CSE320 System Fundamentals II Dynamic Memory Allocation

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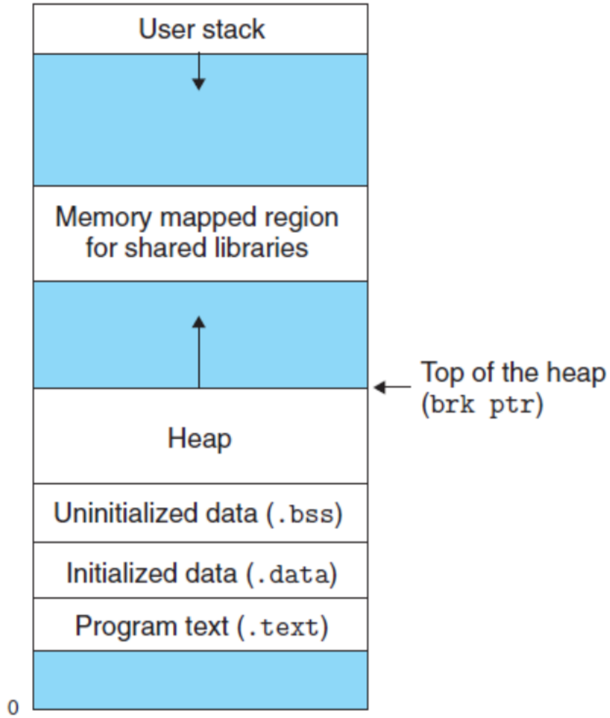
Dynamic Memory Allocation

A dynamic memory allocator maintains an area of a process's virtual memory known as the heap

For each process, the kernel maintains a variable brk that points to the top of the heap.

Explicit allocator
- malloc, free

Implicit allocator
- 'new'
- Garbage collectors



malloc and free

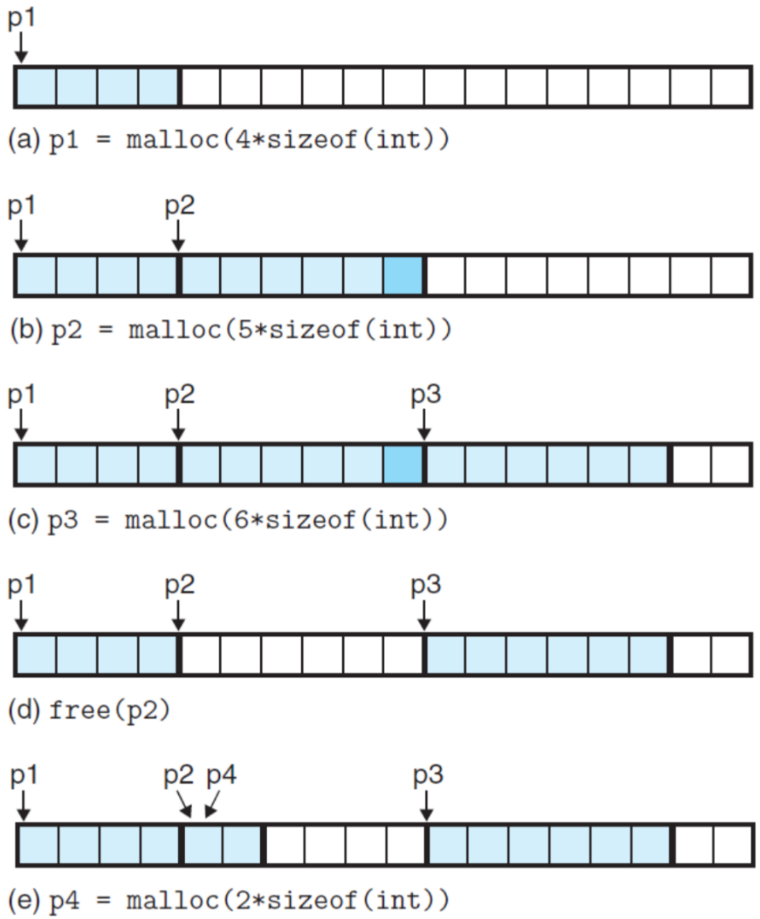
void *malloc(size_t size) allocates at least the request size bytes

