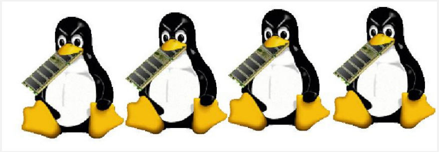
Memory Management



Learning Objectives

- Understand the role and function of the memory manager
- Understand the operation of dynamic memory allocation algorithms used in language runtime such as malloc
- Understand the operation of kernel-level memeory allocators such as the buddy system

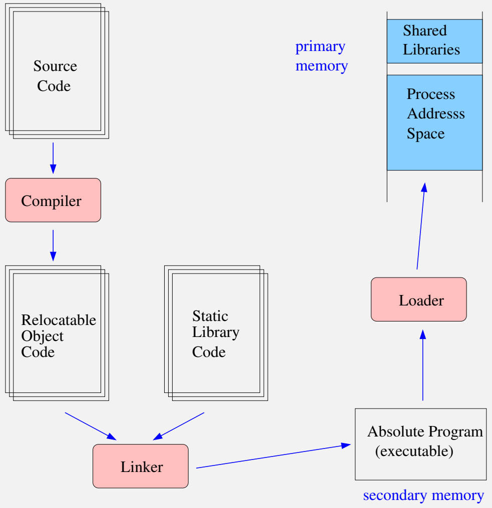
Memory Management: Overview

- Primary role of memory manager:
  - Allocates primary memory to processes
  - Maps process address space to primary memory
  - Minimizes access time using cost effective memory configuration
- Memory management approaches range from primitive bare-machine approach to sophisticated paging and segmentation strategies for implementing virtual memory.

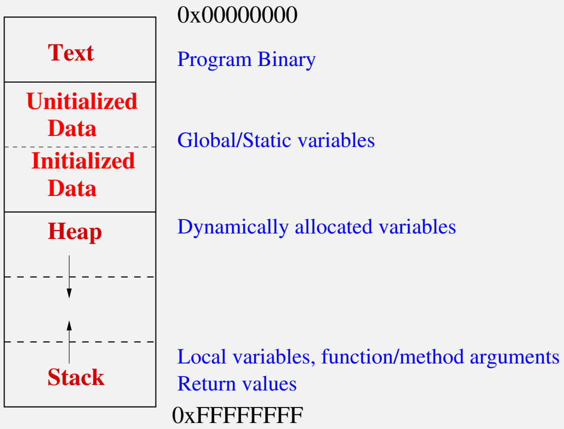
Relocating Executables

- Compile, Link, and Load phases.
- Source program, relocatable object modules, absolute program.
- Dynamic address relocation using relocation registers.
- Memory protection using limit registers. (violating the limit generates an hardware interrupt, often called *segment violation*, that results in a fatal execution error.)

Building the address space



Process Address Space model



Dynamic Memory Allocation in Processes

- Using `malloc` in C or `new` in C/C++/Java and other languages causes memory to be dynamically allocated. Does `malloc` or `new` call the Operating system to get more memory?
- The system creates heap and stack segment for processes at the time of creation. So new/malloc already has some memory to work with without having to call the operating system for every memory request from the program.
- If more memory is needed (either due to malloc/new or due to stack growing), then a system call (`sbrk()` in Linux/Unix) is made to add more space to the area between the heap and the stack in the process address space.

See examples: malloc-and-OS.c, sbrk-test.c

Fixed Partition versus Variable Partition Memory Strategies

Strategies for memory management by the operating system.

- Fixed Partitions: Simple but inflexible. Leads to internal fragmentation.
- Variable partitions: Flexible but more complex. Can lead to external fragmentation (which can be solved using memory compaction)

Free List Management

- Maintain separate lists for free blocks and reserved blocks to speed up allocation but that would make the merging of free blocks more complicated.
- Keep the free blocks sorted by size.
- Instead of a separate data structure, the first word in a free block could be its size and the second word could be the pointer to the next free block.
- Strategies for finding the memory chunk requested:
  - First Fit.
  - Best Fit.
  - Next Fit.
  - Worst Fit.

Comparison of Allocation Strategies

An example where first fit does better than best fit.

Two segments: 1300, 1200.
Requests: 1000, 1100, 250.

First fit does OK but best fit gets stuck.

Similarly, we can come up with examples where best fit does better than first fit. Similarly for worst fit and next fit.

How does dynamic memory allocation work in a program

The memory model is a one-dimensional array. That implies that multi-dimensional arrays, pointers and objects all have to map to one-dimensional array that represents the memory.

