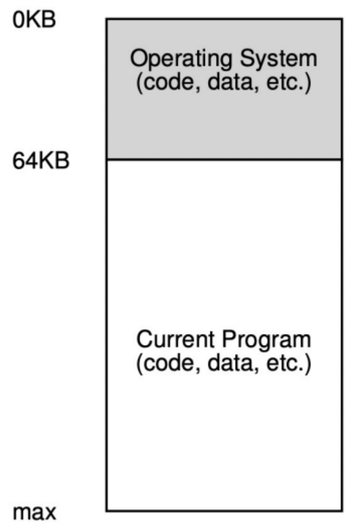
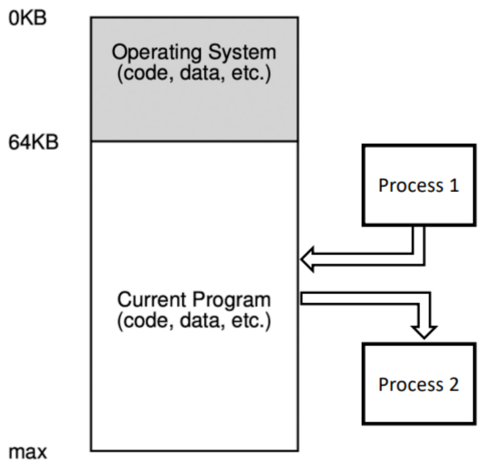
Lecture6 Address Translation

1. Operating System Memory



- 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**
  - eg. Starting at physical address 64k in this example

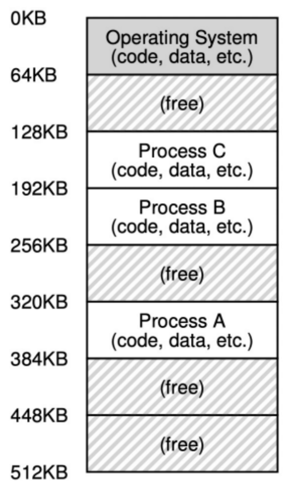
Multiprogramming



- Multiprogramming
  - 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**

Memory Partition

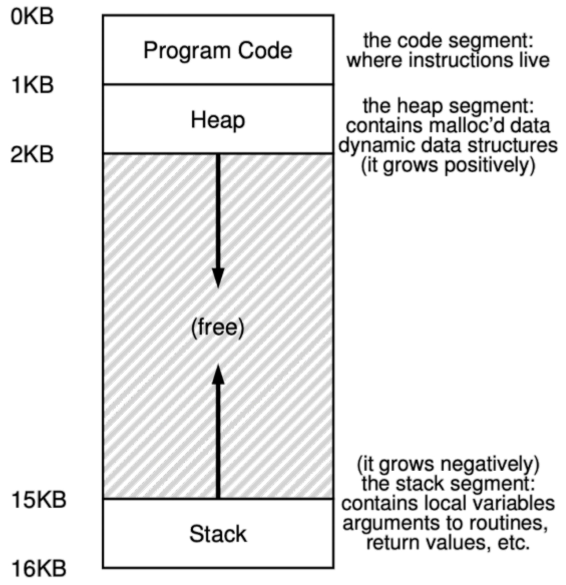


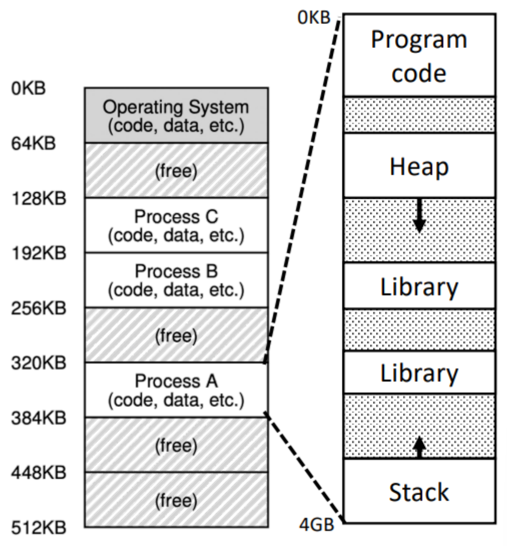
- Solution
    - Leave processes in memory when switching
    - Each process owns **a small part of the physical memory** that is carved out for them
- Potential issues
    - What happens when Process C needs more memory?
    - How to compile Program B so that it knows it will run at 192KB?
        - use virtual address
    - What if Process C has an error and writes to address at 1KB or 330KB?
        - can not access different processes' data