- calloc works like malloc but initializes the memory to 0 in addition

void free(void *ptr) frees the allocated memory

void *sbrk(intptr_t incr) increases brk by incr and returns the old brk.

malloc and free



each cell: 2 byte
int: 2 byte
alignment: 4 byte

Dark blue area is a padding for the alignment

Fragmentation

Internal fragmentation

- Allocated blocks are larger than payloads
- Due to minimum size constraints on allocation
- Due to padding for the alignment.
  - E.g. the dark blue cell in (b), (c) of prev. page

External fragmentation

- There is enough aggregate free memory to satisfy the request, but no single block is large enough.
  - E.g. malloc(5*sizeof(int)) after (e) of prev. page

Implementation Issues

Free block organization

- How to keep track of free blocks?

Placement

- How to choose a free block for a request?

Splitting

- When a part of a free block is allocated, what do we do for the remaining free blocks?

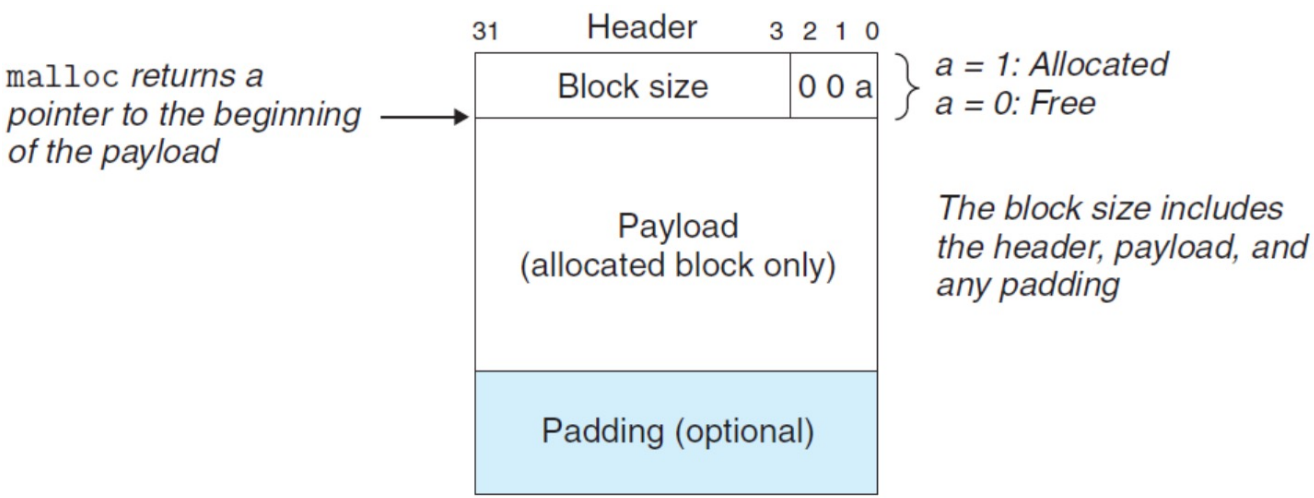
Coalescing

- What do we do with a block that is just freed?

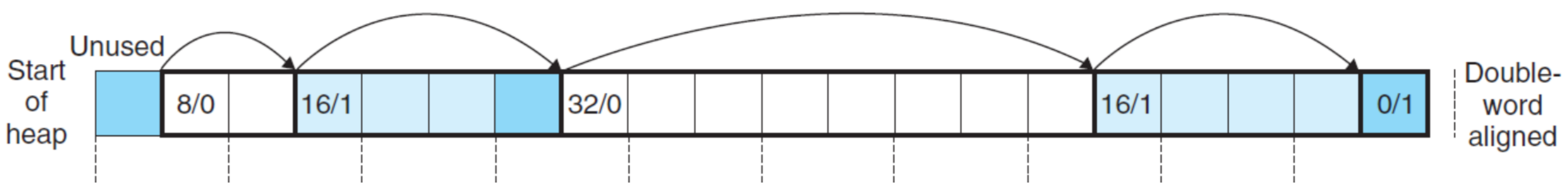
Implicit Free Lists

Any allocator needs some data structure for
- Identifying block boundaries
- Distinguishing between allocated and free blocks

