CS 33

Storage Allocation

All of the slides in this lecture are either from or adapted from slides provided by the authors of the textbook "Computer Systems: A Programmer's Perspective," 2nd Edition and are provided from the website of Carnegie-Mellon University, course 15-213, taught by Randy Bryant and David O'Hallaron in Fall 2010. These slides are indicated "Supplied by CMU" in the notes section of the slides.

Memory-Related Perils and Pitfalls

- Dereferencing bad pointers
- Reading uninitialized memory
- Overwriting memory
- Referencing nonexistent variables
- Freeing blocks multiple times
- Referencing freed blocks
- Failing to free blocks

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Dereferencing Bad Pointers

- The classic `scanf` bug

```
int val;
...
scanf("%d", val);
```


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Reading Uninitialized Memory

- Assuming that heap data is initialized to zero

```
/* return y = Ax */
int *matvec(int **A, int *x) {
   int *y = malloc(N*sizeof(int));
   int i, j;

   for (i=0; i<N; i++)
      for (j=0; j<N; j++)
         y[i] += A[i][j]*x[j];
   return y;
}
```


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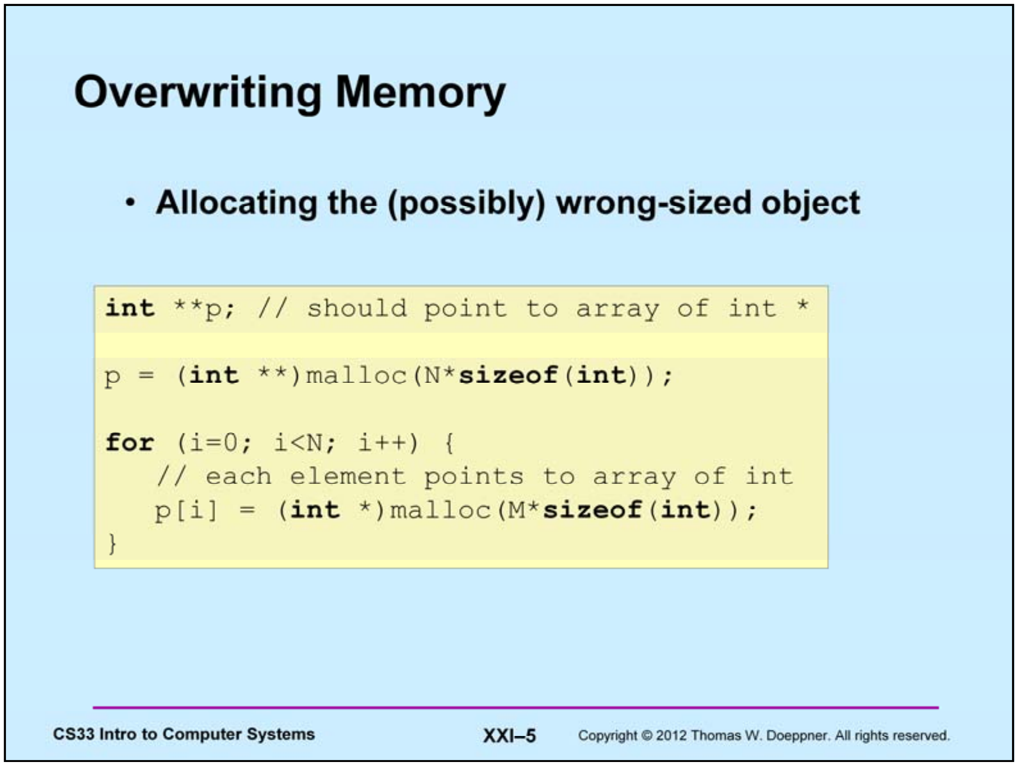

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The problem here is that the storage allocated for p is of size N*sizeof(int), when it should be N*sizeof(int *) — on a 64-bit machine, p won't have been assigned enough storage.

