TCSS 422: OPERATING SYSTEMS

Address Spaces and the Memory API

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FEEDBACK – 5/2

- Can we go over mutual exclusion again?
- Q#4 - mock midterm: Perfect-multi-tasking operating system
- Every process of the same priority will always receive exactly 1/nth of the available CPU time. Important CPU improvements for multi-tasking include: (1) fast context switching to enable jobs to be swapped in-and-out of the CPU very quickly, and (2) the use of a timer interrupt to preempt running jobs without the user voluntarily yielding the CPU. These innovations have enabled major improvements taking positive steps towards achieving a coveted "Perfect Multi-Tasking System".
- What are two challenges complicating the realization of a Perfect Multi-Tasking Operating System?

FEEDBACK – 2

- How can we wake up a specific thread with broadcast?
  - When we call broadcast every thread waiting is guaranteed to be awoken
  - We just don't know the order
  - Set a state variable or thread ID (integer), to allow some to proceed, others to go back to sleep

FEEDBACK - 3

- Can you review compare and swap?
- How come we no longer need locks because of this?
- On a single-core CPU the non-atomic compare-and-swap implementation is correct
- On multi-core the other cores can interrupt the non-atomic compare-and-swap code, resulting in mutual exclusion violation
- Compare-and-swap extends test-and-set to only "swap" (assign the lock to 1), if it is the expected value of 0.

COMPARE AND SWAP

- Compare and Swap

```
int CompareAndSwap(int *ptr, int expected, int new) {
    int actual = *ptr;
    if (actual == expected)
        *ptr = new;
    return actual;
}
```

- Spin lock usage

```
void lock(lock_t *lock) {
    while (CompareAndSwap(&lock->flag, 0, 1) == 1)
        ; // spin
}
```


UPDATES

- Check quiz and tutorial grades
- Under review
  - Program 1
  - Midterm
- Program 2:
  - Due Sunday May 14

OBJECTIVES

- Chapter 13
  - Introduction to memory virtualization
  - The address space
  - Goals of OS memory virtualization
- Chapter 14
  - Memory API
  - Common memory errors
- Chapter 15
  - Address translation
  - Base and bounds
  - HW and OS Support
- Chapter 16
  - Memory segments, fragmentation

MEMORY VIRTUALIZATION

- What is memory virtualization?
- This is not "virtual" memory,
  - Classic use of disk space as additional RAM
  - When available RAM was low
  - Less common recently

MEMORY VIRTUALIZATION - 2

- Presentation of system memory to each process
- Appears as if each process can access the entire machine's address space
- Each process's view of memory is isolated from others
- Everyone has their own sandbox

Process A

Process B

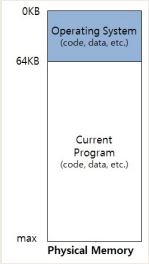
Process C

MOTIVATION FOR MEMORY VIRTUALIZATION

- Easier to program
  - Programs don't need to understand special memory models
- Abstraction enables sophisticated approaches to manage and share memory among processes
- Isolation
  - From other processes: easier to code
- Protection
  - From other processes
  - From programmer error (segmentation fault)

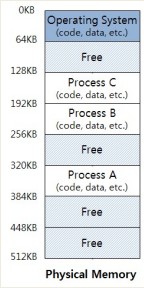
EARLY MEMORY MANAGEMENT

- Load one process at a time into memory
- Poor memory utilization
- Little abstraction



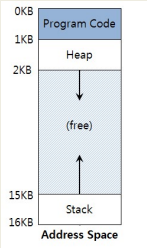
MULTIPROGRAMMING WITH SHARED MEMORY

- Later machines supported running multiple processes
- Swap out processes during I/O waits to increase system utilization and efficiency
- Swap entire memory of a process to disk for context switch
- Too slow, especially for large processes
- Solution→
  - Leave processes in memory
- Need to protect from errant memory accesses in a multiprocessing environment



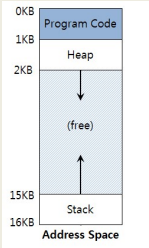
ADDRESS SPACE

- Easy-to-use abstraction of physical memory for a process
- Main elements:
  - Program code
  - Stack
  - Heap
- Example: 16KB address space



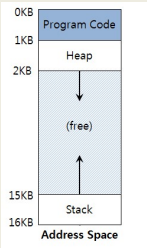
ADDRESS SPACE - 2

- Code
  - Program code
- Stack
  - Program counter (PC)
  - Local variables
  - Parameter variables
  - Return values (for functions)
- Heap
  - Dynamic storage
  - Malloc() new()