A one-word header encodes the block size and whether the block is allocated or free



Implicit Free Lists



Implicit free list

- Free blocks are linked implicitly by the size field in the header
- Last block: terminating header with size 0 and marked as allocated.
- Simple, but searching for a preceding free block is costly

Placing Allocated Blocks

First fit

- Searches the free list from the beginning and chooses the first free block that fits
- Leaves small splinters towards the beginning of the list. Large free blocks towards the end of the list.

Next fit

- Search the free list from the last allocation point.
- Good chances to find a fit in the remainder of the block
- Suffers from poor memory utilization.

Best fit

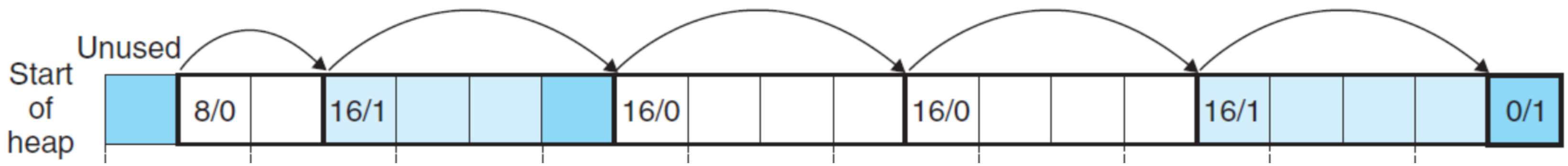
- Searches for a free block with the tightest fit.
- Good memory utilization
- Exhaustive search of the heap

Getting Additional Heap Memory

When the allocator is unable to find a block that fits the request

- Merge adjacent free blocks (coalescing)
- Ask the kernel for additional heap memory by calling sbrk.

Coalescing Free Blocks



False fragmentation

- Adjacent free blocks can serve the request, but individual blocks are too small for the request.

Coalescing merges the adjacent free blocks.

- **Immediate coalescing**: merge free blocks as soon as they are freed.
- **Deferred coalescing**: defer coalescing until later time. (e.g. when some allocation request fails)

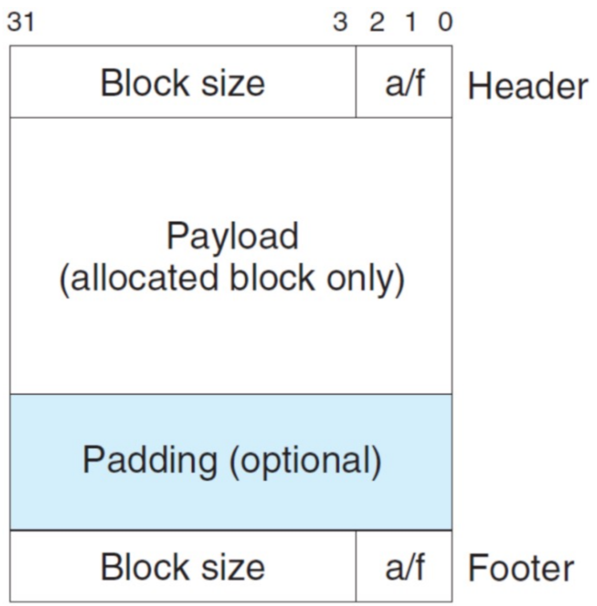
Coalescing with Boundary Tags

Coalescing using the header only

- Coalescing the next free block is straightforward (adding the size to the current block will point to the next block)

- Coalescing with the previous free block requires searching the entire free list