Address Space

- Address space is an important OS abstraction
    - Address space is a **process**' **view** of memory in the computer system

Segments





Segment	Characteristic
Code	
Heap	malloc need to grow
free space	
Stack	local variables, arguments, return values need to grow

- This 16KB address space is just an **abstraction**
- 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

Addressing Memory

- Memory address is the address of a **BYTE**
  - 1 byte = 8 bit
- Address representation
  - hexadecimal: 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

2. Memory Virtualization

- An abstraction of a private, large address space for multiple running processes on top of a single, physical memory
- Virtual address
  - Address in a process' own address space
- Physical address
  - Address of the physical memory
- **Address translation**
  - Virtual to physical address translation

Mechanism

A mechanism that virtualize memory should

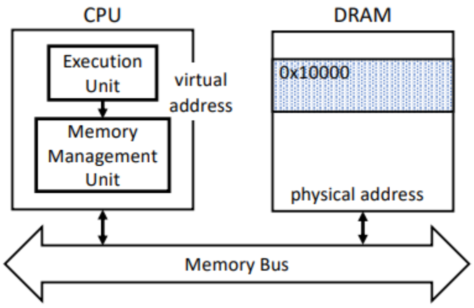
- Be **transparent**
  - Memory virtualization should be **invisible** to processes
  - Processes run as if on a single private memory
- Be **efficient**
  - Time: translation is fast
  - Space: not too space consuming
- Provide **protection**
  - Enable **memory isolation**
  - One process may not access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

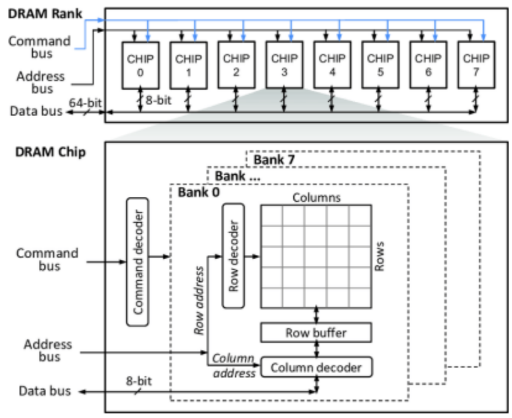
Virtual Address v.s. Physical Address

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

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

- Process uses **virtual** addresses





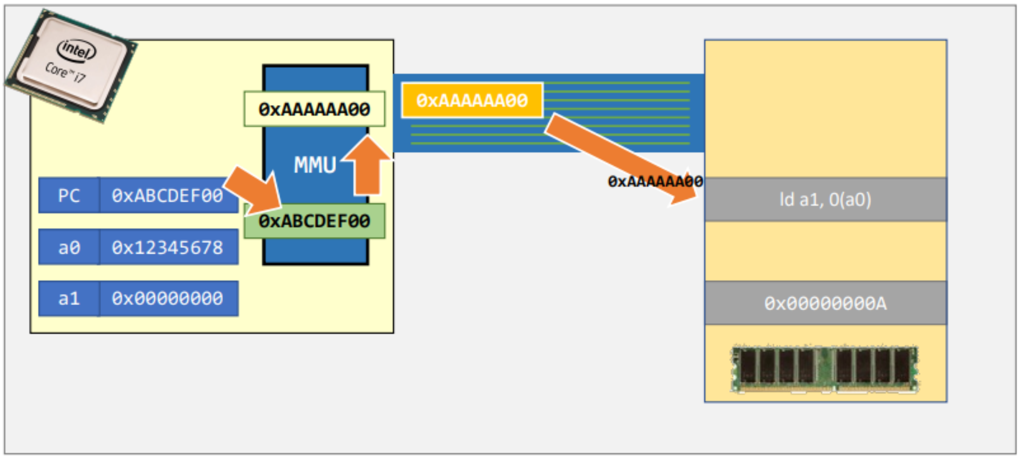
- CPU uses physical addresses to access DRAM