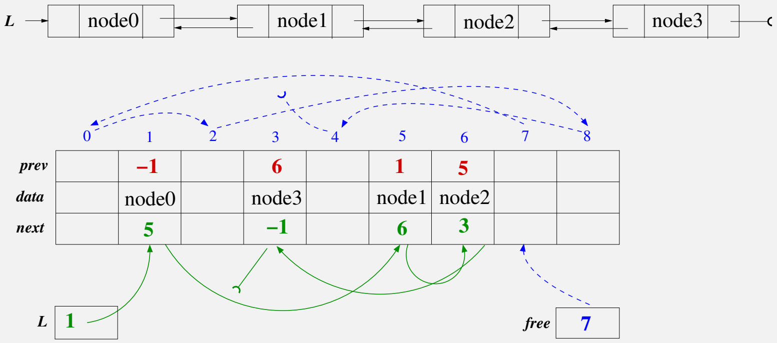
References:

1. *Introduction to Algorithms* by Cormen, Leiserson, Rivest and Stein. Section 10.4 (Implementing Pointers and Objects)
2. *The C Programming Language* by Kernighan and Ritchie. Section 5.4 (Address Arithmetic) and Section 8.7 (A Storage Allocator)

Simple Memory Allocator

- Let's design a simple allocator for a double-linked list that has a *prev*, *data* and *next* fields.
- We will represent the three fields with three separate one-dimensional arrays.
- Pointers will simply be indices into the arrays. We will use -1 as the null pointer.

Simple Memory Allocator example



	0	1	2	3	4	5	6	7	8
prev		**–1**		**6**		**1**	**5**		
data		node0		node3		node1	node2		
next		**5**		**–1**		**6**	**3**		

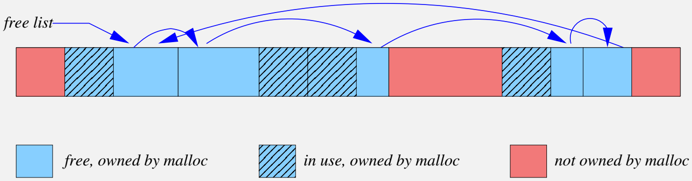
Simple Allocator Code

```
int prev[MAX], data[MAX], next[MAX];
int free;

void init_allocator() {
    for (int i=0; i < MAX - 1 ; i++)
        next[i] = i + 1;
    next[MAX - 1] = -1;
    free = 0;
}

int allocate_object() {
    int ptr = -1;
    if (free != -1) {
        ptr = free;
        free = next[free];
    }
    return ptr;
}

void free_object(int ptr) {
    next[ptr] = free;
    free = ptr;
}
```

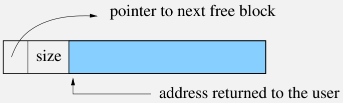
Simple Memory Allocator Exercises

1. Why don't we need to set or reset prev fields of the objects in the `allocate_object` or `free_object` methods.
2. How would we compact the memory in-place? (that is, we can only use a constant number of extra variables). By compaction, we mean move the nodes in use to the start of the arrays and collect the free nodes at the end. (*Hint*: Use a permutation).
3. Generalize to use a single one-dimensional array.
4. Write pseudocode for a homogeneous collection of objects implemented by a single array representation.

Malloc: Storage Allocator



Memory layout for malloc



A block returned by malloc

Malloc Algorithms

- The free storage is kept as a list of free blocks. Each block contains a pointer to the next free block, a size, and the space itself. The blocks are kept in increasing order of addresses and the last block points to the first.
- To allocate memory, the free list is scanned until a big enough block is found ("first-fit" algorithm). One optimization done is to leave the free list pointer where the last block was found ("next-fit" algorithm). Then one of the following three steps is taken.
  - If the block is exactly the right size, it is unlinked from the list and returned to the user.
  - If the block is too big, it is split, and the proper amount is returned to the user while the residue remains on the free list.
  - If no big-enough chunk is found, then another large chunk is obtained from the operating system and linked into the free list. Then a part of this new free block is split and returned to the user.
- To free an allocated block, we search the free list to find the proper place to insert it. If the block being freed is adjacent to a free block on either side, they are coalesced into a single bigger block, so the storage does not become fragmented.

Malloc Block Layout and Allocation

```
typedef double Align; /* for alignment to double boundary */
union header { /* block header */
    struct {
        union header *ptr; /* next block if on free list */
        unsigned size; /* size of this block */
    } s;
    Align x; /* force alignment of blocks */
};
typedef union header Header;
```

- The requested size in bytes is rounded up to proper number of header-sized units; the block that will be allocated contains one more unit, for the header itself, and this is the value recorded in the size field.
- The pointer returned by `malloc` points at the free space, not at the header itself.

Simple Malloc Implementation

- See examples `simple-malloc.h`, `simple-malloc.c` and related test files in the folder:
  - memory-management/simple-malloc/
- These are based directly from the K&R C book, Section 8.7.

Getting the source for the Standard C library

- Add some package management tools:
  `sudo dnf rpm-devel rpm-build`
- Download the source `rpm` for gcc C library named `glibc`:
  `sudo dnf -source glibc`
- Download dependencies for glibc:
  `sudo dnf builddep glibc`
- Install the source package:
  `rpm -ivh glibc-*src.rpm`
- Finally prep the source code.

  `rpmbuild -bp ~/rpmbuild/SPECS/glibc.spec`
- Now you can look at the source for the `glibc` (replace with the version that you downloaded)
  `cd ∼/rpmbuild/BUILD/glibc-2.23-85-g422facf`
- You can also build it and install it if you wish!