Coalescing with Boundary Tags



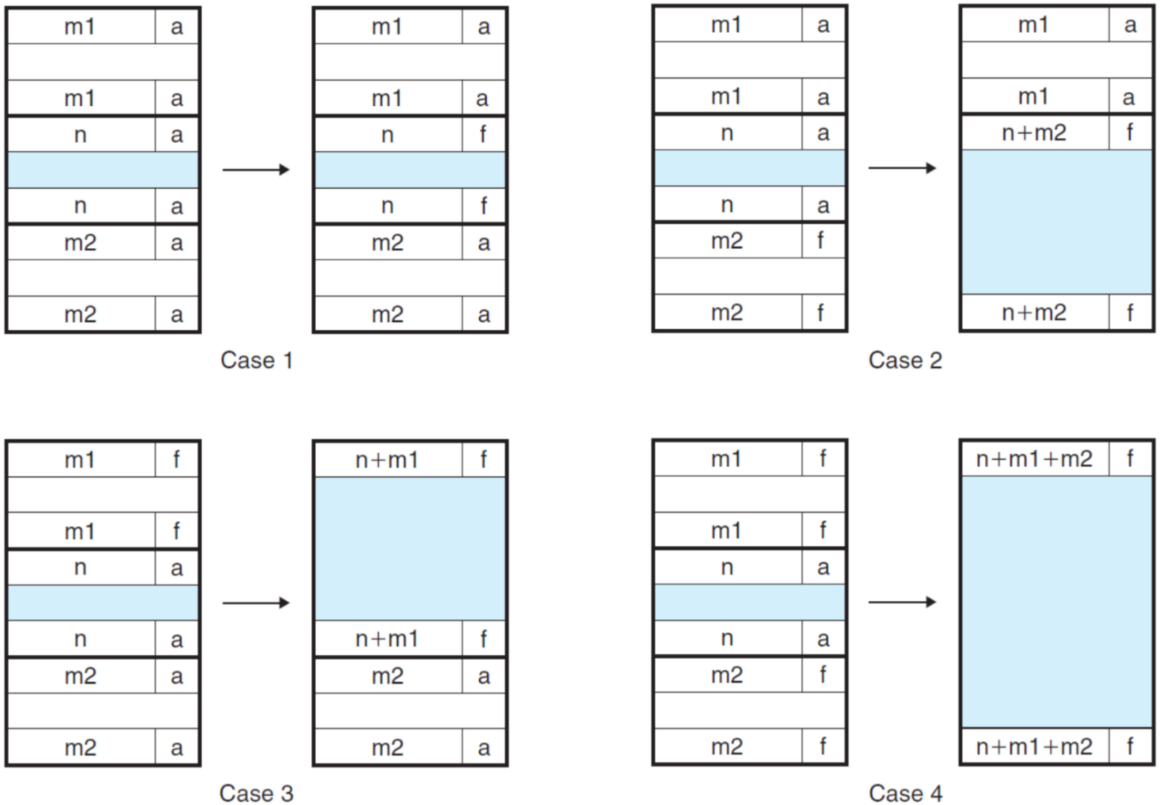
Boundary tag is a footer at the end of the block, where the footer is the replica of the header

Finding the previous block is easy

- Get the size of the previous block from its footer

- If the allocated/free bit for the previous block is encoded at the current block, the footer can be used only for the free blocks

Coalescing with Boundary Tags Example:



4 cases: (1) both prev and next are alloc'd, (2) prev is alloc'd and next is free, (3) prev is free and next is alloc'd, (4) both prev and next are free.

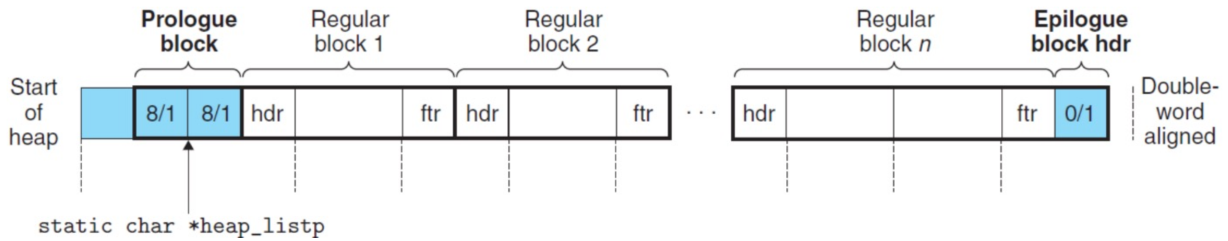
A Simple Allocator

```c
/*
 * mem_init - Initialize the memory system model
 */
void mem_init(void)
{
    mem_heap = (char *)Malloc(MAX_HEAP);
    mem_brk = (char *)mem_heap;
    mem_max_addr = (char *)(mem_heap + MAX_HEAP);
}

/*
 * mem_sbrk - Simple model of the sbrk function. Extends the heap
 *    by incr bytes and returns the start address of the new area. In
 *    this model, the heap cannot be shrunk.
 */
void *mem_sbrk(int incr)
{
    char *old_brk = mem_brk;

    if ( (incr < 0) || ((mem_brk + incr) > mem_max_addr)) {
        errno = ENOMEM;
        fprintf(stderr, "ERROR: mem_sbrk failed. Ran out of memory...\n");
        return (void *)-1;
    }
    mem_brk += incr;
    return (void *)old_brk;
}
```

