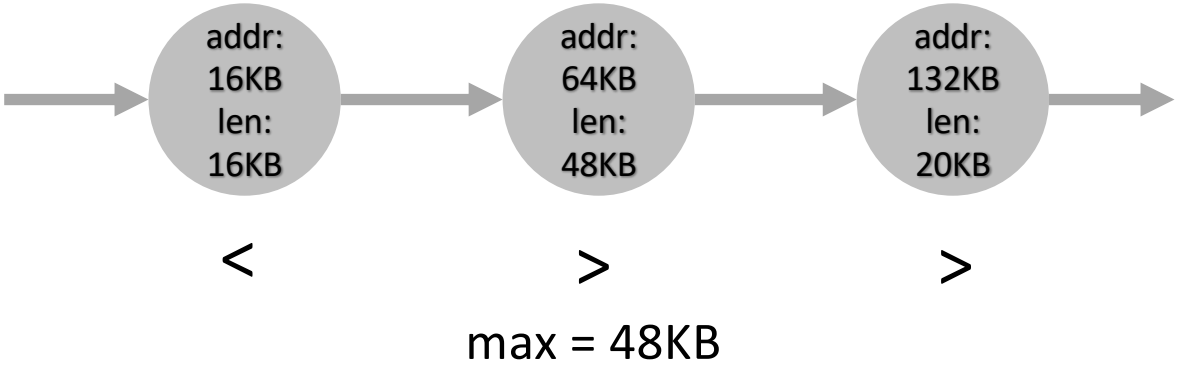
Basic Strategies: Worst Fit

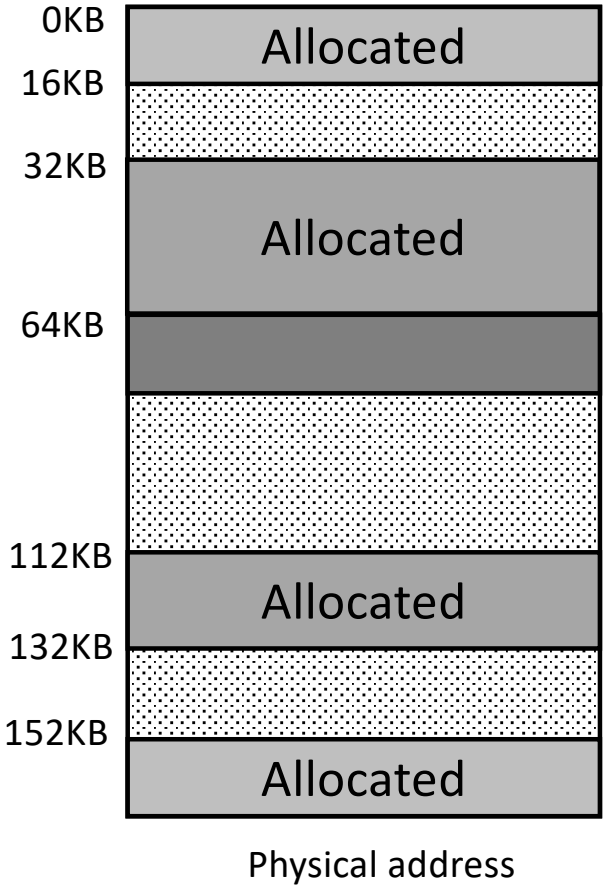
- Idea
  - search through the free list and find chunks of free memory that are as big or bigger than the requested size.
  - return the one that is the **largest** in that group of candidates;
- Pros
  - Leaves larger "holes" in physical memory
- Cons
  - exhaustive search is slow
  - severe fragmentation in practice



Basic Strategies: Worst Fit (Cont'd)