Buddy System Memory Management

The Walrus and the Coder
"The time has come," the Walrus said,
"To talk of many things:
Of shells–and system calls–and sealing-stacks–
Of threads–and pointers–
And why the C code is pointing over–
And whether buddies have wings."

Modified from the original "The Walrus and the Carpenter" by by Lewis Carroll in *"Through the Looking-Glass and What Alice Found There*, 1872"

"The time has come," the Walrus said,
"To talk of many things:
Of shoes–and ships–and sealing-wax–
Of cabbages–and kings–
And why the sea is boiling hot–
And whether pigs have wings."

Buddy System

- Assume that the memory pool is of size 2^m, with addresses 0 through $2^m - 1$.
- Block sizes are of powers of two, 2^k, $0 \leq k \leq m$. There are $m+1$ different lists: *avail[0], avail[1], . . . , avail[m]*. The ith list keeps track of blocks of size 2^i. At the beginning there is one block of size 2^m.
- All memory allocations are always done in sizes that are powers of two. Each block has a *tag* field which denotes if the block is free or reserved. Each block also has the usual links *next, prev* to maintain each list as a doubly-linked list. Finally each block also has a *kval* field that stores the size of the block (the value k is stored for a block of size 2^k.)

Buddy System (contd.)

- Address of a block of size 2^k is a multiple of 2^k (that is, at least k zeroes on the right). For example, a block of size 32 has an address of the form $xxx \dots xx00000$. After splitting the addresses of the two buddy blocks of size 16 are $xxx \dots xx00000$ and $xxx \dots xx10000$.
- Whenever a block is split into two halves, the two new blocks are called *buddies.* If we know the address of a block and its size, then we also know the address of its buddy.

$$\text{buddy}_k(x) = \begin{cases} x + 2^k & \text{if } x \bmod 2^{k+1} = 0 \\ x - 2^k & \text{if } x \bmod 2^{k+1} = 2^k \end{cases}$$

- The address of the buddy can be computed using an exclusive-or operation. In Java and C, the exclusive-or operator is ˆ. So the buddy calculation can be written as follows:

$$x\hat{}(1 << k)$$

Buddy System Allocation

- **Step A1**: Find block. To allocate a block of size 2^k, search the kth list and return the first free block. If the kth list is empty, then search the next higher list and so on until we find a free block. If no such list is found, then the allocation was unsuccessful and returns a null value. Otherwise, let the block be found in the jth list.
- **Step A2**: Remove from list. Remove first block from the jth list.
- **Step A3**: Split required? If j equals k, we have found a block of the right size. Return the appropriate address and exit.
- **Step A4**: Split. Split the first block in the jth list and add the unused half to the $(j-1)$th list. Set $j \leftarrow j-1$. Go back to Step A3.

Buddy System Free

Free a block of size 2^k at address L.

- **Step F1**: Is buddy available? Check for a buddy of size 2^k for block at address L. Go to Step F3 if the buddy isn't available.
- **Step F2**: Merge with buddy. Merge freed block with buddy in kth list. Set $k \leftarrow k+1$. Go back to Step F1.
- **Step F3**: Put on list. Add freed block to the front of the kth list.

Buddy System–Examples

Memory pool size $n = 2^m = 2^{20} = 1\text{MB}$.

- The first example shows the initial lists.
- The second example shows what happens when we allocate 1 byte. Note that the minimum block size is 32 in the system so that's why the allocation stops at 2^5.
- The third example shows that the blocks merge back up when we free the memory allocated.
- The fourth example shows a series of alloc/free calls.

Buddy System–Example 1

```
Buddy system initialized.
Buddy system lists after initialization.

List 0: head = 0x7f344e6500b8 --> <null>
List 1: head = 0x7f344e6500d0 --> <null>
List 2: head = 0x7f344e6500e8 --> <null>
List 3: head = 0x7f344e650100 --> <null>
List 4: head = 0x7f344e650118 --> <null>
List 5: head = 0x7f344e650130 --> <null>
List 6: head = 0x7f344e650148 --> <null>
List 7: head = 0x7f344e650160 --> <null>
List 8: head = 0x7f344e650178 --> <null>
List 9: head = 0x7f344e650190 --> <null>
List 10: head = 0x7f344e6501a8 --> <null>
List 11: head = 0x7f344e6501c0 --> <null>
List 12: head = 0x7f344e6501d8 --> <null>
List 13: head = 0x7f344e6501f0 --> <null>
List 14: head = 0x7f344e650208 --> <null>
List 15: head = 0x7f344e650220 --> <null>
List 16: head = 0x7f344e650238 --> <null>
List 17: head = 0x7f344e650250 --> <null>
List 18: head = 0x7f344e650268 --> <null>
List 19: head = 0x7f344e650280 --> <null>
List 20: head = 0x7f344e650298 --> [tag=1,kval=20,addr=0xf98000] --> <null>

 Number of available blocks = 1
```

