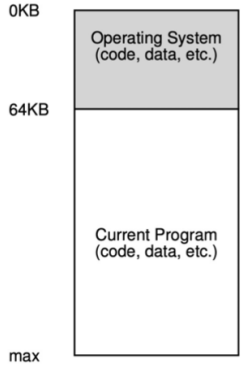
Operating System in Early Days

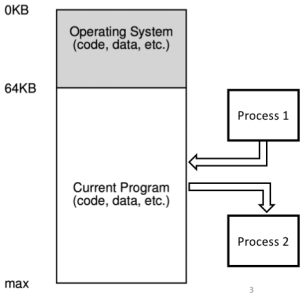
- The OS is a set of routines (a library) that uses lower memory
  - Starting at physical address 0 in this example
- One running program uses the rest of memory
  - Starting at physical address 64k in this example



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

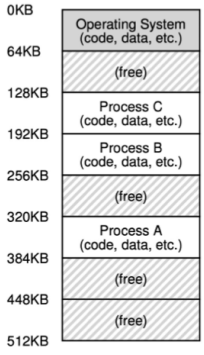
[DV66] Jack B. Dennis, Earl C. Van Horn. "Programming Semantics for Multiprogrammed Computations". 1966



更好利用CPU资源

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



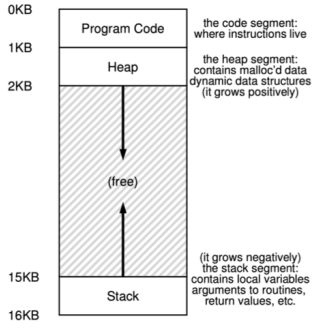
- Potential issues:
  - What happens when Process C needs more memory?
  - How to compile Program B so that it knows it will run at 192KB?
  - What if Process C has an error and writes to address at 1KB or 330KB?

进程的内存不好增长

Address Space

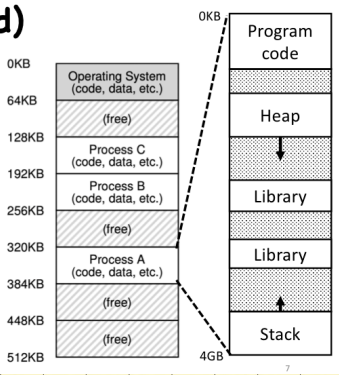
Address Space

- 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)

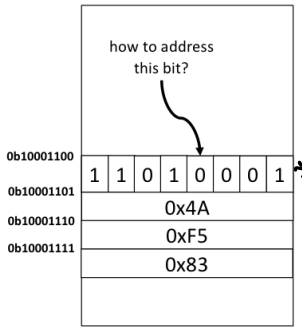
- This 16KB address space is just an abstraction
  - 0KB in the address space is not 0KB of physical memory
- This 16KB address space is just an illustration
  - 32-bit CPU supports up to 2^32 Byte (4GB) address space
  - 64-bit CPU supports up to 2^64 (4EB) Byte
    - But most CPU would reserve higher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



地址空间的内容是私有的.

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



地址是以byte为单位的.
不能访问bit

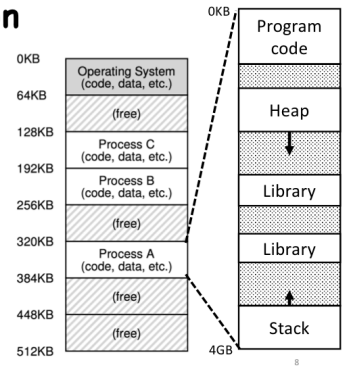
→0xd1

大端序：高位存于低地址中
小端序：低位存于低地址中.

Memory Virtualization

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
  - example: 0KB -> 320KB



有了虚拟内存后，不同进程的内存都会映射.
一般影响不到其他进程.

- 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

透明：内存虚拟化是不可见的，进程不会意识到虚拟内存.

高效

保护

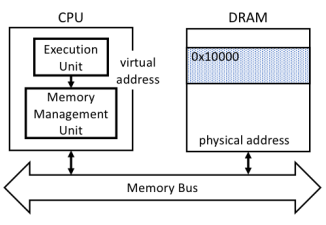
Virtual Address vs. Physical Address

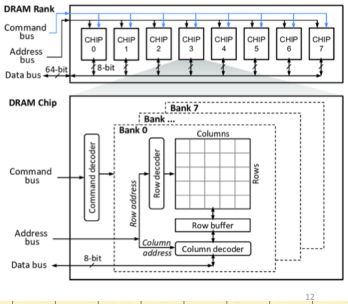
- Process uses virtual addresses

```c
#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
```