ADDRESS SPACE - 3

- Program code
  - Static size
- Heap and stack
  - Dynamic size
  - Grow and shrink during program execution
  - Placed at opposite ends
- Addresses are virtual
  - They must be physically mapped by the OS



VIRTUAL ADDRESSING

- Every address is virtual
  - OS translates virtual to physical addresses

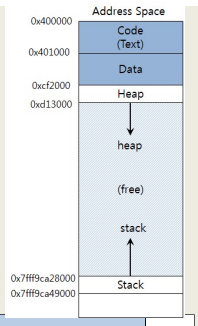
```
#include <stdio.h>
#include <stdlib.h>

int main(int argc, char *argv[]){

    printf("location of code  : %p\n", (void *) main);
    printf("location of heap  : %p\n", (void *) malloc(1));
    int x = 3;
    printf("location of stack : %p\n", (void *) &x);

    return x;
}
```

  - EXAMPLE: virtual.c

VIRTUAL ADDRESSING - 2

- Output from 64-bit Linux:

location of code: 0x400686
location of heap: 0x1129420
location of stack: 0x7ffe040d77e4



GOALS OF OS MEMORY VIRTUALIZATION

- Transparency
  - Memory shouldn't appear virtualized to the program
  - OS multiplexes memory among different jobs behind the scenes
- Protection
  - Isolation among processes
  - OS itself must be isolated
  - One program should not be able to affect another (or the OS)

GOALS - 2

- Efficiency
  - Time
    - Performance: virtualization must be fast
  - Space
    - Virtualization must not waste space
    - Consider data structures for organizing memory
    - Hardware support TLB: Translation Lookaside Buffer
- Goals considered when evaluation memory virtualization schemes

CHAPTER 14: THE MEMORY API

MALLOC

```
#include <stdlib.h>

void* malloc(size_t size)
```

- Allocates memory on the heap
- size_t unsigned integer (must be +)
- size size of memory allocation in bytes
- Returns
- SUCCESS: A void * to a memory address
- FAIL: NULL
- sizeof() often used to ask the system how large a given datatype or struct is

SIZEOF()

- Not safe to assume data type sizes using different compilers, systems
- Dynamic array of 10 ints
- Static array of 10 ints

```
int *x = malloc(10 * sizeof(int));
printf("%d\n", sizeof(x));
```

```
4
```

```
int x[10];
printf("%d\n", sizeof(x));
```

```
40
```


FREE()

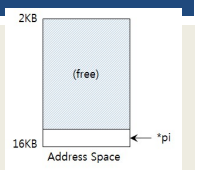
```
#include <stdlib.h>

void free(void* ptr)
```

- Free memory allocated with malloc()
- Provide: (void *) ptr to malloc'd memory
- Returns: nothing

VIRTUAL ADDRESS SPACE

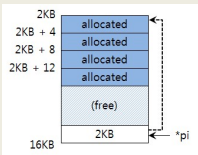
```
int *pi; // local variable
```

- Pointer is a local variable on the stack



- Malloc returns space on the heap

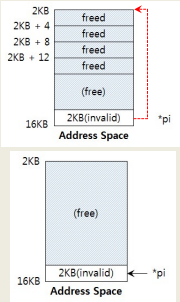
```
pi = (int *)malloc(sizeof(int)* 4);
```



VIRTUAL ADDRESS SPACE - 2

- Releases heap space pointed to by the pointer on the stack

```
free(pi);
```



COMMON MEMORY ERRORS

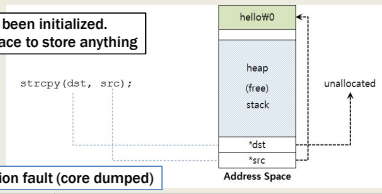
- Forgetting to malloc memory
- Unterminated string
- Uninitialized memory
- Memory leak
- Dangling pointer

FORGETTING TO MALLOC

- C is not Java
- When forgetting to maloc:

```
char *src = "hello"; //character string constant
char *dst;           //unallocated
strcpy(dst, src);    //segfault and die
```

dst has not been initialized.
It has no place to store anything

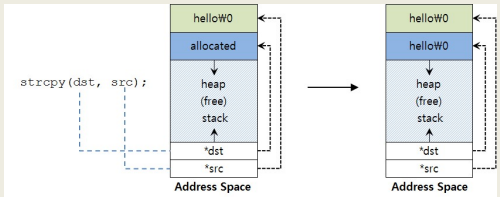


Segmentation fault (core dumped)