Buddy System–Example 2

```
Buddy system succeeding in allocating 1 byte.
Buddy system lists after malloc'ing 1 byte.

List 0: head = 0x7f344e6500b8 --> <null>
List 1: head = 0x7f344e6500d0 --> <null>
List 2: head = 0x7f344e6500e8 --> <null>
List 3: head = 0x7f344e650100 --> <null>
List 4: head = 0x7f344e650118 --> <null>
List 5: head = 0x7f344e650130 --> [tag=1,kval=5,addr=0xf98020] --> <null>
List 6: head = 0x7f344e650148 --> [tag=1,kval=6,addr=0xf98040] --> <null>
List 7: head = 0x7f344e650160 --> [tag=1,kval=7,addr=0xf98080] --> <null>
List 8: head = 0x7f344e650178 --> [tag=1,kval=8,addr=0xf98100] --> <null>
List 9: head = 0x7f344e650190 --> [tag=1,kval=9,addr=0xf98200] --> <null>
List 10: head = 0x7f344e6501a8 --> [tag=1,kval=10,addr=0xf98400] --> <null>
List 11: head = 0x7f344e6501c0 --> [tag=1,kval=11,addr=0xf98800] --> <null>
List 12: head = 0x7f344e6501d8 --> [tag=1,kval=12,addr=0xf99000] --> <null>
List 13: head = 0x7f344e6501f0 --> [tag=1,kval=13,addr=0xf9a000] --> <null>
List 14: head = 0x7f344e650208 --> [tag=1,kval=14,addr=0xf9c000] --> <null>
List 15: head = 0x7f344e650220 --> [tag=1,kval=15,addr=0xfa0000] --> <null>
List 16: head = 0x7f344e650238 --> [tag=1,kval=16,addr=0xfa8000] --> <null>
List 17: head = 0x7f344e650250 --> [tag=1,kval=17,addr=0xfb8000] --> <null>
List 18: head = 0x7f344e650268 --> [tag=1,kval=18,addr=0xfd8000] --> <null>
List 19: head = 0x7f344e650280 --> [tag=1,kval=19,addr=0x1018000] --> <null>
List 20: head = 0x7f344e650298 --> <null>

 Number of available blocks = 15
```

Buddy System–Example 3

```
Buddy system succeeding in free'ing 1 byte.
Buddy system lists after free'ing the block .

List 0: head = 0x7f344e6500b8 --> <null>
List 1: head = 0x7f344e6500d0 --> <null>
List 2: head = 0x7f344e6500e8 --> <null>
List 3: head = 0x7f344e650100 --> <null>
List 4: head = 0x7f344e650118 --> <null>
List 5: head = 0x7f344e650130 --> <null>
List 6: head = 0x7f344e650148 --> <null>
List 7: head = 0x7f344e650160 --> <null>
List 8: head = 0x7f344e650178 --> <null>
List 9: head = 0x7f344e650190 --> <null>
List 10: head = 0x7f344e6501a8 --> <null>
List 11: head = 0x7f344e6501c0 --> <null>
List 12: head = 0x7f344e6501d8 --> <null>
List 13: head = 0x7f344e6501f0 --> <null>
List 14: head = 0x7f344e650208 --> <null>
List 15: head = 0x7f344e650220 --> <null>
List 16: head = 0x7f344e650238 --> <null>
List 17: head = 0x7f344e650250 --> <null>
List 18: head = 0x7f344e650268 --> <null>
List 19: head = 0x7f344e650280 --> <null>
List 20: head = 0x7f344e650298 --> [tag=1,kval=20,addr=0xf98000] --> <null>

 Number of available blocks = 1
```

Buddy System–Example 4

Memory pool size $n = 2^m = 2^{20} = 1\text{MB}$.
Work out what happens with the following example.
Requests: 70KB (Process A), 35KB (Process B), 80KB (Process C), free A, 60KB (Process D), free B, free D, free C.
Each request is rounded up to the next power of two.

Buddy System–Example 4 (contd.)

```
Buddy system initialized.
Buddy system lists after initialization.

List 0: head = 0x7f272c5331f8 --> <null>
List 1: head = 0x7f272c533210 --> <null>
List 2: head = 0x7f272c533228 --> <null>
List 3: head = 0x7f272c533240 --> <null>
List 4: head = 0x7f272c533258 --> <null>
List 5: head = 0x7f272c533270 --> <null>
List 6: head = 0x7f272c533288 --> <null>
List 7: head = 0x7f272c5332a0 --> <null>
List 8: head = 0x7f272c5332b8 --> <null>
List 9: head = 0x7f272c5332d0 --> <null>
List 10: head = 0x7f272c5332e8 --> <null>
List 11: head = 0x7f272c533300 --> <null>
List 12: head = 0x7f272c533318 --> <null>
List 13: head = 0x7f272c533330 --> <null>
List 14: head = 0x7f272c533348 --> <null>
List 15: head = 0x7f272c533360 --> <null>
List 16: head = 0x7f272c533378 --> <null>
List 17: head = 0x7f272c533390 --> <null>
List 18: head = 0x7f272c5333a8 --> <null>
List 19: head = 0x7f272c5333c0 --> <null>
List 20: head = 0x7f272c5333d8 --> [tag=1,kval=20,addr=0x1123000] --> <null>

 Number of available blocks = 1
```