A Simple Allocator (cont)

```c
/* Basic constants and macros */
#define WSIZE       4       /* Word and header/footer size (bytes) */
#define DSIZE       8       /* Double word size (bytes) */
#define CHUNKSIZE  (1<<12)  /* Extend heap by this amount (bytes) */

#define MAX(x, y) ((x) > (y)? (x) : (y))

/* Pack a size and allocated bit into a word */
#define PACK(size, alloc)  ((size) | (alloc))

/* Read and write a word at address p */
#define GET(p)       (*(unsigned int *)(p))
#define PUT(p, val)  (*(unsigned int *)(p) = (val))

/* Read the size and allocated fields from address p */
#define GET_SIZE(p)  (GET(p) & ~0x7)
#define GET_ALLOC(p) (GET(p) & 0x1)

/* Given block ptr bp, compute address of its header and footer */
#define HDRP(bp)       ((char *)(bp) - WSIZE)
#define FTRP(bp)       ((char *)(bp) + GET_SIZE(HDRP(bp)) - DSIZE)

/* Given block ptr bp, compute address of next and previous blocks */
#define NEXT_BLKP(bp)  ((char *)(bp) + GET_SIZE(((char *)(bp) - WSIZE)))
#define PREV_BLKP(bp)  ((char *)(bp) - GET_SIZE(((char *)(bp) - DSIZE)))
```

A Simple Allocator (cont)




```
int mm_init(void)
{
    /* Create the initial empty heap */
    if ((heap_listp = mem_sbrk(4*WSIZE)) == (void *)-1)
        return -1;
    PUT(heap_listp, 0);                            /* Alignment padding */
    PUT(heap_listp + (1*WSIZE), PACK(DSIZE, 1)); /* Prologue header */
    PUT(heap_listp + (2*WSIZE), PACK(DSIZE, 1)); /* Prologue footer */
    PUT(heap_listp + (3*WSIZE), PACK(0, 1));     /* Epilogue header */
    heap_listp += (2*WSIZE);

    /* Extend the empty heap with a free block of CHUNKSIZE bytes */
    if (extend_heap(CHUNKSIZE/WSIZE) == NULL)
        return -1;
    return 0;
}
```

A Simple Allocator (cont)

```
static void *extend_heap(size_t words)
{
    char *bp;
    size_t size;

    /* Allocate an even number of words to maintain alignment */
    size = (words % 2) ? (words+1) * WSIZE : words * WSIZE;
    if ((long)(bp = mem_sbrk(size)) == -1)
        return NULL;

    /* Initialize free block header/footer and the epilogue header */
    PUT(HDRP(bp), PACK(size, 0));         /* Free block header */
    PUT(FTRP(bp), PACK(size, 0));         /* Free block footer */
    PUT(HDRP(NEXT_BLKP(bp)), PACK(0, 1)); /* New epilogue header */

    /* Coalesce if the previous block was free */
    return coalesce(bp);
}
```

