Virtual Memory

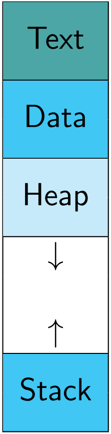
Operating Systems
Based on: Three Easy Pieces by Arpaci-Dusseaux

Moshe Sulamy

Tel-Aviv Academic College

Processes & Memory

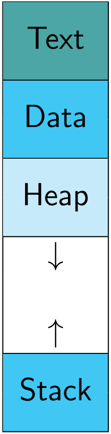
- Each process has its own **address space**
  - 4GB (32-bit)
    - Not really. Linux takes top 1GB. Windows top 2GB.
  - Heap, Stack, Data, Code (Text)



Processes & Memory

- Each process has its own **address space**
  - 4GB (32-bit)
    - Not really. Linux takes top 1GB. Windows top 2GB.
  - Heap, Stack, Data, Code (Text)

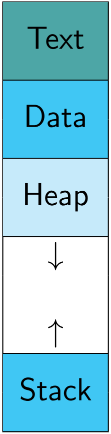
- Heap
  - Dynamic memory allocation
- Stack
  - Automatic memory allocation



Processes & Memory

- Each process has its own **address space**
  - 4GB (32-bit)
    - Not really. Linux takes top 1GB. Windows top 2GB.
  - Heap, Stack, Data, Code (Text)

- Heap
  - Dynamic memory allocation
- Stack
  - Automatic memory allocation
- Data
  - Static (Global/Local) values and variables
- Code
  - Program instructions



Processes & Memory

- Each process has its own **address space**
  - 4GB (32-bit)
- Ten processes: 40GB of RAM!
  - Typically we have much less physical memory
  - And many more processes

> How can the OS provide a private, potentially large address space for multiple running processes?

Virtualizing Memory

- OS virtualizes physical memory
- Goals:
  - **Transparency**:
    - Invisible to the running program
    - A process “thinks” it has a continuous **address space**
  - **Efficiency**:
    - Not making programs run much more slowly
    - Not using too much memory to support virtualization
  - **Protection**:
    - Protect processes from one another, and the OS from processes
    - **Isolation** among processes

Address Translation

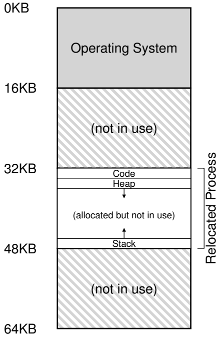
- **Hardware-based address translation**
  - On every memory reference, address translation is performed
  - Hardware redirects memory references to physical locations
- OS manages memory locations
  - Which are free and which are in use
- Hardware support
  - e.g., registers, TLBs, page-table

Assumptions

1. Address space must be placed contiguously
2. The size is less than the physical memory size
3. Each address space is the same size

Dynamic Relocation

- Also called: **base and bounds**
  - Hardware registers: **base** and **bounds**
  - OS decides where in physical memory a process is loaded
    - Sets **base** register to that value
  - Memory references are **translated** by **base**
    - `physical address = virtual address + base`
  - Processor checks reference is within **bounds** of base



Hardware Support

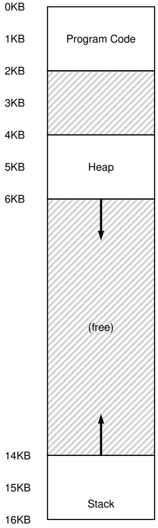
- Two (or more) CPU modes:
  - OS runs in **privileged mode** (or **kernel mode**)
  - Applications run in **user mode**
- **Base** and **bounds** registers
  - Hardware is called **memory management unit (MMU)**
- Generate **exceptions** on illegal access
  - Execute OS **exception handler**

Issues

- A process starts running:
  - Find space for address space in physical memory
  - Maintain a **free list** of free address spaces
- A process is terminated:
  - Reclaim the memory for use
  - Add it back to the **free list**
- Context switch:
  - Save and restore the base and bounds registers
  - In the process structure (PCB)

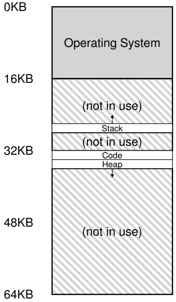
Segmentation

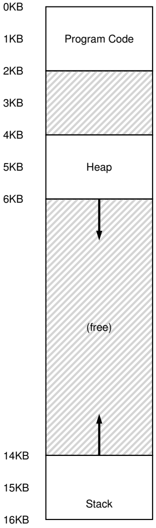
- Base and bounds is problematic
  - Big chunk of free space
  - Still taking up physical memory
- Solution?