Buddy System–Example 4 (contd.)

```
Buddy system lists after malloc'ing 70KB.

List 0: head = 0x7f272c5331f8 --> <null>
List 1: head = 0x7f272c533210 --> <null>
List 2: head = 0x7f272c533228 --> <null>
List 3: head = 0x7f272c533240 --> <null>
List 4: head = 0x7f272c533258 --> <null>
List 5: head = 0x7f272c533270 --> <null>
List 6: head = 0x7f272c533288 --> <null>
List 7: head = 0x7f272c5332a0 --> <null>
List 8: head = 0x7f272c5332b8 --> <null>
List 9: head = 0x7f272c5332d0 --> <null>
List 10: head = 0x7f272c5332e8 --> <null>
List 11: head = 0x7f272c533300 --> <null>
List 12: head = 0x7f272c533318 --> <null>
List 13: head = 0x7f272c533330 --> <null>
List 14: head = 0x7f272c533348 --> <null>
List 15: head = 0x7f272c533360 --> <null>
List 16: head = 0x7f272c533378 --> <null>
List 17: head = 0x7f272c533390 --> [tag=1,kval=17,addr=0x1143000] --> <null>
List 18: head = 0x7f272c5333a8 --> [tag=1,kval=18,addr=0x1163000] --> <null>
List 19: head = 0x7f272c5333c0 --> [tag=1,kval=19,addr=0x11a3000] --> <null>
List 20: head = 0x7f272c5333d8 --> <null>

 Number of available blocks = 3
```

Buddy System–Example 4 (contd.)

```
Buddy system lists after malloc'ing 35KB.

List 0: head = 0x7f272c5331f8 --> <null>
List 1: head = 0x7f272c533210 --> <null>
List 2: head = 0x7f272c533228 --> <null>
List 3: head = 0x7f272c533240 --> <null>
List 4: head = 0x7f272c533258 --> <null>
List 5: head = 0x7f272c533270 --> <null>
List 6: head = 0x7f272c533288 --> <null>
List 7: head = 0x7f272c5332a0 --> <null>
List 8: head = 0x7f272c5332b8 --> <null>
List 9: head = 0x7f272c5332d0 --> <null>
List 10: head = 0x7f272c5332e8 --> <null>
List 11: head = 0x7f272c533300 --> <null>
List 12: head = 0x7f272c533318 --> <null>
List 13: head = 0x7f272c533330 --> <null>
List 14: head = 0x7f272c533348 --> <null>
List 15: head = 0x7f272c533360 --> <null>
List 16: head = 0x7f272c533378 --> [tag=1,kval=16,addr=0x1153000] --> <null>
List 17: head = 0x7f272c533390 --> <null>
List 18: head = 0x7f272c5333a8 --> [tag=1,kval=18,addr=0x1163000] --> <null>
List 19: head = 0x7f272c5333c0 --> [tag=1,kval=19,addr=0x11a3000] --> <null>
List 20: head = 0x7f272c5333d8 --> <null>

 Number of available blocks = 3
```

Buddy System–Example 4 (contd.)

```
Buddy system lists after malloc'ing 80KB.

List 0: head = 0x7f272c5331f8 --> <null>
List 1: head = 0x7f272c533210 --> <null>
List 2: head = 0x7f272c533228 --> <null>
List 3: head = 0x7f272c533240 --> <null>
List 4: head = 0x7f272c533258 --> <null>
List 5: head = 0x7f272c533270 --> <null>
List 6: head = 0x7f272c533288 --> <null>
List 7: head = 0x7f272c5332a0 --> <null>
List 8: head = 0x7f272c5332b8 --> <null>
List 9: head = 0x7f272c5332d0 --> <null>
List 10: head = 0x7f272c5332e8 --> <null>
List 11: head = 0x7f272c533300 --> <null>
List 12: head = 0x7f272c533318 --> <null>
List 13: head = 0x7f272c533330 --> <null>
List 14: head = 0x7f272c533348 --> <null>
List 15: head = 0x7f272c533360 --> <null>
List 16: head = 0x7f272c533378 --> [tag=1,kval=16,addr=0x1153000] --> <null>
List 17: head = 0x7f272c533390 --> [tag=1,kval=17,addr=0x1183000] --> <null>
List 18: head = 0x7f272c5333a8 --> <null>
List 19: head = 0x7f272c5333c0 --> [tag=1,kval=19,addr=0x11a3000] --> <null>
List 20: head = 0x7f272c5333d8 --> <null>

 Number of available blocks = 3
```