Overwriting Memory

- Off-by-one error

```
int **p;

p = malloc(N*sizeof(int *));

for (i=0; i<=N; i++) {
   p[i] = malloc(M*sizeof(int));
}
```


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Overwriting Memory

- **Not checking the max string size**

```
char s[8];
int i;

gets(s);  /* reads "123456789" from stdin */
```

- **Basis for classic buffer overflow attacks**

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Overwriting Memory

- **Misunderstanding pointer arithmetic**

```
int *search(int *p, int val) {

   while (*p && *p != val)
      p += sizeof(int);

   return p;
}
```


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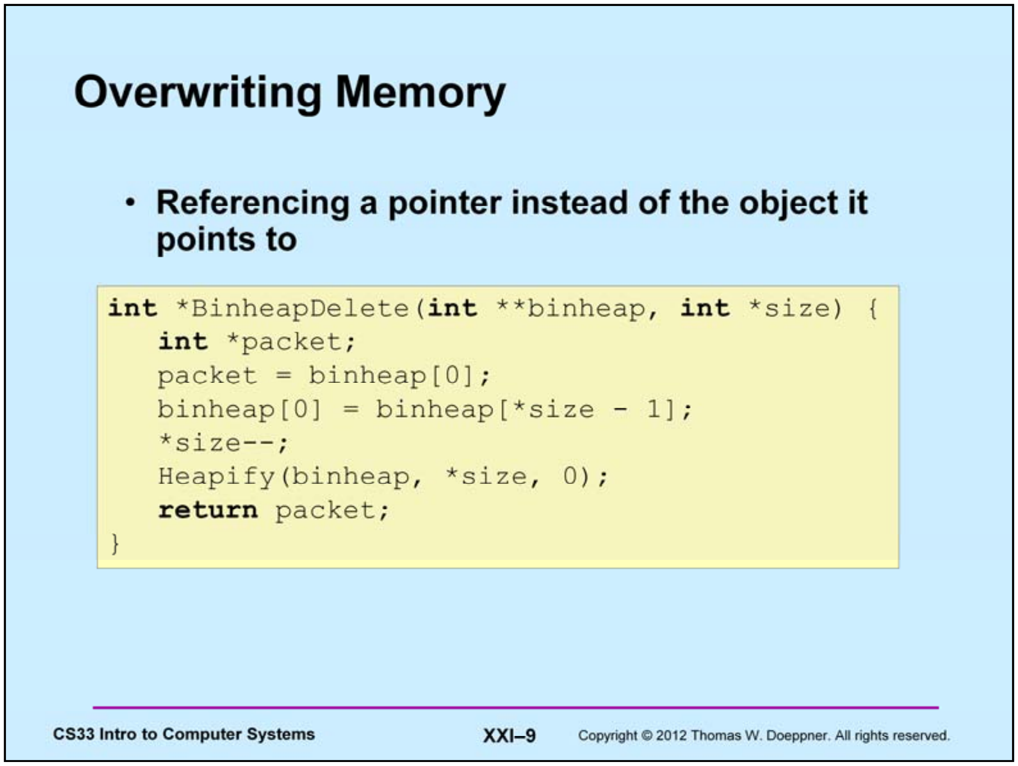

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It should be (*size)--.

Referencing Nonexistent Variables

- Forgetting that local variables disappear when a function returns

```
int *foo () {
   int val;

   return &val;
}
```


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Freeing Blocks Multiple Times

- **Nasty!**

```
x = (int *)malloc(N*sizeof(int));
        <manipulate x>
free(x);

y = (int *)malloc(M*sizeof(int));
        <manipulate y>
free(x);
```


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Referencing Freed Blocks

- **Evil!**

```
x = (int *)malloc(N*sizeof(int));
  <manipulate x>
free(x);
   ...
y = (int *)malloc(M*sizeof(int));
for (i=0; i<M; i++)
   y[i] = x[i]++;
```


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Failing to Free Blocks (Memory Leaks)

- **Slow, long-term killer!**

```
foo() {
    int *x = malloc(N*sizeof(int));
    ...
    return;
}
```


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Failing to Free Blocks (Memory Leaks)

- **Freeing only part of a data structure**

```
struct list {
   int val;
   struct list *next;
};

foo() {
   struct list *head = malloc(sizeof(struct list));
   head->val = 0;
   head->next = NULL;
   <create and manipulate the rest of the list>
    ...
   free(head);
   return;
}
```