- CPU uses physical addresses to access DRAM





Address Translation

Address Translation

- 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
- 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

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

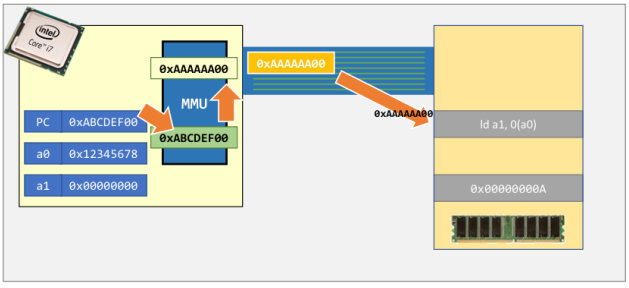
MMU通常在CPU芯片上，但也可以不在也可以是软件.

内存管理单元(MMU)

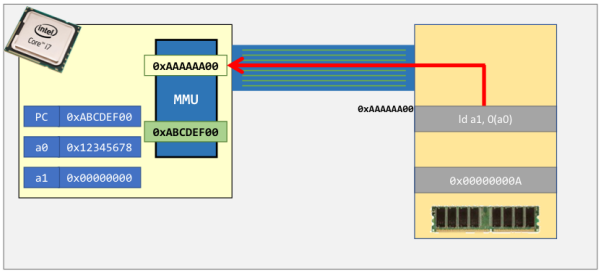
操作系统做转换.

Address Translation in Action

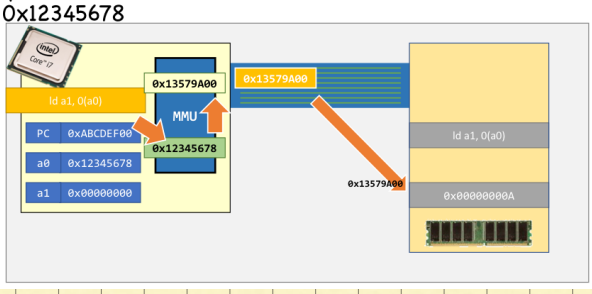
- Step 1: Fetch instruction at virtual address 0xabcdef00



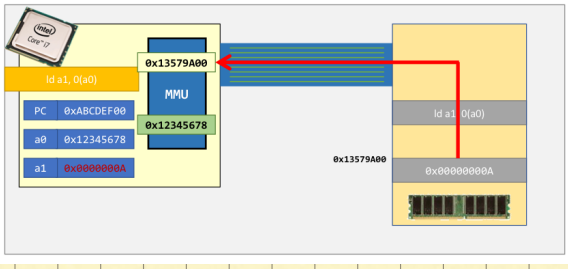
- Step 2: Instruction fetched from physical address 0xaaaaaa00



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

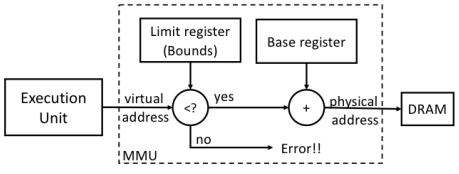


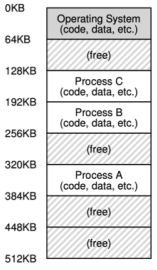
- Step 4. Data retrieved from physical address 0x13579a00 into EAX



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.

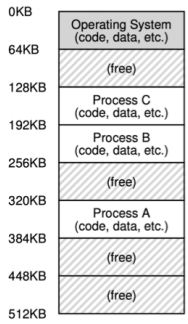
Handware & OS Coordination

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

Limitation 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



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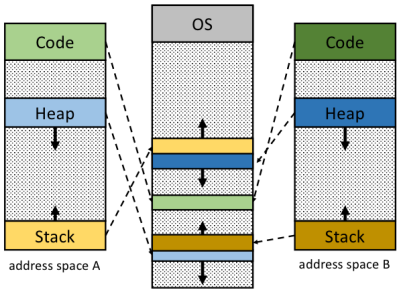
在heap和stack之间的空间无法使用.

Segmentation : Generalized Base / Bounds

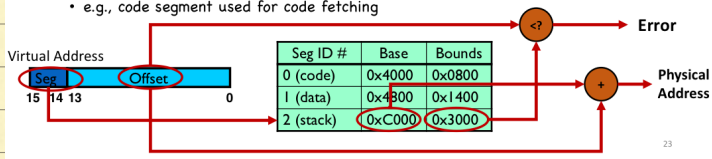
- A pair of base/bounds registers for each segment
  - code, stack, heap
- Each segment mapped to a different region of the physical memory
  - internal fragmentation?
  - larger address space?
  - inter-process sharing?