Buddy System–Example 4 (contd.)

```
Buddy system lists after free'ing the 70KB block .

List 0: head = 0x7f272c5331f8 --> <null>
List 1: head = 0x7f272c533210 --> <null>
List 2: head = 0x7f272c533228 --> <null>
List 3: head = 0x7f272c533240 --> <null>
List 4: head = 0x7f272c533258 --> <null>
List 5: head = 0x7f272c533270 --> <null>
List 6: head = 0x7f272c533288 --> <null>
List 7: head = 0x7f272c5332a0 --> <null>
List 8: head = 0x7f272c5332b8 --> <null>
List 9: head = 0x7f272c5332d0 --> <null>
List 10: head = 0x7f272c5332e8 --> <null>
List 11: head = 0x7f272c533300 --> <null>
List 12: head = 0x7f272c533318 --> <null>
List 13: head = 0x7f272c533330 --> <null>
List 14: head = 0x7f272c533348 --> <null>
List 15: head = 0x7f272c533360 --> <null>
List 16: head = 0x7f272c533378 --> [tag=1,kval=16,addr=0x1153000] --> <null>
List 17: head = 0x7f272c533390 --> [tag=1,kval=17,addr=0x1123000] -->
                                         [tag=1,kval=17,addr=0x1183000] --> <null>
List 18: head = 0x7f272c5333a8 --> <null>
List 19: head = 0x7f272c5333c0 --> [tag=1,kval=19,addr=0x11a3000] --> <null>
List 20: head = 0x7f272c5333d8 --> <null>

 Number of available blocks = 4
```

Buddy System–Example 4 (contd.)

```
Buddy system lists after malloc'ing 60KB.

List 0: head = 0x7f272c5331f8 --> <null>
List 1: head = 0x7f272c533210 --> <null>
List 2: head = 0x7f272c533228 --> <null>
List 3: head = 0x7f272c533240 --> <null>
List 4: head = 0x7f272c533258 --> <null>
List 5: head = 0x7f272c533270 --> <null>
List 6: head = 0x7f272c533288 --> <null>
List 7: head = 0x7f272c5332a0 --> <null>
List 8: head = 0x7f272c5332b8 --> <null>
List 9: head = 0x7f272c5332d0 --> <null>
List 10: head = 0x7f272c5332e8 --> <null>
List 11: head = 0x7f272c533300 --> <null>
List 12: head = 0x7f272c533318 --> <null>
List 13: head = 0x7f272c533330 --> <null>
List 14: head = 0x7f272c533348 --> <null>
List 15: head = 0x7f272c533360 --> <null>
List 16: head = 0x7f272c533378 --> <null>
List 17: head = 0x7f272c533390 --> [tag=1,kval=17,addr=0x1123000] -->
                                      [tag=1,kval=17,addr=0x1183000] --> <null>
List 18: head = 0x7f272c5333a8 --> <null>
List 19: head = 0x7f272c5333c0 --> [tag=1,kval=19,addr=0x11a3000] --> <null>
List 20: head = 0x7f272c5333d8 --> <null>

 Number of available blocks = 3
```

Buddy System–Example 4 (contd.)

```
Buddy system lists after free'ing the  35KB block .

List 0: head = 0x7f272c5331f8 --> <null>
List 1: head = 0x7f272c533210 --> <null>
List 2: head = 0x7f272c533228 --> <null>
List 3: head = 0x7f272c533240 --> <null>
List 4: head = 0x7f272c533258 --> <null>
List 5: head = 0x7f272c533270 --> <null>
List 6: head = 0x7f272c533288 --> <null>
List 7: head = 0x7f272c5332a0 --> <null>
List 8: head = 0x7f272c5332b8 --> <null>
List 9: head = 0x7f272c5332d0 --> <null>
List 10: head = 0x7f272c5332e8 --> <null>
List 11: head = 0x7f272c533300 --> <null>
List 12: head = 0x7f272c533318 --> <null>
List 13: head = 0x7f272c533330 --> <null>
List 14: head = 0x7f272c533348 --> <null>
List 15: head = 0x7f272c533360 --> <null>
List 16: head = 0x7f272c533378 --> [tag=1,kval=16,addr=0x1143000] --> <null>
List 17: head = 0x7f272c533390 --> [tag=1,kval=17,addr=0x1123000] -->
                                        [tag=1,kval=17,addr=0x1183000] --> <null>
List 18: head = 0x7f272c5333a8 --> <null>
List 19: head = 0x7f272c5333c0 --> [tag=1,kval=19,addr=0x11a3000] --> <null>
List 20: head = 0x7f272c5333d8 --> <null>

 Number of available blocks = 4
```

Buddy System–Example 4 (contd.)

```
Buddy system lists after free'ing the 60KB block .

List 0: head = 0x7f272c5331f8 --> <null>
List 1: head = 0x7f272c533210 --> <null>
List 2: head = 0x7f272c533228 --> <null>
List 3: head = 0x7f272c533240 --> <null>
List 4: head = 0x7f272c533258 --> <null>
List 5: head = 0x7f272c533270 --> <null>
List 6: head = 0x7f272c533288 --> <null>
List 7: head = 0x7f272c5332a0 --> <null>
List 8: head = 0x7f272c5332b8 --> <null>
List 9: head = 0x7f272c5332d0 --> <null>
List 10: head = 0x7f272c5332e8 --> <null>
List 11: head = 0x7f272c533300 --> <null>
List 12: head = 0x7f272c533318 --> <null>
List 13: head = 0x7f272c533330 --> <null>
List 14: head = 0x7f272c533348 --> <null>
List 15: head = 0x7f272c533360 --> <null>
List 16: head = 0x7f272c533378 --> <null>
List 17: head = 0x7f272c533390 --> [tag=1,kval=17,addr=0x1183000] --> <null>
List 18: head = 0x7f272c5333a8 --> [tag=1,kval=18,addr=0x1123000] --> <null>
List 19: head = 0x7f272c5333c0 --> [tag=1,kval=19,addr=0x11a3000] --> <null>
List 20: head = 0x7f272c5333d8 --> <null>

 Number of available blocks = 3
```