Address Translation

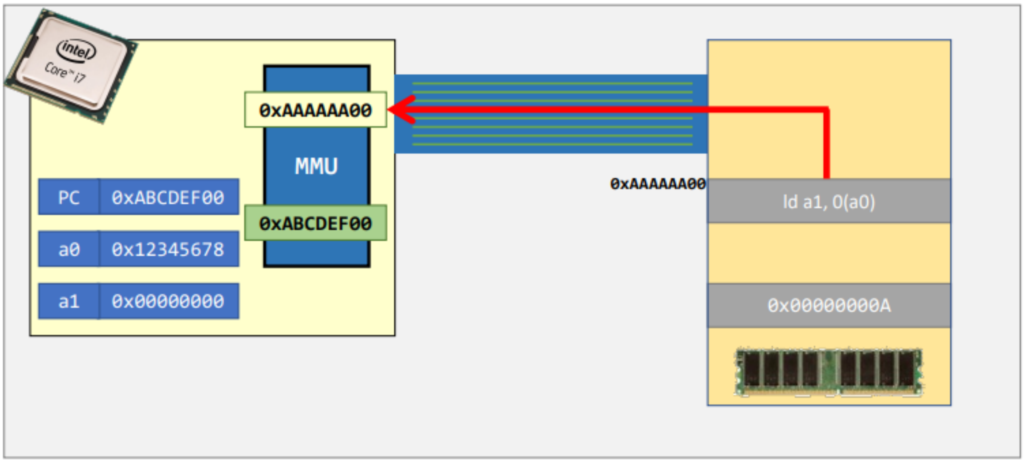
- Coordination between CPU hardware and OS software
- CPU: **Memory Management Unit (MMU)**
    - Translate virtual address used by instruction to physical address understood by DRAM
    - CPU **interposes** every memory access
        - Interposition: a generic and powerful technique used in computer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

Steps

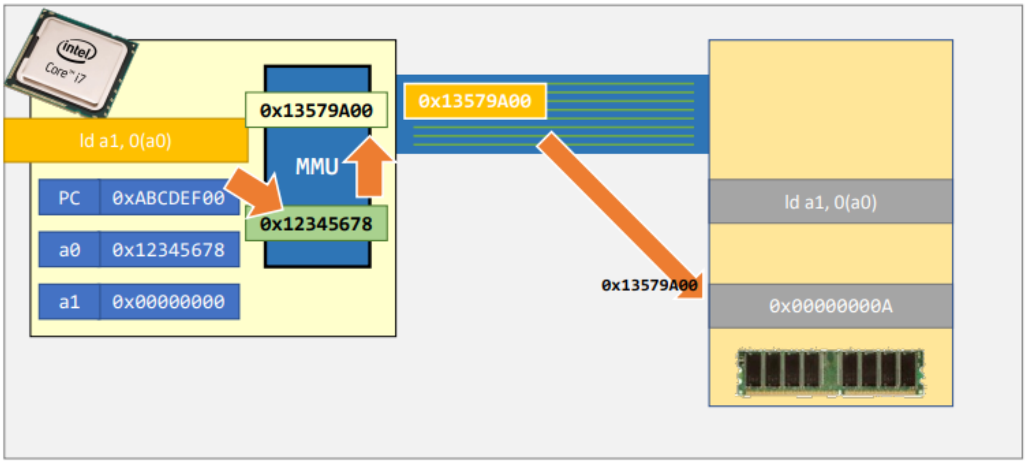
Fetch instruction at virtual address 0xabcdef00



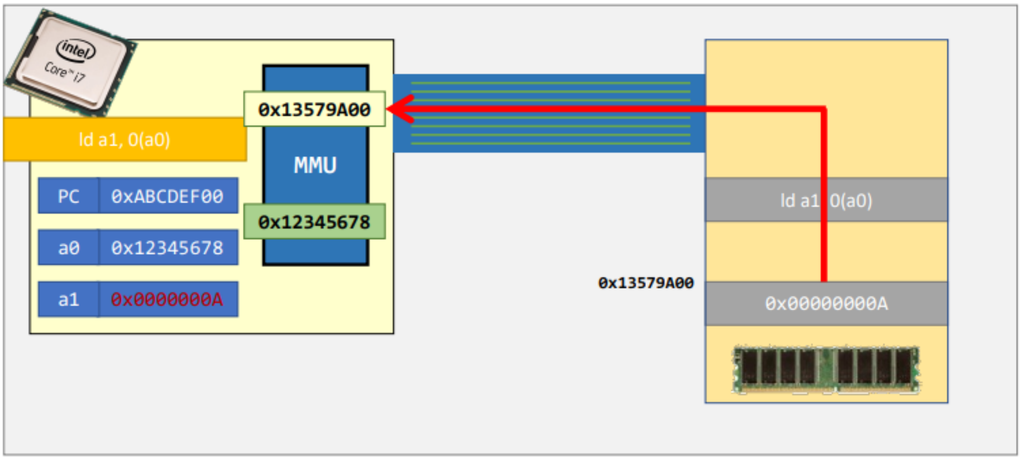
Instruction fetched from physical address 0xaaaaaa00