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Dealing With Memory Bugs

- **Conventional debugger (`gdb`)**
  - good for finding bad pointer dereferences
  - hard to detect the other memory bugs
- **Debugging `malloc` (UToronto CSRI `malloc`)**
  - wrapper around conventional `malloc`
  - detects memory bugs at `malloc` and `free` boundaries
    - » memory overwrites that corrupt heap structures
    - » some instances of freeing blocks multiple times
    - » memory leaks
  - cannot detect all memory bugs
    - » overwrites into the middle of allocated blocks
    - » freeing block twice that has been reallocated in the interim
    - » referencing freed blocks

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Dealing With Memory Bugs (cont.)

- **Some malloc implementations contain checking code**
  - **Linux glibc malloc:** `setenv MALLOC_CHECK_ 2`
  - **FreeBSD:** `setenv MALLOC_OPTIONS AJR`
- **Binary translator: valgrind (Linux), Purify**
  - **powerful debugging and analysis technique**
  - **rewrites text section of executable object file**
  - **can detect all errors as debugging** `malloc`
  - **can also check each individual reference at runtime**
    - » **bad pointers**
    - » **overwriting**
    - » **referencing outside of allocated block**

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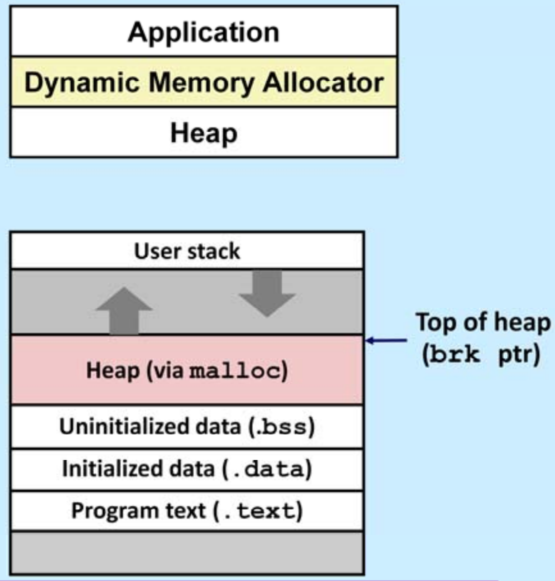
Dynamic Memory Allocation

- Programmers use ***dynamic memory allocators*** (such as `malloc`) to acquire VM at run time
  - for data structures whose size is only known at runtime
- Dynamic memory allocators manage an area of process virtual memory known as the ***heap***



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Dynamic Memory Allocation

- Allocator maintains heap as collection of variable sized ***blocks***, which are either ***allocated*** or ***free***
- Types of allocators
  - ***explicit allocator***: application allocates and frees space
    - » e.g., `malloc` and `free` in C
  - ***implicit allocator:*** application allocates, but does not free space
    - » e.g. garbage collection in Java, ML, and Lisp