Buddy System–Example 4 (contd.)

```
Buddy system lists after free'ing the 80KB block .

List 0: head = 0x7f272c5331f8 --> <null>
List 1: head = 0x7f272c533210 --> <null>
List 2: head = 0x7f272c533228 --> <null>
List 3: head = 0x7f272c533240 --> <null>
List 4: head = 0x7f272c533258 --> <null>
List 5: head = 0x7f272c533270 --> <null>
List 6: head = 0x7f272c533288 --> <null>
List 7: head = 0x7f272c5332a0 --> <null>
List 8: head = 0x7f272c5332b8 --> <null>
List 9: head = 0x7f272c5332d0 --> <null>
List 10: head = 0x7f272c5332e8 --> <null>
List 11: head = 0x7f272c533300 --> <null>
List 12: head = 0x7f272c533318 --> <null>
List 13: head = 0x7f272c533330 --> <null>
List 14: head = 0x7f272c533348 --> <null>
List 15: head = 0x7f272c533360 --> <null>
List 16: head = 0x7f272c533378 --> <null>
List 17: head = 0x7f272c533390 --> <null>
List 18: head = 0x7f272c5333a8 --> <null>
List 19: head = 0x7f272c5333c0 --> <null>
List 20: head = 0x7f272c5333d8 --> [tag=1,kval=20,addr=0x1123000] --> <null>

 Number of available blocks = 1
```

Buddy System–Analysis

Advantages:

- Searching a block of size k requires searching only one list of free blocks of size k instead of all the free blocks.
- Merging free blocks is much faster by design.

Disadvantages:

- All memory requests have to be rounded up to the nearest power of two, which may cause significant internal fragmentation.

A modified version of the buddy system is used in Linux.

Buddy System References

- Kenneth C. Knowlton. *A Fast storage allocator. Communications of the ACM* 8(10):623-625, Oct 1965. also Kenneth C Knowlton. *A programmer's description of L6*. Communications of the ACM, 9(8):616-625, Aug. 1966.
- Donald Knuth. *Fundamental Algorithms. The Art of Computer Programming 1* (Second ed.) pp. 435-455. Addison-Wesley.
- Wikipedia: `http://en.wikipedia.org/wiki/Buddy_memory_system`

So what is used in modern operating systems?

Modern operating systems all use some form of variable partitioning. However, memory is allocated in fixed-size blocks (called “pages”), which greatly simplifies free list management.

- The Linux kernel also uses the buddy system, with further modifications to minimize external fragmentation, along with various slab allocators to manage the memory within blocks. These are listed below:
    - SLAB is a complex allocator that performs well on a variety of workloads. See article at `http://en.wikipedia.org/wiki/Slab_allocation`
    - SLUB, the kernel's default, has a much simpler design and superior debugging features. However it has significant regressions on some benchmarks.
    - SLOB (Simple List of Blocks) allocator for embedded devices and machines that require a very small kernel footprint.
- BSD-based systems like Mac OS X also use a slab-based allocation system.
- jemalloc is a modern memory allocator that is a replacement for malloc that employs, among others, the buddy technique.

So what is used in modern operating systems? (contd)

Microsoft Windows memory management:

- Multiple memory pools of two types: Nonpaged pool and Paged pool. System starts with four paged pools and one non-paged pool and can grow up to 64 pools to support multicore architecture.
- On 64-bit systems, nonpaged pool has a maximum size of 75% of the physical memory or 128GB, whichever is smaller. Paged pool has a maximum size of 128GB.
- Use process explorer (Sysinternals tools) to see pool information. Click on *View* and then *System Information*.
- Look-aside Lists for faster allocation of fixed-size blocks. These lists will automatically grow or shrink depending upon usage.
- Heap Manager manages memory inside smaller chunks. It has a granularity of 8/16 bytes on 32-bit/64-bit systems.

Program and Data Locality

- Program locality...most programs spend 90% of the time in 10% of the code.
- How good is the data locality for the following data structures?
  - stacks,
  - queues,
  - linked lists,
  - heap data-structure,
  - binary search trees.

Swapping

- Swapping relies on dynamic relocation hardware. The decision as to when to swap is made by the memory manager.
- The memory manager can deallocate the memory for a blocked process and allocate the memory to other processes.
- In a time sharing system, a process could be swapped out even if it is not blocked to equitably share memory and the CPU (for example, swapping can be activated when the number of active users exceeds a certain threshold).
- When a swapped out process returns to ready state, the process manager informs the memory manager to swap it back in.
- Swapping takes considerable time. Hence the memory manager should swap only when it is needed.