A Simple Allocator (cont)

```
void mm_free(void *bp)
{
    size_t size = GET_SIZE(HDRP(bp));

    PUT(HDRP(bp), PACK(size, 0));
    PUT(FTRP(bp), PACK(size, 0));
    coalesce(bp);
}

static void *coalesce(void *bp)
{
    size_t prev_alloc = GET_ALLOC(FTRP(PREV_BLKP(bp)));
    size_t next_alloc = GET_ALLOC(HDRP(NEXT_BLKP(bp)));
    size_t size = GET_SIZE(HDRP(bp));

    if (prev_alloc && next_alloc) {            /* Case 1 */
        return bp;
    }
```

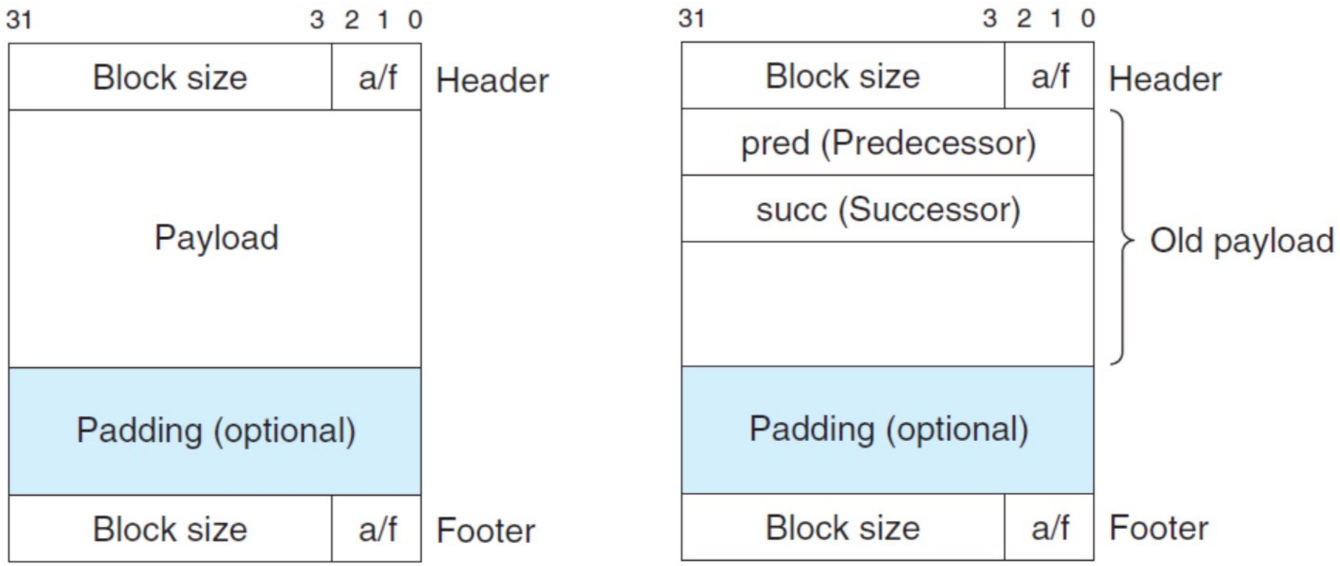
A Simple Allocator (cont)

```
    else if (prev_alloc && !next_alloc) {      /* Case 2 */
        size += GET_SIZE(HDRP(NEXT_BLKP(bp)));
        PUT(HDRP(bp), PACK(size, 0));
        PUT(FTRP(bp), PACK(size,0));
    }

    else if (!prev_alloc && next_alloc) {      /* Case 3 */
        size += GET_SIZE(HDRP(PREV_BLKP(bp)));
        PUT(FTRP(bp), PACK(size, 0));
        PUT(HDRP(PREV_BLKP(bp)), PACK(size, 0));
        bp = PREV_BLKP(bp);
    }

    else {                                     /* Case 4 */
        size += GET_SIZE(HDRP(PREV_BLKP(bp))) +
            GET_SIZE(FTRP(NEXT_BLKP(bp)));
        PUT(HDRP(PREV_BLKP(bp)), PACK(size, 0));
        PUT(FTRP(NEXT_BLKP(bp)), PACK(size, 0));
        bp = PREV_BLKP(bp);
    }
    return bp;
}
```