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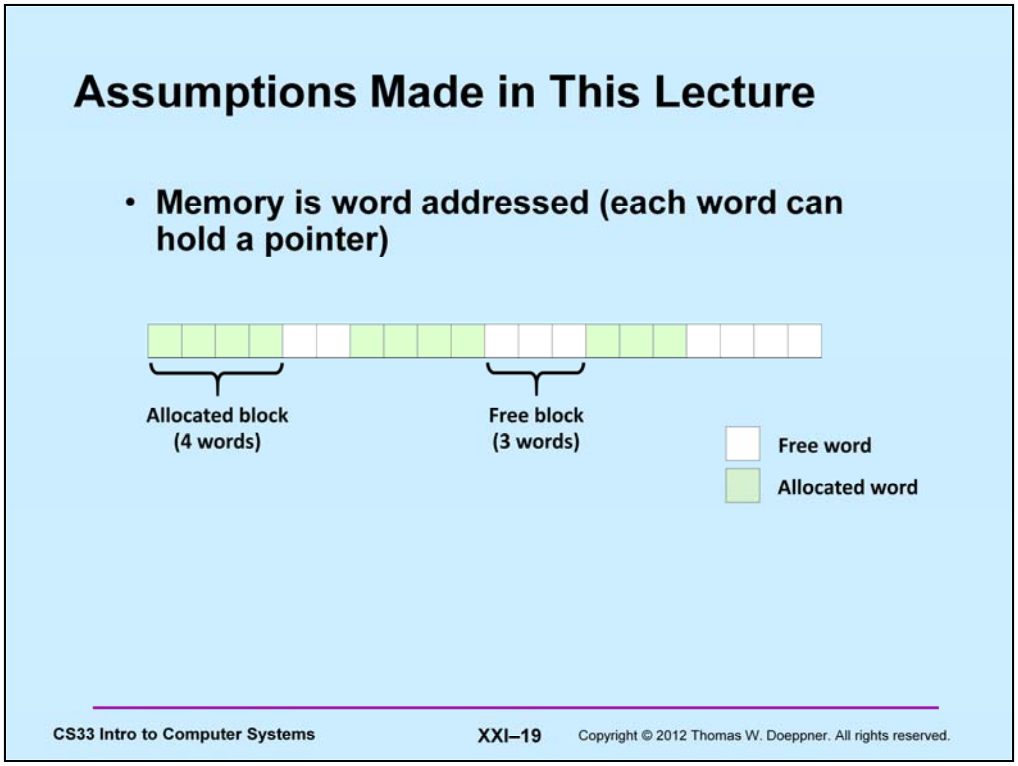

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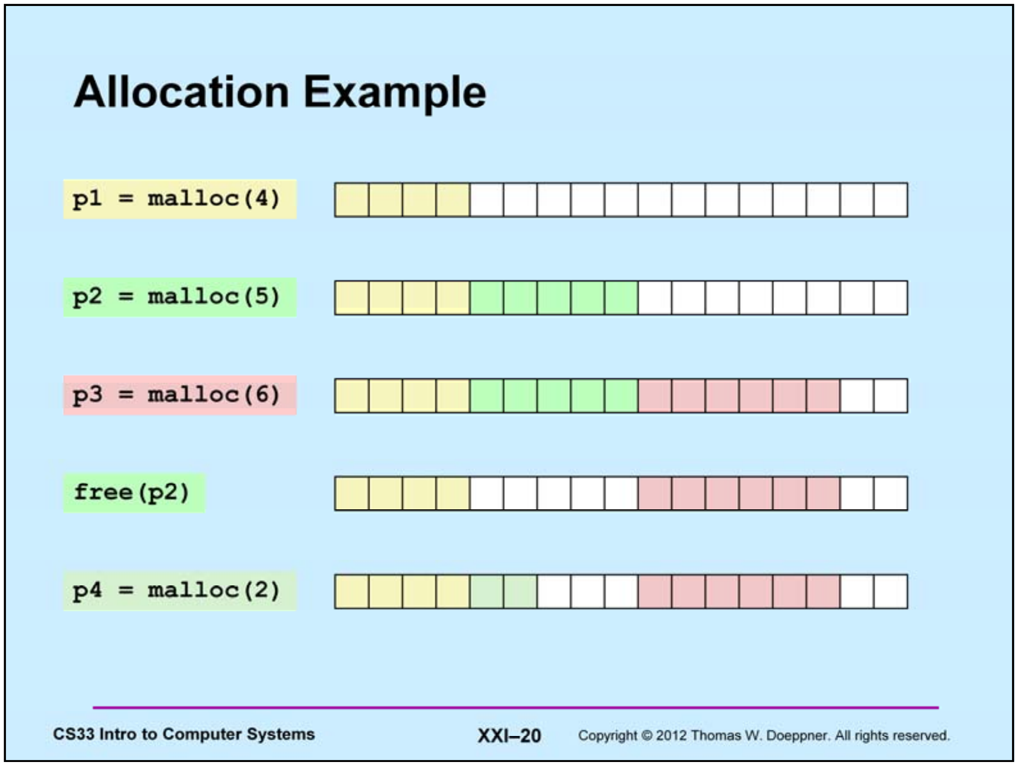