CPU executes the instruction and access virtual address at 0x12345678

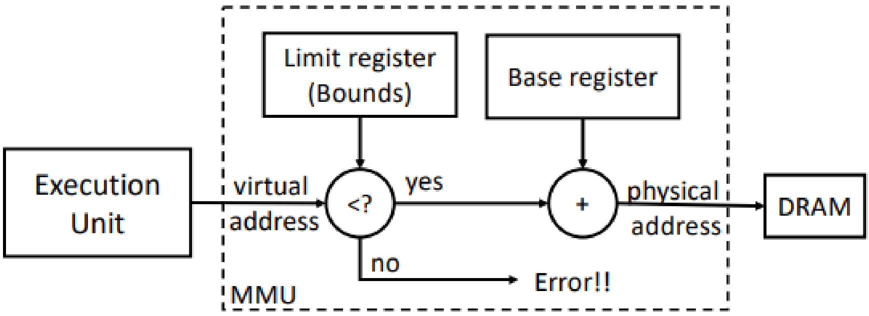


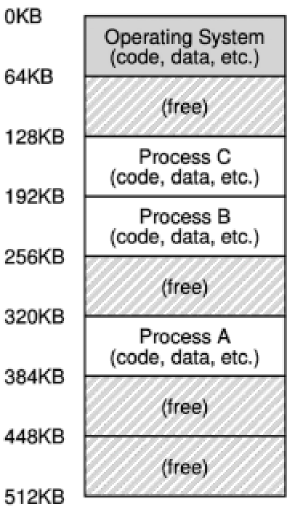
Data retrieved from physical address 0x13579a00 into EAX



3. How to Translate Virtual Address to Physical Address

Base & Bounds



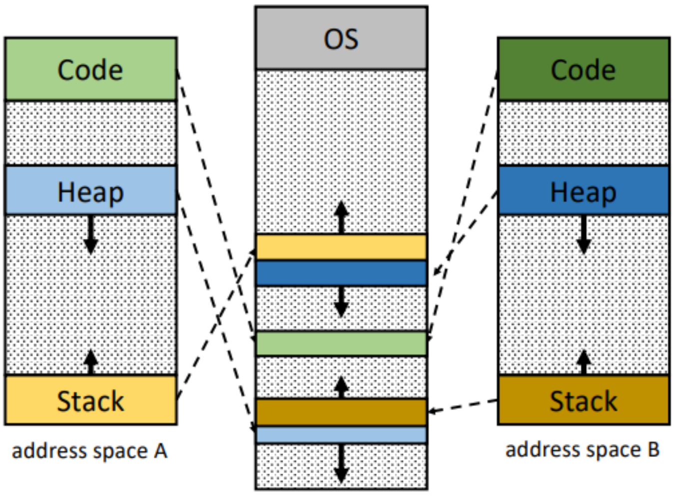


- Two hardware registers
  - **base register**
  - **bounds register** (also called a limit register)
  - eg. Process A, base 320KB, bounds 64KB

Limitation

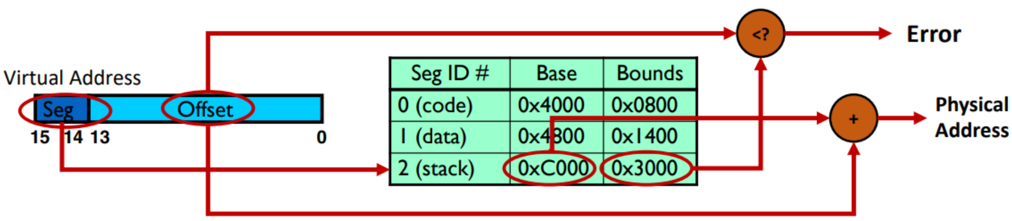
- **Internal fragmentation**
  - wasted memory between heap and stack
- Cannot support **larger** address space
  - Address space equals the allocated slot in memory
  - example: Process C's address space is at most 64KB
- Hard to do inter-process sharing
  - Want to share code segments when possible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

Segmentation



- A pair of base/bounds registers for each segment
  - code, stack, heap
- Each segment mapped to a **different region of the physical memory**
  - internal fragmentation -> no more!
  - larger address space -> yes!
  - inter-process sharing -> yes!