A Simple Allocator (cont)

```
void *mm_malloc(size_t size)
{
    size_t asize;      /* Adjusted block size */
    size_t extendsize; /* Amount to extend heap if no fit */
    char *bp;

    /* Ignore spurious requests */
    if (size == 0)
        return NULL;

    /* Adjust block size to include overhead and alignment reqs. */
    if (size <= DSIZE)
        asize = 2*DSIZE;
    else
        asize = DSIZE * ((size + (DSIZE) + (DSIZE-1)) / DSIZE);

    /* Search the free list for a fit */
    if ((bp = find_fit(asize)) != NULL) {
        place(bp, asize);
        return bp;
    }

    /* No fit found. Get more memory and place the block */
    extendsize = MAX(asize,CHUNKSIZE);
    if ((bp = extend_heap(extendsize/WSIZE)) == NULL)
        return NULL;
    place(bp, asize);
    return bp;
}
```

Explicit Free List



(a) Allocated block

(b) Free block

For the free blocks, add pred and next link to the previous and the next free blocks.

Reducing Allocation Time

- Segregated Free Lists
  - Free blocks organized into different *equivalence classes* based on size
  - Numerous approaches differing in several aspects
    - How size classes are defined
    - When they coalesce
    - When they request additional heap storage
    - If blocks are split
    - Others…
  - Two popular approaches
    - Simple Segregated Storage
    - Segregated Fits

Simple Segregated Storage

- Block sizes are powers of 2: [4, 8, 16, 32,64, 128, 256, etc]
- Separate free lists for each size
- Blocks are not split. Allocations come from the next larger size based on request:
  - Request for 58 bytes gets a block from the list of 64 byte blocks (which can handle 33-64 byte requests)
  - Request for 130 bytes comes from list of 256 byte blocks
- When no blocks of right size available:
  - More heap space requested
  - Divided into a new list of the correct size

Simple Segregated Storage

- Pluses:
  - Fast constant time allocation
  - No allocation flag or header/footer needed (no coalescing)
  - Only need Single linked list (allocations all from front of ech list)
- Minuses:
  - Susceptible to both internal and external fragmentation

Segregated Fits

- Maintain several free lists based on size classes
- Blocks in a specific size class vary in size (instead of all the same size)
- Do a ‘first fit’ allocation. If none fit from the list, move to next larger size equivalence class
- Blocks are coalesced when freed and added to the correct free list

Segregated Fits

- Pluses:
  - Search times reduced due to searching only appropriate size classes
  - Fast and efficient
  - Memory efficient since it approximates best fit across entire heap

Buddy Systems

Special case of Segregated Fits

All blocks are sized as powers of 2 (2^2, 2^3, 2^4, 2^5, 2^6, etc.)

Process:

- Heap starts as 1 block of size 2^m
- **Allocation:**
  - Block requests rounded up to power of 2 (2^k)
  - Find Free blocks on list with block sizes as close as possible (2^j)
    - k <= j <= m
    - if j == k, done
    - Otherwise: recursively split block until j == k. Add unallocated 'buddy' to the correct size free list.
- Free:
  - As long as matching 'buddy' is free, coalesce blocks
  - Add final coalesced block to the correct free list

Buddy Systems

Addresses of allocated blocks and 'buddies' differe by 1 bit at position (k-1):