CORRECTION

```
char *src = "hello";  //character string constant
char *dst (char *)malloc(strlen(src) + 1 ); // allocated
strcpy(dst, src);     //work properly
```

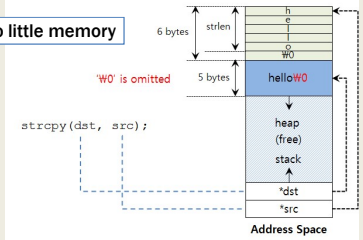
- Why do we malloc length + 1 ?



UNTERMINATED STRING

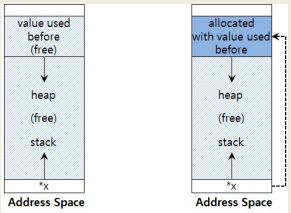
```
char *src = "hello"; //character string constant
char *dst (char *)malloc(strlen(src)); // too small
strcpy(dst, src);    //work properly
```

Malloc too little memory

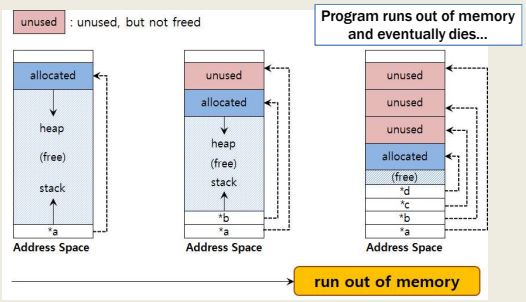


FORGETTING TO INITIALIZE

```
int *x = (int *)malloc(sizeof(int)); // allocated
printf("*x = %d\n", *x); // uninitialized memory access
```



MEMORY LEAK




```
#include<stdio.h>

int * set_magic_number_a()
{
  int a =53247;
  return &a;
}

void set_magic_number_b()
{
  int b = 11111;
}

int main()
{
  int * x = NULL;
  x = set_magic_number_a();
  printf("The magic number is=%d\n",*x);
  set_magic_number_b();
  printf("The magic number is=%d\n",*x);
  return 0;
}
```

What will this code do?

32

```
#include<stdio.h>

int * set_magic_number_a()
{
  int a =53247;
  return &a;
}

void set_magic_number_b()
{
  int b = 11111;
}

int main()
{
  int * x = NULL;
  x = set_magic_number_a();
  printf("The magic number is=%d\n",*x);
  set_magic_number_b();
  printf("The magic number is=%d\n",*x);
  return 0;
}
```

What will this code do?

Output:
```
$ ./pointer_error
The magic number is=53247
The magic number is=11111
```

We have not changed *x but the value has changed!!

Why?

33

DANGLING POINTER (1/2)

- Dangling pointers arise when a variable referred (a) goes "out of scope", and it's memory is destroyed/overwritten (by b) without modifying the value of the pointer (*x).
- The pointer still points to the original memory location of the deallocated memory (a), which has now been reclaimed for (b).

DANGLING POINTER (2/2)

- Fortunately in the case, a compiler warning is generated:

```
$ g++ -o pointer_error -std=c++0x pointer_error.cpp

pointer_error.cpp: In function 'int*
set_magic_number_a()':
pointer_error.cpp:6:7: warning: address of local
variable 'a' returned [enabled by default]
```

- This is a common mistake - - - accidentally referring to addresses that have gone "out of scope"

CALLOC()

```
#include <stdlib.h>

void *calloc(size_t num, size_t size)
```

- Allocate "C"lear memory on the heap
- Calloc wipes memory in advance of use…
- `size_t num` : number of blocks to allocate
- `size_t size` : size of each block(in bytes)
- Calloc() prevents…

```
char *dest = malloc(20);
printf("dest string=%s\n", dest);

dest string=►►F
```

REALLOC()

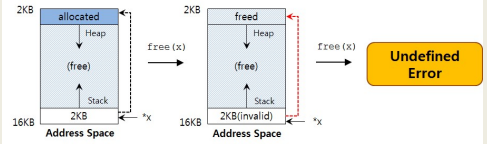
```
#include <stdlib.h>

void *realloc(void *ptr, size_t size)
```