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Constraints

- **Applications**
  - can issue arbitrary sequence of `malloc` and `free` requests
  - `free` request must be to a malloc'd block
- **Allocators**
  - can't control number or size of allocated blocks
  - must respond immediately to `malloc` requests
    - » i.e., can't reorder or buffer requests
  - must allocate blocks from free memory
    - » i.e., can only place allocated blocks in free memory
  - must align blocks so they satisfy all alignment requirements
    - » 8-byte alignment for GNU `malloc` (`libc malloc`) on Linux boxes
  - can manipulate and modify only free memory
  - can't move the allocated blocks once they are `malloc`'d
    - » i.e., compaction is not allowed

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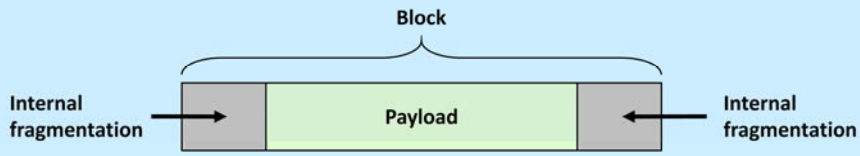
Internal Fragmentation

- For a given block, ***internal fragmentation*** occurs if payload is smaller than block size



- Caused by
  - overhead of maintaining heap data structures
  - padding for alignment purposes
  - explicit policy decisions (e.g., to return a big block to satisfy a small request)
- Depends only on the pattern of ***previous*** requests
  - thus, easy to measure

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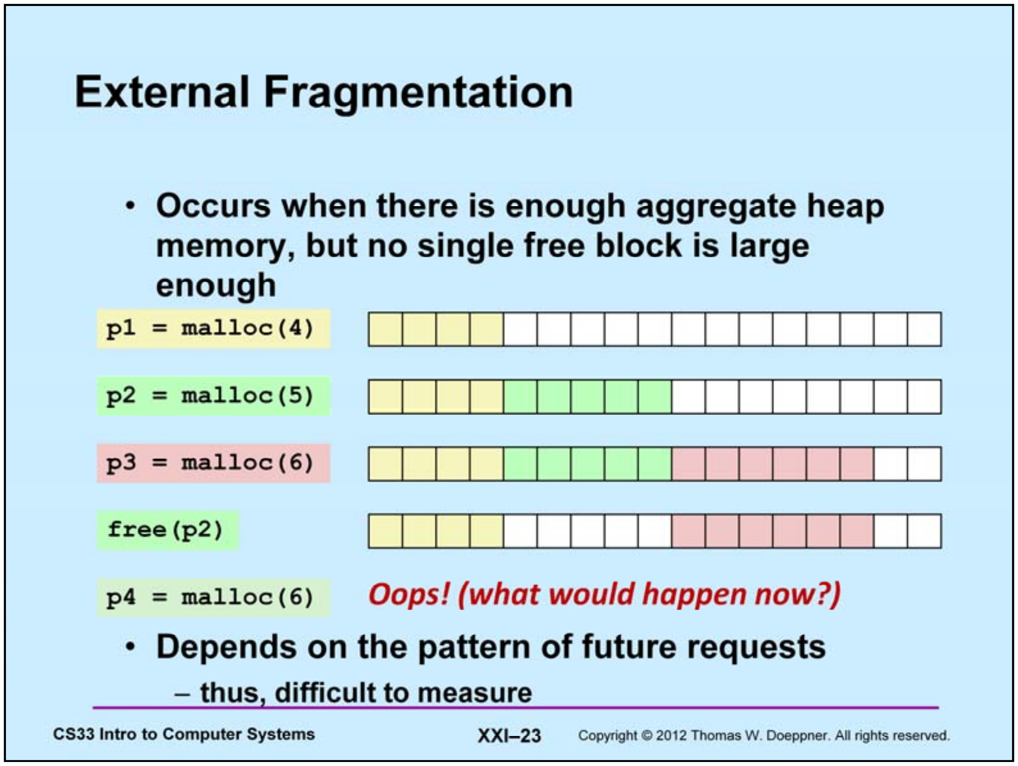

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Implementation Issues

- How do we know how much memory to free given just a pointer?
- How do we keep track of the free blocks?
- What do we do with the extra space when allocating a structure that is smaller than the free block it is placed in?
- How do we pick a block to use for allocation — many might fit?
- How do we reinsert freed block?