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 rang
- Use segments explicitly
  - **Segment addressed by top bits of virtual address**

More about Segmentation

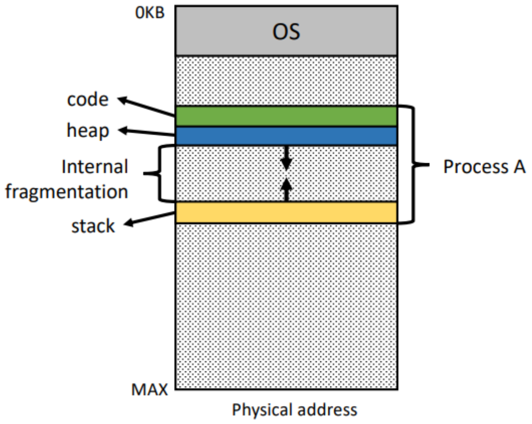
Seg ID	Base	Bounds	protection
0 (code)	0x4000	0x0800	Read-Execute
1 (data)	0x4800	0x1400	Read-Write
2 (stack)	0xC000	0x3000	Read-Write

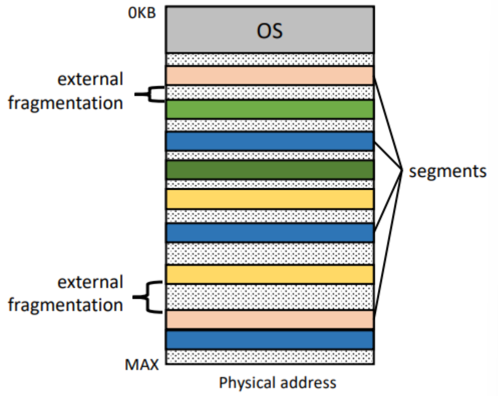
- Memory sharing with segmentation
  - **Code** sharing on modern OS is very common
  - If multiple processes use the same program code or library code
    - Their address space may **overlap** in the physical memory
    - The corresponding segments have the same base/bounds
  - Memory sharing needs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

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

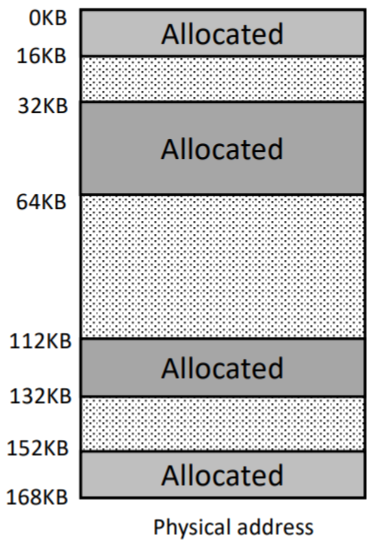
Internal fragmentation & External fragmentation





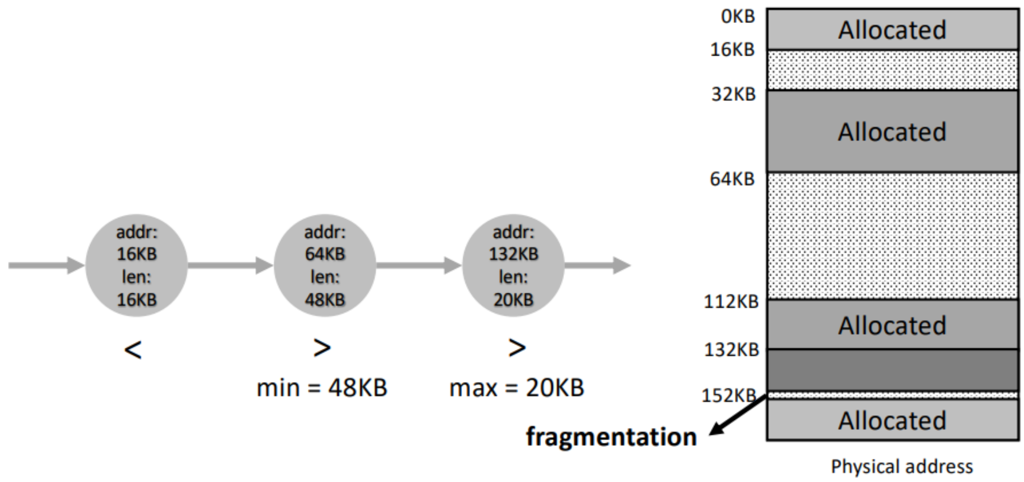
- **Internal fragmentation** with Base & Bounds
    - Space between heap and stack may be wasted
- **External fragmentation** with segmentation
    - free spaces are curved into small chunks
        - each is too small for further allocation
        - added together could be a huge waste