Segmentation

- Base and bounds is problematic
  - Big chunk of free space
  - Still taking up physical memory
- Solution? **segmentation**
  - Base and bounds pair for each segment





Segmentation

- A contiguous portion of the address space
  - Logical segments: code, stack, heap
- Each can be placed in a different part of the physical memory
- `physical address = offset + base`
  - Not `virtual address + base`!
  - e.g., offset of virtual address 100 is `100`
  - Offset of virtual address 4200 can be `104`
    - Since it is `104` in the heap segment

Segmentation

- Ever encountered a **segmentation fault**?
- If an **illegal address** beyond the segment is referenced:
  - Hardware detects **out of bounds** access
  - OS event: **segmentation fault**

Support for Sharing

- Segment can be shared between address spaces (processes)
  - **Code sharing** is common
  - Same program, no need to load the code twice
- Extra hardware support: **protection bits**
  - Code segment is read-only
  - Can be shared without harming **isolation**

Segment	Base	Size	Grows Positive?	Protection
Code	32K	2K	1	Read-Execute
Heap	34K	3K	1	Read-Write
Stack	28K	2K	0	Read-Write

Fine-Grained vs. Coarse-Grained

- Thus far: just a few segments
    - Code, stack, heap
    - **Coarse-grained**
- **Fine-grained**
    - Large number of smaller segments
    - **Segment table** stored in memory
    - More flexible

OS Support

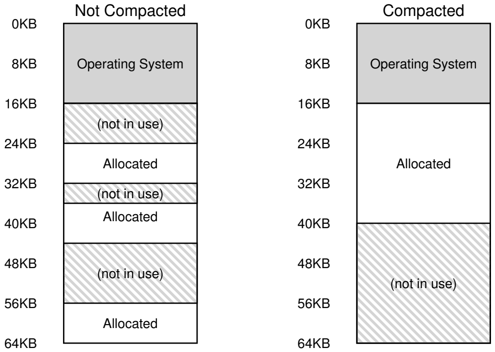
- On context switch: segment registers saved and restored
- On memory allocation/free: update segment size

OS Support

- On context switch: segment registers saved and restored
- On memory allocation/free: update segment size
- **External fragmentation**
  - Physical memory becomes full of little holes of free space
  - Difficult to allocate new segments, or grow existing ones

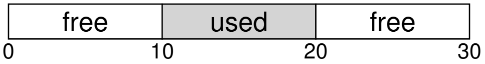
Compaction

- **Compaction**
  - Stop running processes
  - Copy data to contiguous region
  - Change segment registers accordingly
  - Compaction is expensive!



External Fragmentation

- Detour to discuss **free-space management**
- Also applies to user-level memory allocation
  - e.g., `malloc()` and `free()`
- Not a problem with fixed-size chunks
  - Can use a free-list



20 free bytes fragmented into chunks of 10

External Fragmentation

Assume:

- A basic `heap` interface:
  - `malloc(size_t size)` allocates `size` or more bytes
  - `free(void *ptr)` frees corresponding chunk
    - Note that no size is provided
- Only **external fragmentation**
  - Allocators also have **internal fragmentation**
  - Unused space in chunks bigger than requested
- No memory relocation
  - No **compaction** of free space

Splitting

Splitting

`malloc(2048)`

Splitting

`malloc(2048)`

Splitting

`malloc(2048)=15KB`

Splitting

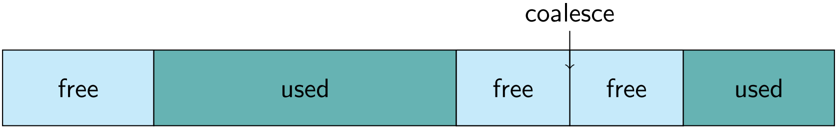
Coalescing

`free(15KB)`

Coalescing

`free(15KB)`

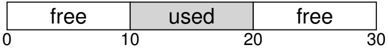
Coalescing



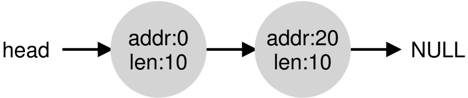
Coalescing

Splitting

- Find a free chunk to satisfy request and split it into two
  - Assume the following 30-byte heap:



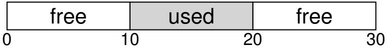
  - Its free list is:



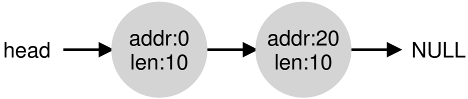
  - After a 1-byte request:

Splitting

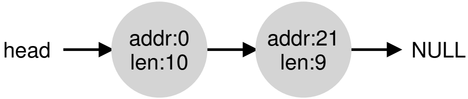
- Find a free chunk to satisfy request and split it into two
  - Assume the following 30-byte heap:



  - Its free list is:

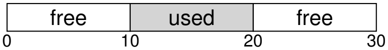


  - After a 1-byte request:

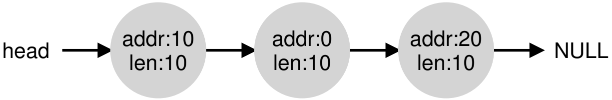


Coalescing

- Coalesce free space when memory is freed
  - i.e., merge contiguous free chunk
  - Consider our previous heap:



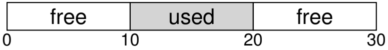
  - After a call to `free(10)`:



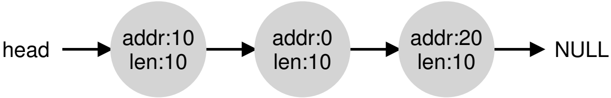
  - With coalescing:

Coalescing

- Coalesce free space when memory is freed
  - i.e., merge contiguous free chunk
  - Consider our previous heap:



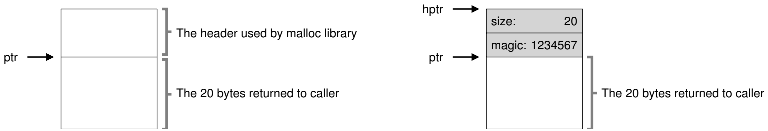
  - After a call to `free(10)`:



  - With coalescing:

Tracking The Size

- Interface to `free(void *ptr)` does not provide size
- Store extra information in a **header** block
  - Usually just before chunk of memory
  - Magic number for integrity checking

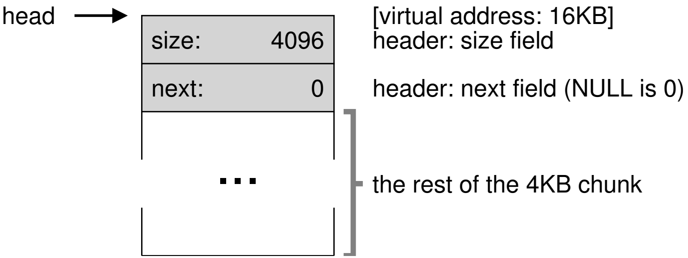


Free List

- Need to implement the **free list** itself
  - Can't call `malloc()` - we are implementing it!
  - Need to embed the list inside the free space itself

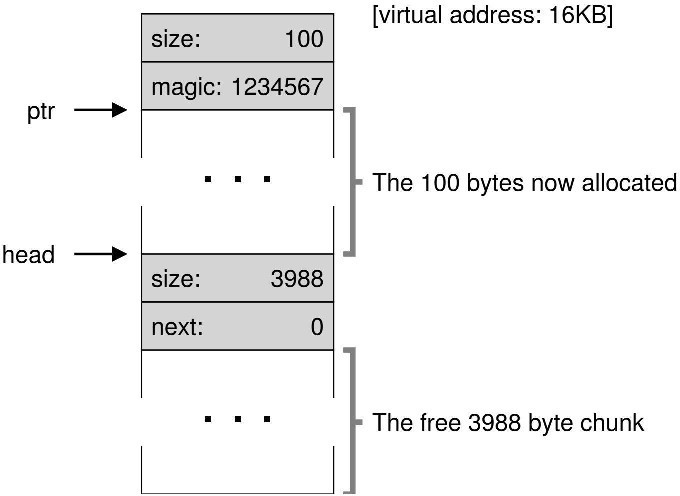
Free List

- Need to implement the **free list** itself
  - Can't call `malloc()` - we are implementing it!
  - Need to embed the list inside the free space itself
- Example: manage 4096-byte chunk
  - Maintain `size` and `next` for each node:



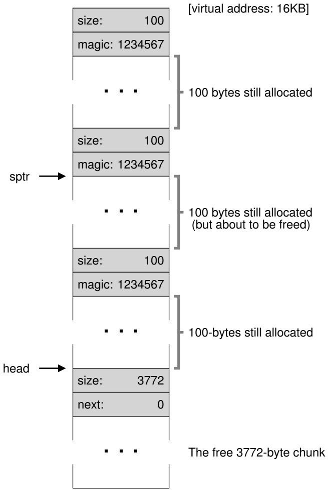
Free List

- 100 bytes are requested: **split** chunk



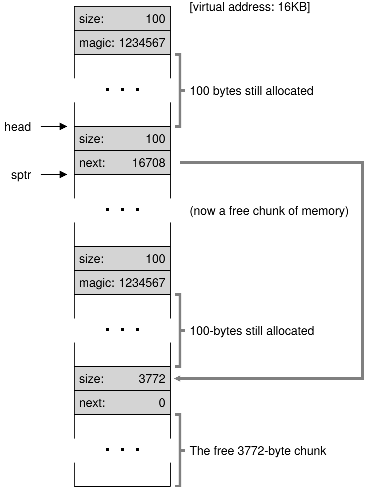
Free List

- Three allocated regions of 100 bytes:



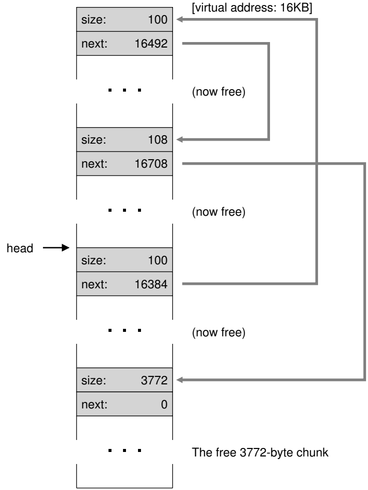
Free List

- After `free(16500)`:
  - Region start: 16384, previous chunk: 108, current header: 8



Free List

- Free last two chunks: fragmentation!
  - Need to **coalesce** the list



Managing Free Space

- **Best Fit**
  - Return smallest chunk that's as big or bigger than requested size
  - Exhaustive search: heavy performance penalty
- **Worst Fit**
  - Opposite of best fit: return largest chunk
  - Still requires full search, bad performance, excess fragmentation

Managing Free Space

- **First Fit**
  - Return first block that is big enough
  - Speed advantage, but pollutes beginning of list
- **Next Fit**
  - As first fit, but start where stopped previously
  - Spreads the searches throughout the list

Managing Free Space

- Examples: allocation request size 15

  head $\rightarrow$ 10 $\rightarrow$ 30 $\rightarrow$ 20 $\rightarrow$ NULL

- Best-fit:

  head $\rightarrow$ 10 $\rightarrow$ 30 $\rightarrow$ 5 $\rightarrow$ NULL

- Worst-fit:

  head $\rightarrow$ 10 $\rightarrow$ 15 $\rightarrow$ 20 $\rightarrow$ NULL

- First-fit: same as worst-fit, but faster

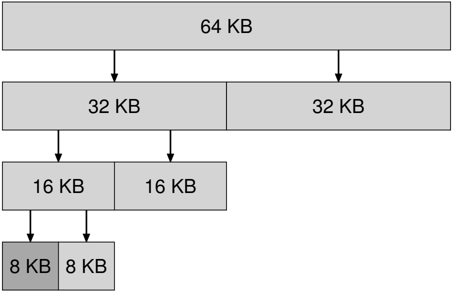
Segregated Lists

- Keep lists for fixed-size objects
- General memory allocator for the rest

- **Slab allocator** allocates **object caches**
  - For common kernel objects (locks, file-system inodes, etc.)
  - When a cache is running low: request **slab** of memory from general allocator

Buddy Allocation

- Make coalescing simple: **binary buddy allocator**
- Divide free space by two until a block is found
  - Further split into two is too small
  - Suffers from **internal fragmentation**
  - Easy to coalesce:
    - Recursively up the the tree
    - Buddy address differs by a single bit



Summary

- Virtualize RAM into process **address space**
- Address translation:
  - Dynamic relocation (**base and bounds**)
  - Segmentation
    - **Coarse-grained**: just a few segments
    - **Fine-grained**: large number of smaller segments
- **External fragmentation**
  - Free memory fragments into small parts
  - Splitting & coalescing
- **Compaction**
  - Stop processes, copy data to contiguous region