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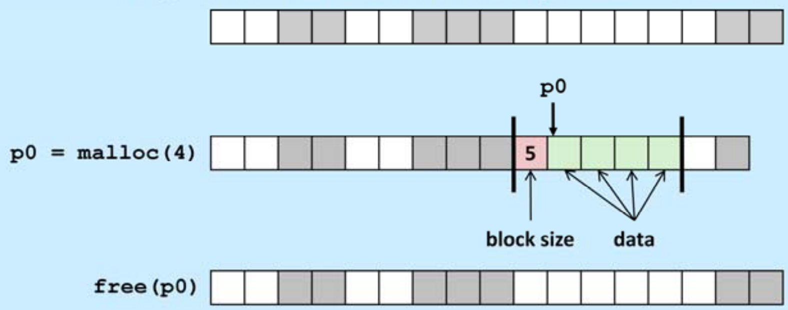
Knowing How Much to Free

- **Standard method**
  - keep the length of a block in the word preceding the block.
    - » this word is often called the ***header field*** or ***header***
  - requires an extra word for every allocated block



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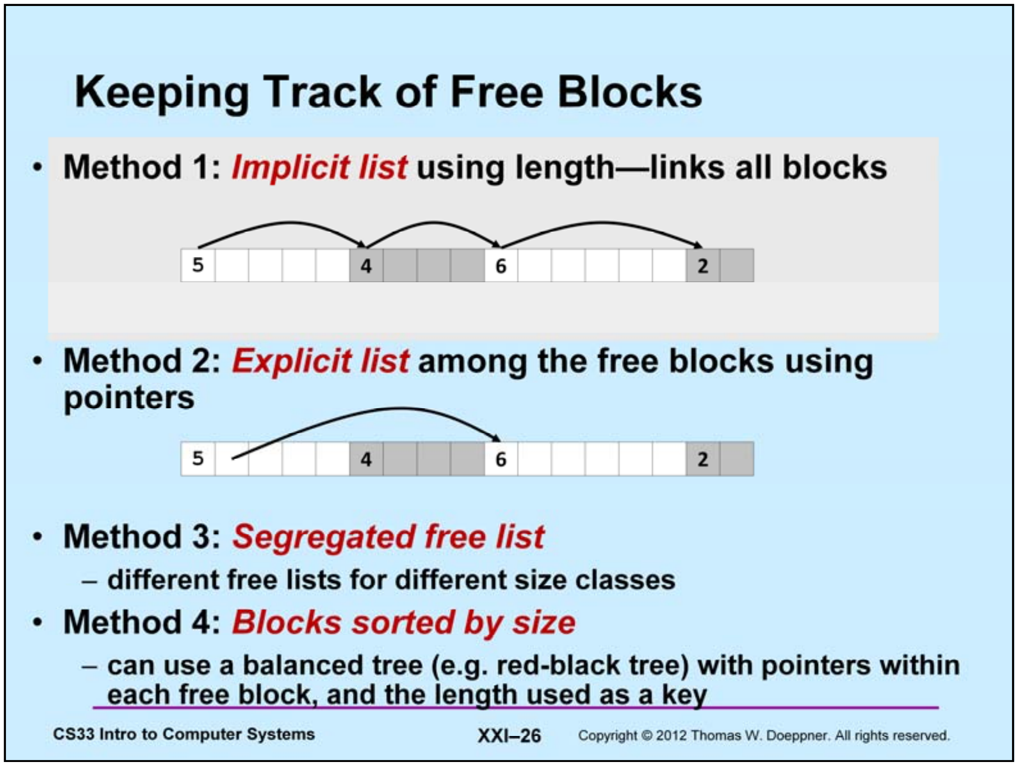

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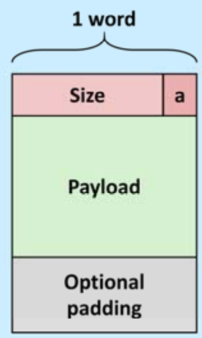
Method 1: Implicit List