- Resize an existing memory allocation
- Returned pointer may be same address, or a new address
  - New if memory allocation must move
- `void *ptr`: Pointer to memory block allocated with malloc, calloc, or realloc
- `size_t size`: New size for the memory block(in bytes)
- EXAMPLE: realloc.c
- EXAMPLE: nom.c

DOUBLE FREE

```
int *x = (int *)malloc(sizeof(int)); // allocated
free(x); // free memory
free(x); // free repeatedly
```

- Can't deallocate twice
- Second call core dumps



SYSTEM CALLS

- brk(), sbrk()
- Used to change data segment size (the end of the heap)
- Don't use these
- Mmap(), munmap()
- Can be used to create an extra independent "heap" of memory for a user program
- See man page

CHAPTER 15: ADDRESS TRANSLATION

OBJECTIVES

- Address translation
- Base and bounds
- HW and OS Support
- Memory segments
- Memory fragmentation

MEMORY VIRTUALIZATION

- Using hardware support provide virtualization that is:
  - Efficient
  - Flexible
  - Secure and isolated

HARDWARE BASED ADDRESS TRANSLATION

- For each and every memory reference… address translation is performed
- Hardware transforms
  - Virtual address → physical address
- OS tracks which memory locations are free / in-use

EXAMPLE: ADDRESS TRANSLATION

```
void func()
        int x=0;
        ...
        x = x + 3; // this is the line of code we are interested in
```

- **Load** value from memory
- **Increment** by three
- **Store** value back in memory
- In assembly…

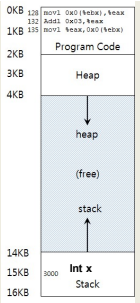
EXAMPLE: ADDRESS TRANSLATION - 2

```
128 : movl 0x0(%ebx), %eax        ; load 0+ebx into eax
132 : addl $0x03, %eax            ; add 3 to eax register
135 : movl %eax, 0x0(%ebx)        ; store eax back to mem
```

- Load value at address into register (eax)
- Add (3) to eax register
- Store the value of eax back into memory

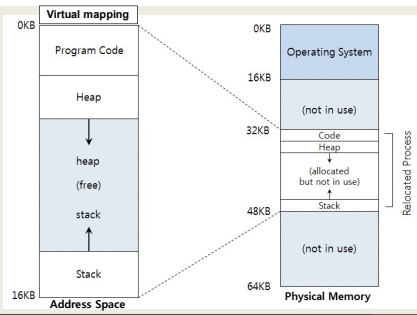
EXAMPLE: ADDRESS TRANSLATION - 3

- Fetch instruction at address 128
- Execute this instruction (load from address 15KB)
- Fetch instruction at address 132
- Execute this instruction (no memory reference)
- Fetch the instruction at address 135
- Execute this instruction (store to address 15 KB)
- Program's perspective:
  - Address space starts at 0
- Machine's perspective:
  - Program is located somewhere, not at 0



PLACEMENT IN PHYSICAL RAM

- 64KB Address space example
- Translation: mapping virtual to physical



BASE AND BOUNDS

- Dynamic relocation
- Two registers base & bounds: **on the CPU**
- OS places program in memory
- Sets base register

$$physical\ address = virtual\ address + base$$

- Bounds register
  - Stores size of program address space (16KB)
- OS verifies that every address:

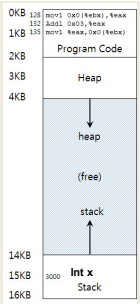
$$0 \leq virtual\ address < bounds$$

INSTRUCTION EXAMPLE

```
128 : movl 0x0(%ebx), %eax
```

- Base = 32768
- Bounds =16384
- Fetch instruction at 128 (virt addr) ↑
  - Phy addr = virt addr + base reg
  - 32896 = 128 + 32768 (base)
- Execute instruction
  - Load from address (var x is @ 15kb=15360)
  - 48128 = 15360 + 32768 (base) -- found x…
- Bounds register: terminate process if
  - ACCESS VIOLATION: Virtual address > bounds reg

$$physical\ address = virtual\ address + base$$



MEMORY MANAGEMENT UNIT

- MMU
  - Portion of the CPU dedicated to address translation
  - Contains base & bounds registers
- Base & Bounds Example:
  - Consider address translation
  - 4 KB (4096 bytes) address space, loaded at 16 KB physical location

	Virtual Address	Physical Address
	0	16384
	1024	17408
	3000	19384
FAULT	4400	20784 (out of bounds)