段中有一对寄存器给 base / bound

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



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可通过 Segment ID 查到 base / bound register

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

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

表中增加了一列用于保护.

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.

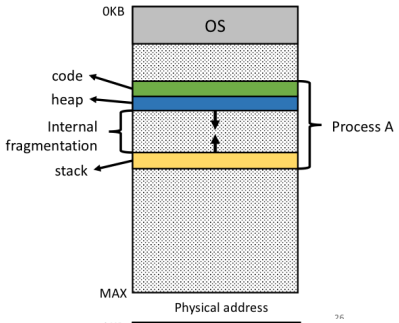
OS在上下文切换时需保存 base / bound register 的内容.

外碎片: segment 之间的空间碎片

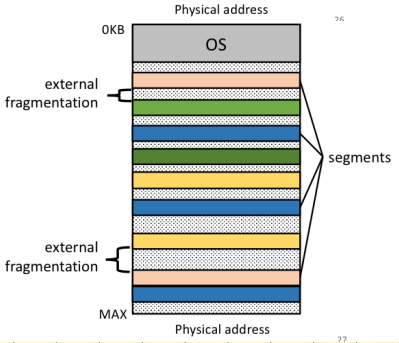
内碎片: segment 之内的空间碎片 (Heap. stack 之间)

Fragmentation Illustrated

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

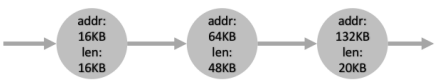


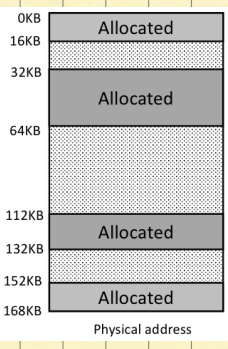
- External fragmentation with segmentation
- free spaces are curved into small chunks
  - each is too small for further allocation
  - added together could be a huge waste



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**.

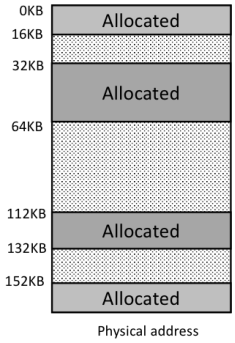




快速，最小化碎片

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

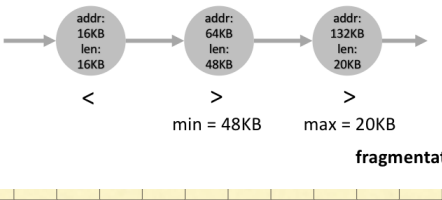


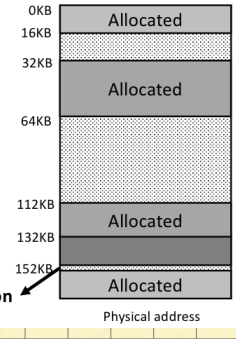
找到最小能容纳所需空间的chunk.

external fragmentation是最小的

查找过慢.

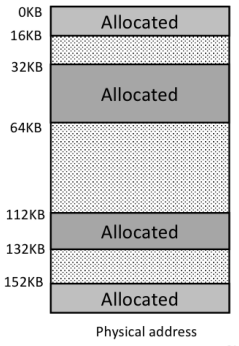
- Example
  - Requested space is 18KB
  - Allocated at 132KB



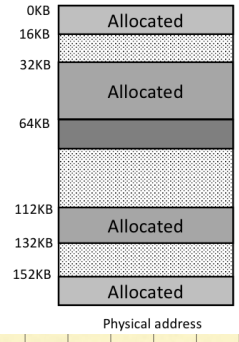


Basic Strategies: Worst Fit

- 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

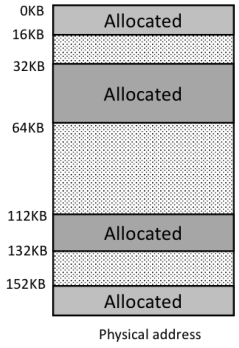


- Example
  - Requested space is 18KB
  - Allocated at 64KB

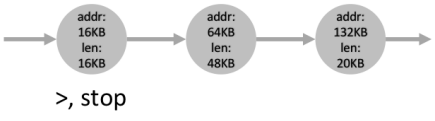


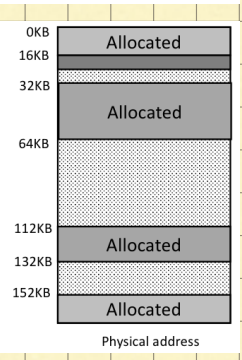
Basic Strategies: First Fit

- 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



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





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