- For each block we need both size and allocation status
  - could store this information in two words: wasteful!
- Standard trick
  - if blocks are aligned, some low-order address bits are always 0
  - instead of storing an always-0 bit, use it as a allocated/free flag
  - when reading size word, mask out this bit

Format of allocated and free blocks



a = 1: Allocated block
a = 0: Free block

Size: block size

Payload: application data (allocated blocks only)

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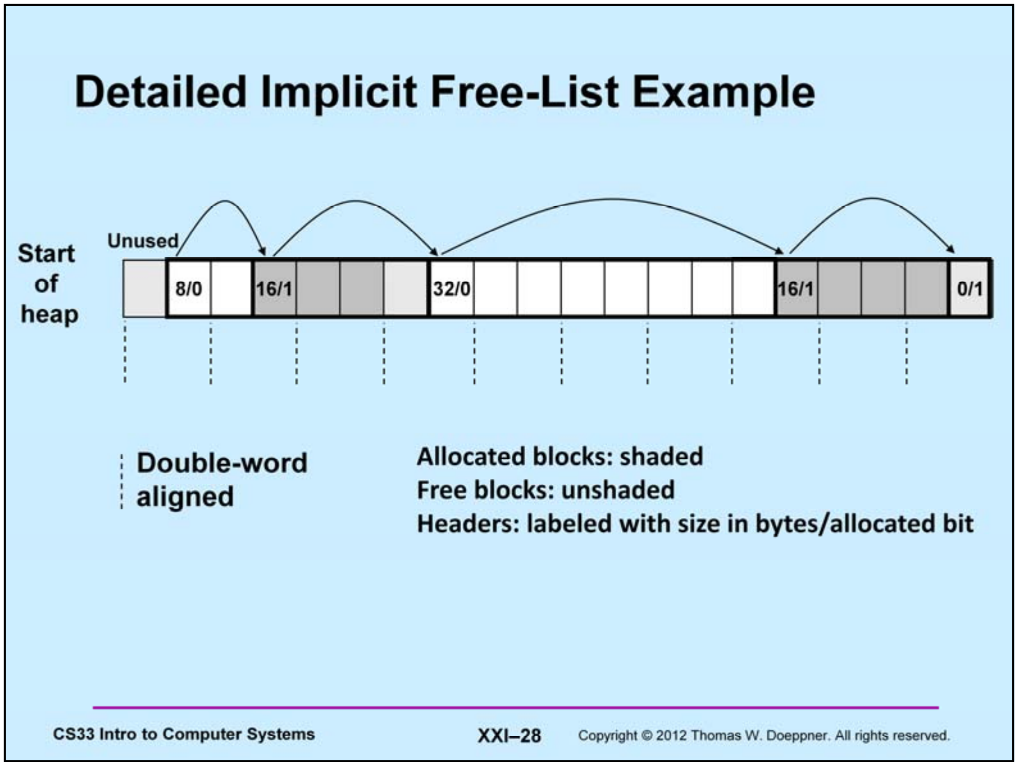

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Implicit List: Finding a Free Block

- ***First fit:***
  - search list from beginning, choose ***first*** free block that fits:

```
p = start;
while ((p < end) &&       // not passed end
       ((*p & 1) ||       // already allocated
       (*p <= len)))      // too small
  p = p + (*p & -2);      // goto next block (word addressed)
```

  - can take linear time in total number of blocks (allocated and free)
  - in practice it can cause “splinters” at beginning of list
- ***Next fit:***
  - like first fit, but search list starting where previous search finished
  - should often be faster than first fit: avoids re-scanning unhelpful blocks
  - some research suggests that fragmentation is worse
- ***Best fit:***
  - search the list, choose the ***best*** free block: fits, with fewest bytes left over
  - keeps fragments small—usually helps fragmentation
  - will typically run slower than first fit

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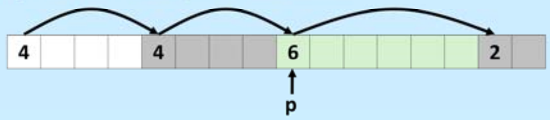
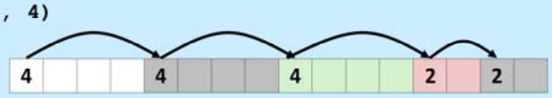
Implicit List: Allocating in Free Block