Introduction to Virtual Memory

- Allows a process to use more memory than present physically.
- Also allows only part of the address space of a process to be present in the primary memory. This makes multiprogramming more effective.
- Relies on *spatial reference locality* of program text and data.
- Relies on dynamic relocation hardware as well as other specialized hardware support.

Shared Memory Multiprocessors

- Processes (potentially running on different CPUs) communicate using shared memory.
- The simplest way to set up shared memory is to let processes share parts of their address space.
- If each CPU has its own cache, then we have the problem of *cache coherence*. Caches could be *strongly consistent* or *weakly consistent*.
- Shared memory can also be set up among unrelated processes on a single processor system as an efficient means of communication. (example on next few frames).

Shared Memory Segments

- Older style shared memory calls: shmget(...), shmat(...), shmdt(...), shmdtl(...)
  Check the shared memory segments with the command: `ipcs`
- POSIX standard shared memory calls. (supported under Linux and Mac OS X) shm_open(...), ftruncate(...), mmap(...), shm_unlink(...) Under Linux, check the shared memory segments with the command:
  `ls -l /dev/shm`
- Under MS Windows use CreateFileMapping(...), MapViewOfFile(...), UnmapViewOfFile(...). See examples in ms-windows/memory-management/

Memory Mapping

- **Under Linux/Mac OS X**. Use `mmap(...)` and `munmap(...)`.

```
//.. appropriate header files
void  *mmap(void *start, size_t length, int prot, int flags,
            int fd, off_t offset);
int munmap(void *start, size_t length);
```

- **Under MS Windows**. Use VirtualAlloc(...) and VirtualFree(...)

```
LPVOID WINAPI VirtualAlloc(
  __in_opt  LPVOID lpAddress,
  __in      SIZE_T dwSize,
  __in      DWORD flAllocationType,
  __in      DWORD flProtect
);
BOOL WINAPI VirtualFree(
  __in  LPVOID lpAddress,
  __in  SIZE_T dwSize,
  __in  DWORD dwFreeType
);
```

(POSIX) Shared Memory Examples

- create_posix_shmem.c
- access_posix_shmem.c

Observing POSIX Shared Memory Segments

The kernel keeps the POSIX shared memory segments in a virtual file system /dev/shm. By default, it is usually equal to half the installed memory size on the system (but can be altered in /etc/fstab). Use `ls` on that folder to see the shared memory segments.

```
[amit@kohinoor memory-management]: ls -l /dev/shm
total 5784
-rw-rw-r-- 1 amit amit   100000 Nov  7 13:58 amit
-r-------- 1 amit amit 67108904 Oct 19 09:47 pulse-shm-1210480228
-r-------- 1 amit amit 67108904 Oct 19 11:20 pulse-shm-1469689579
-r-------- 1 gdm  gdm  67108904 Oct 19 09:47 pulse-shm-2908712043
-r-------- 1 amit amit 67108904 Oct 26 14:24 pulse-shm-3200708632
-r-------- 1 amit amit 67108904 Oct 19 09:47 pulse-shm-3973641630
-r-------- 1 amit amit 67108904 Nov  4 03:27 pulse-shm-722623938
-rw-rw-rw- 1 amit amit       16 Oct 20 09:45 sem.ADBE_ReadPrefs_amit
-rw-rw-rw- 1 amit amit       16 Oct 20 09:45 sem.ADBE_REL_amit
-rw-rw-rw- 1 amit amit       16 Oct 20 09:45 sem.ADBE_WritePrefs_amit
[amit@kohinoor memory-management]:
```

Observing Shared Memory Segments (older style)

The utility ipcs lets us find out about active older (non-POSIX) style shared memory segments in the system (as well as message queues and semaphores). Here is a sample output from the ipcs command.

```
[amit@kohinoor]: ipcs
------ Shared Memory Segments --------
key        shmid      owner      perms      bytes      nattch     status
0x73727372 0          root        666        44172      0
0x7b01333d 1          amit        600        1024       3
0x00000000 1486850    amit        777        196608     2          dest
------ Semaphore Arrays --------
key        semid      owner      perms      nsems      status
0x6c737372 0          root        666        3
------ Message Queues --------
key        msqid      owner      perms      used-bytes  messages
```

A corresponding command ipcrm lets a user remove shared memory segments etc. (if they have the right permissions).

Synchronization and Shared Segments

- If multiple processes are modifying data structures stored in a shared memory segment, then we need to synchronize them (similar to global variables in a multi-threaded program).
- Note that the mutexes, semaphores built in with Pthreads library are not shared among processes (by default). They can be made shared by setting the appropriate flag and putting them into a shared memory segment.
- We can also use global semaphores provided via system calls in Linux. See examples memory-management/semdemo.c and memory-management/semrm.c.
- In the MS Windows API, sempahores and mutexes can be assigned a string handle and shared between processes.