- $32 = 2^5$

xxxxx…x00000

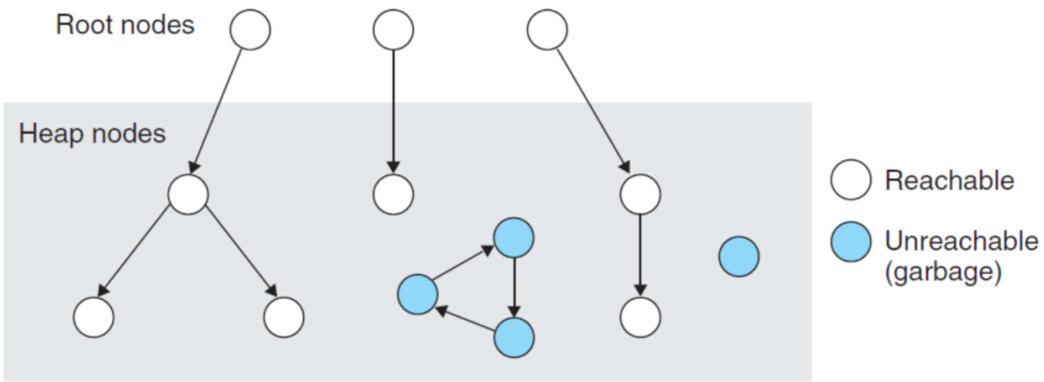
k = 5

xxxxx…x10000

This makes coallescing easy and no header/footer words are required

Garbage Collection

```
void CreateGarbage()
{
    int *p = (int*)
          malloc(100);
    return;
}
```



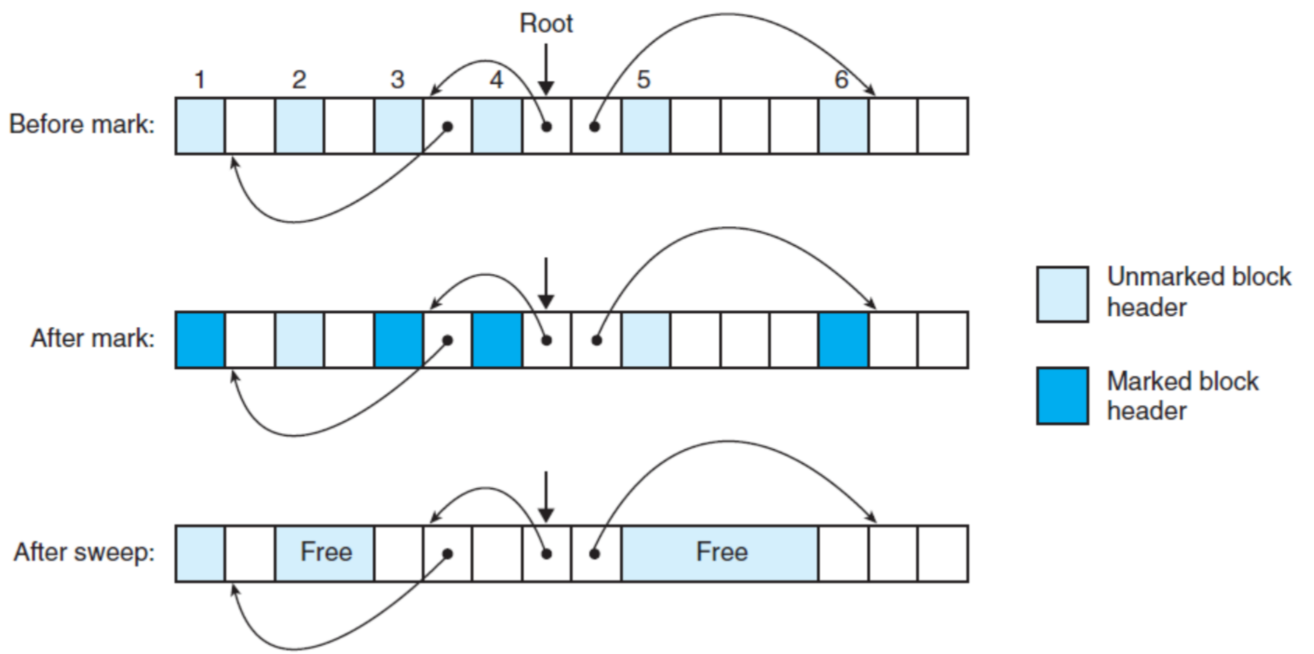
Garbage

- Any variable not reachable from your program

Reachability Graph

- Nodes are variables
- If a pointer variable v_i is pointing to another variable v_j, there is an edge $v_i \rightarrow v_j$
- A variable v_i is reachable if there is a path to v_i from any root variables (live variables not in the heap)

Garbage Collection



Mark&Sweep Garbage Collector

- Mark phase: mark all variables reachable from any root variables
- Sweep phase: free the variables not marked during the mark phase.

Questions?