DYNAMIC RELOCATION OF PROGRAMS

- Hardware requirements:

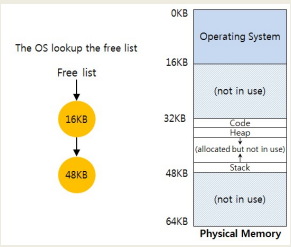
Requirements	HW support
Privileged mode	CPU modes: kernel, user
Base / bounds registers	Registers to support address translation
Translate virtual addr; check if in bounds	Translation circuitry, check limits
Privileged instruction(s) to update base / bounds regs	Instructions for modifying base/bound registers
Privileged instruction(s) to register exception handlers	Set code pointers to OS code to handle faults
Ability to raise exceptions	For out-of-bounds memory access, or attempts to access privileged instr.

OS SUPPORT FOR MEMORY VIRTUALIZATION

- For base and bounds OS support required
  - When process starts running
    - Allocate address space in physical memory
  - When a process is terminated
    - Reclaiming memory for use
  - When context switch occurs
    - Saving and storing the base-bounds pair
  - Exception handlers
    - Function pointers set at OS boot time

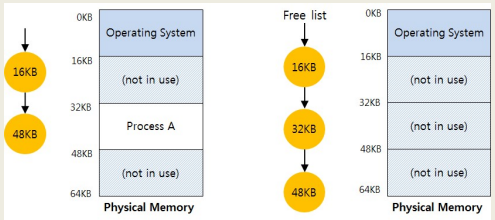
OS: WHEN PROCESS STARTS RUNNING

- OS searches for free space for new process
  - Free list: data structure that tracks available memory slots



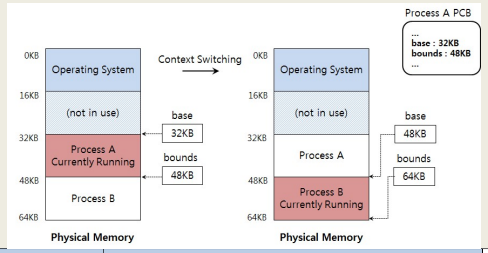
OS: WHEN PROCESS IS TERMINATED

- OS places memory back on the free list



OS: WHEN CONTEXT SWITCH OCCURS

- OS must save base and bounds registers
  - Saved to the Process Control Block PCB (task_struct in Linux)



DYNAMIC RELOCATION

- OS can move process data when not running

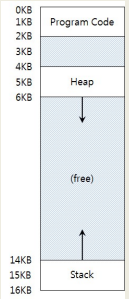
1. OS deschedules process from scheduler
2. OS copies address space from current to new location
3. OS updates PCB (base and bounds registers)
4. OS reschedules process

- When process runs new base register is restored to CPU
- **Process doesn't know it was even moved!**

CHAPTER 16: SEGMENTATION

BASE AND BOUNDS INEFFICIENCIES

- Address space
  - Contains significant unused memory
  - Is relatively large
  - Preallocates space to handle stack/heap growth
- Large address spaces
  - Hard to fit in memory
- How can these issues be addressed?

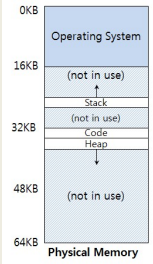


MULTIPLE SEGMENTS

- Memory segmentation
- Address space has (3) segments
  - Contiguous portions of address space
  - Logically separate segments for: code, stack, heap
- Each segment can placed separately
- Track base and bounds for each segment (registers)

SEGMENTS IN MEMORY

- Consider 3 segments:



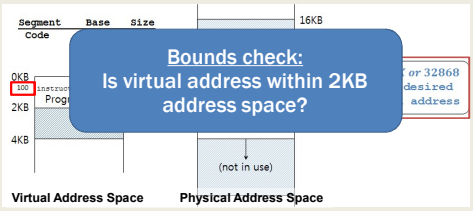
Much smaller

Segment	Base	Size
Code	32K	2K
Heap	34K	2K
Stack	28K	2K

ADDRESS TRANSLATION: CODE SEGMENT

$$physical\ address = offset + base$$

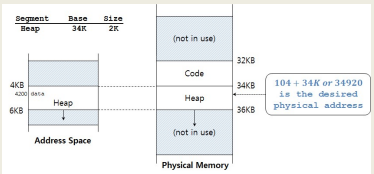
- Code segment - physically starts at 32KB (base)
- Starts at "0" in virtual address space



ADDRESS TRANSLATION: HEAP

$Virtual\ address + base$ is not the correct physical address.