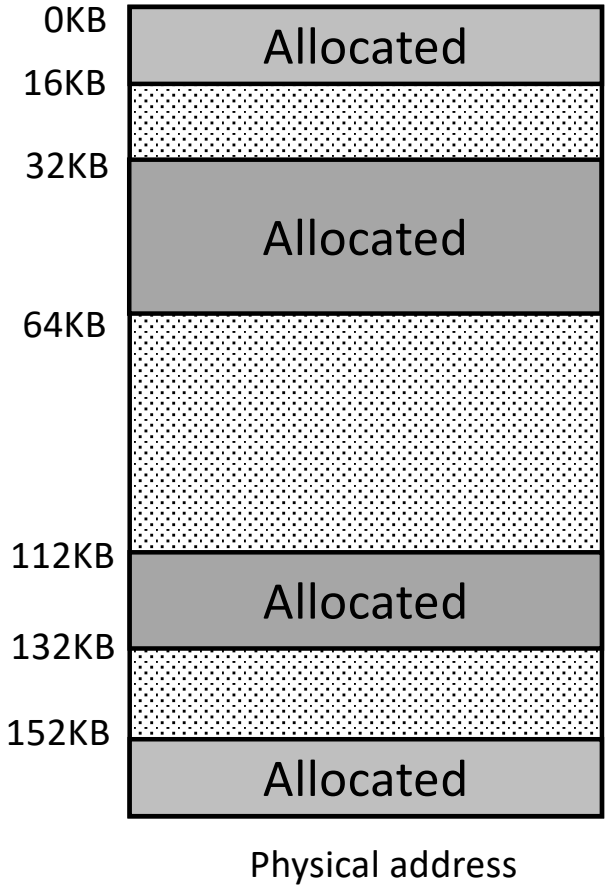
- Example
  - Requested space is 18KB
  - Allocated at 64KB





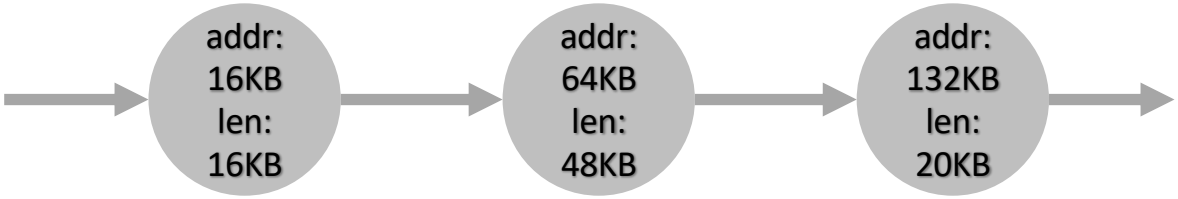
Basic Strategies: First Fit

- Idea
  - find the first block that is big enough and returns the requested size
- Pros
  - Fast
- Cons
  - pollutes the beginning of the free list with small chunks

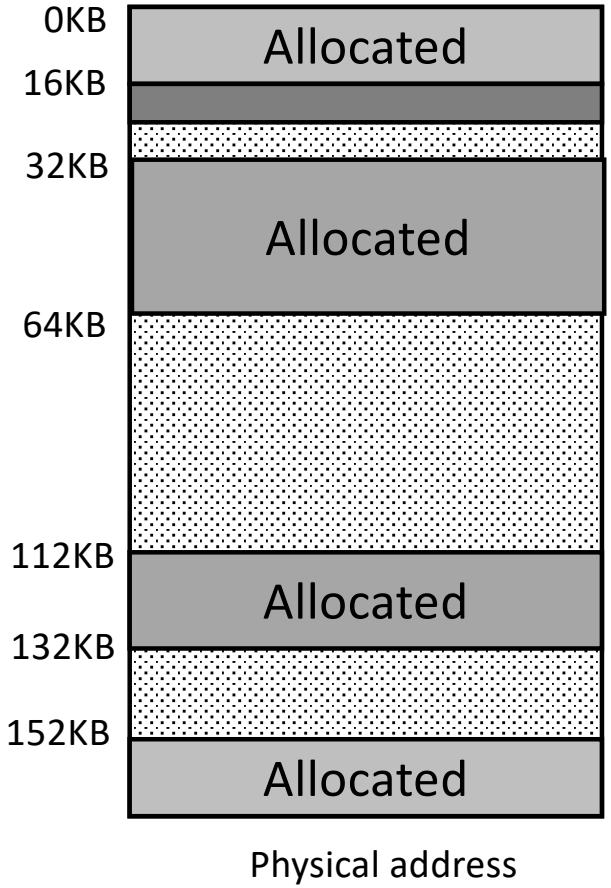


Basic Strategies: First Fit (Cont'd)

- Example
  - Requested space is 8KB
  - Allocated at 16KB



>, stop



Summary

- Address space is a key abstraction of OS
- Address translation requires hardware/software coorperation
- Two schemes so far: (1) Base & Bounds (2) segmentation
- Internal/external fragmentation is an issue
- Best/worst/first fit, no best option

Thank you!