4. Memory Allocation



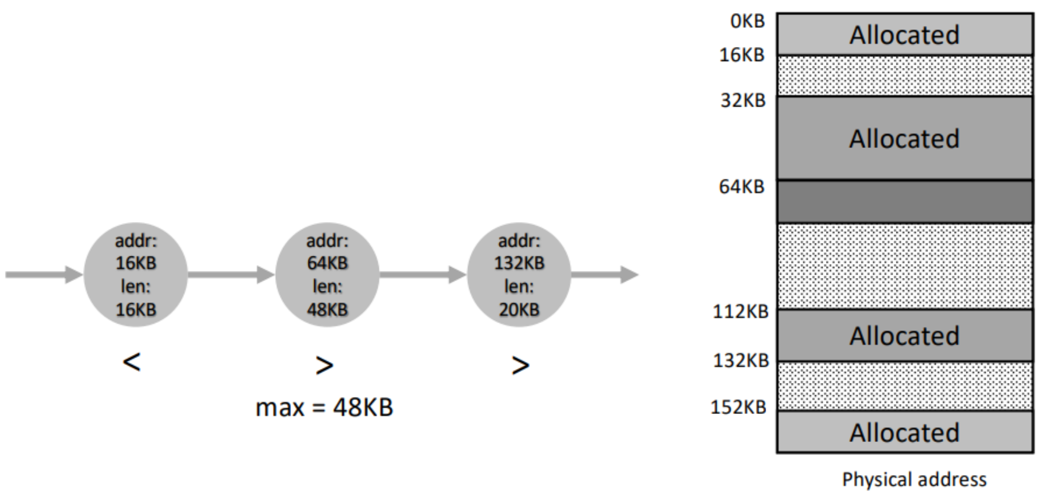
- OS needs to manage all free physical memory regions
- A basic solution is to maintain a **linked list** of free slots
- An ideal allocation algorithm is both **fast** and **minimizes fragmentation**

Best Fit



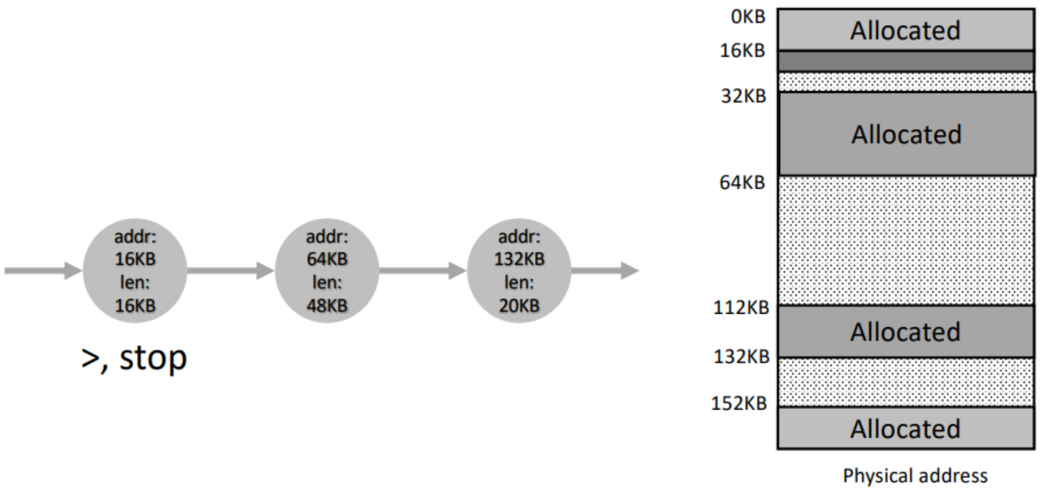
- Idea
  - search through the free list and find chunks of free memory that are as big or bigger than the requested size
  - return the one that is the **smallest** in that group of candidates
- Pros
  - Satisfy the request with **minimal external fragmentation**
- Cons
  - exhaustive search is slow

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

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