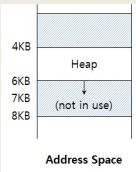
- Heap starts at virtual address 4096
- The data is at 4200
- Offset= 4200 – 4096 = 104 (virt addr – virt heap start)
- Physical address = 104 + 34816 (offset + heap base)



SEGMENTATION FAULT

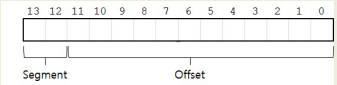
- Access beyond the address space
- Heap starts at virtual address: 4096
- Data pointer is to 7KB (7168)
- Is data pointer valid?

- Heap starts at 4096 + 2 KB seg size = 6144
- Offset= 7168 > 4096 + 2048 (6144)

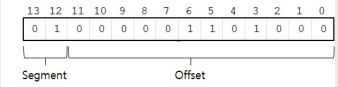


SEGMENT REGISTERS

- Used to dereference memory during translation



- First two bits identify segment type
- Remaining bits identify memory offset
- Example: virtual heap address 4200 (01000001101000)



Segment	bits
Code	00
Heap	01
Stack	10
-	11

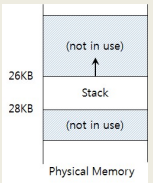
SEGMENTATION DEREFERENCE

```
// get top 2 bits of 14-bit VA
Segment = (VirtualAddress & SEG_MASK) >> SEG_SHIFT
// now get offset
Offset = VirtualAddress & OFFSET_MASK
if (Offset >= Bounds[Segment])
     RaiseException(PROTECTION_FAULT)
else
     PhysAddr = Base[Segment] + Offset
     Register = AccessMemory(PhysAddr)
```

- VIRTUAL ADDRESS = 01000001101000 (on heap)
- SEG_MASK = 0x3000 (11000000000000)
- SEG_SHIFT = 01 → ***heap*** (mask gives us segment code)
- OFFSET_MASK = 0xFFF (00111111111111)
- OFFSET = 000001101000 = 104 (isolates segment offset)
- OFFSET < BOUNDS : 104 < 2048

STACK SEGMENT

- Stack grows backwards (FILO)
- Requires hardware support:
- Direction bit: tracks direction segment grows



Segment Register(with Negative-Growth Support)

Segment	Base	Size	Grows Positive?
Code	32K	2K	1
Heap	34K	2K	1
Stack	28K	2K	0

SHARED CODE SEGMENTS

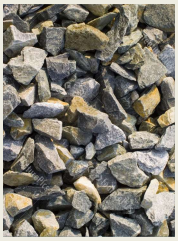
- Code sharing: enabled with HW support
- Supports storing shared libraries in memory only once
- DLL: dynamic linked library
- .so (linux): shraed object in Linux (under /usr/lib)
- Many programs can access them
- Protection bits: track permissions to segment

Segment Register Values(with Protection)

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

SEGMENTATION GRANULARITY

- Coarse-grained
- Manage memory as large purpose based segments:
  - Code segment
  - Heap segment
  - Stack segment

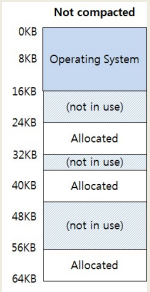


SEGMENTATION GRANULARITY - 2

- Fine-grained
- Manage memory as list of segments
- Code, heap, stack segments composed of multiple smaller segments
- Segment table
  - On early systems
  - Stored in memory
  - Tracked large number of segments

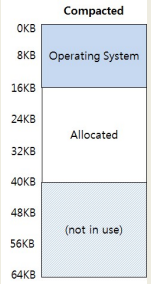
MEMORY FRAGMENTATION

- Consider how much free space?
- We'll say about 24 KB
- Request arrives to allocate a 20 KB heap segment
- Can we fulfil the request for 20 KB of contiguous memory?



COMPACTION

- Supports rearranging memory
- Can we fulfil the request for 20 KB of contiguous memory?
- **Drawback:** Compaction is slow
  - Rearranging memory is time consuming
  - 64KB is fast
  - 4GB+ … slow
- Algorithms:
  - Best fit: keep list of free spaces, allocate the most snug segment for the request
  - Others: worst fit, first fit… (in future chapters)



QUESTIONS