- **Allocating in a free block: *splitting***
  - **since allocated space might be smaller than free space, we might want to split the block**



addblock(p, 4)




```
void addblock(ptr p, int len) {
  int newsize = ((len + 1) >> 1) << 1;  // round up to even
  int oldsize = *p & -2;                // mask out low bit
  *p = newsize | 1;                     // set new length
  if (newsize < oldsize)
    *(p+newsize) = oldsize - newsize;   // set length in remaining
}                                       //   part of block
```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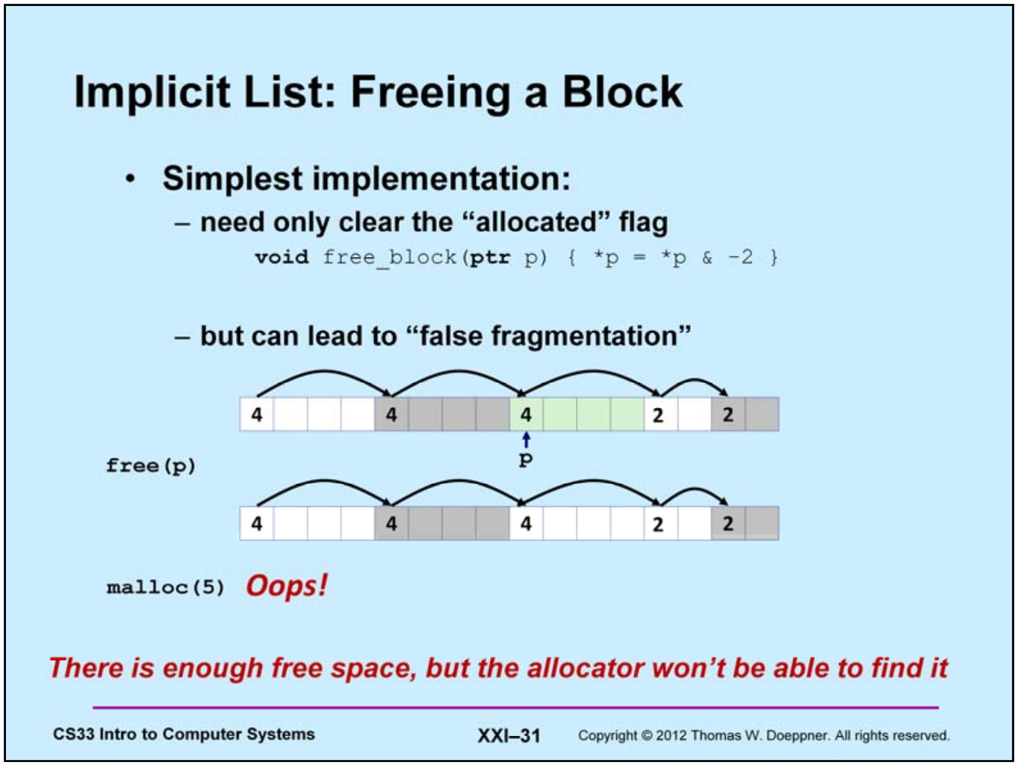

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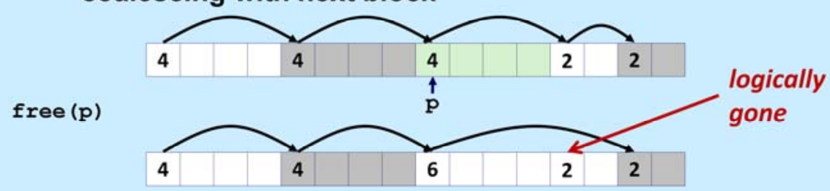
Implicit List: Coalescing

- **Join *(coalesce)* with next/previous blocks, if they are free**
  - **coalescing with next block**




```
void free_block(ptr p) {
    *p = *p & -2;           // clear allocated flag
    next = p + *p;          // find next block
    if ((*next & 1) == 0)
      *p = *p + *next;      // add to this block if
}                           //    not allocated
```

  - **but how do we coalesce with *previous* block?**

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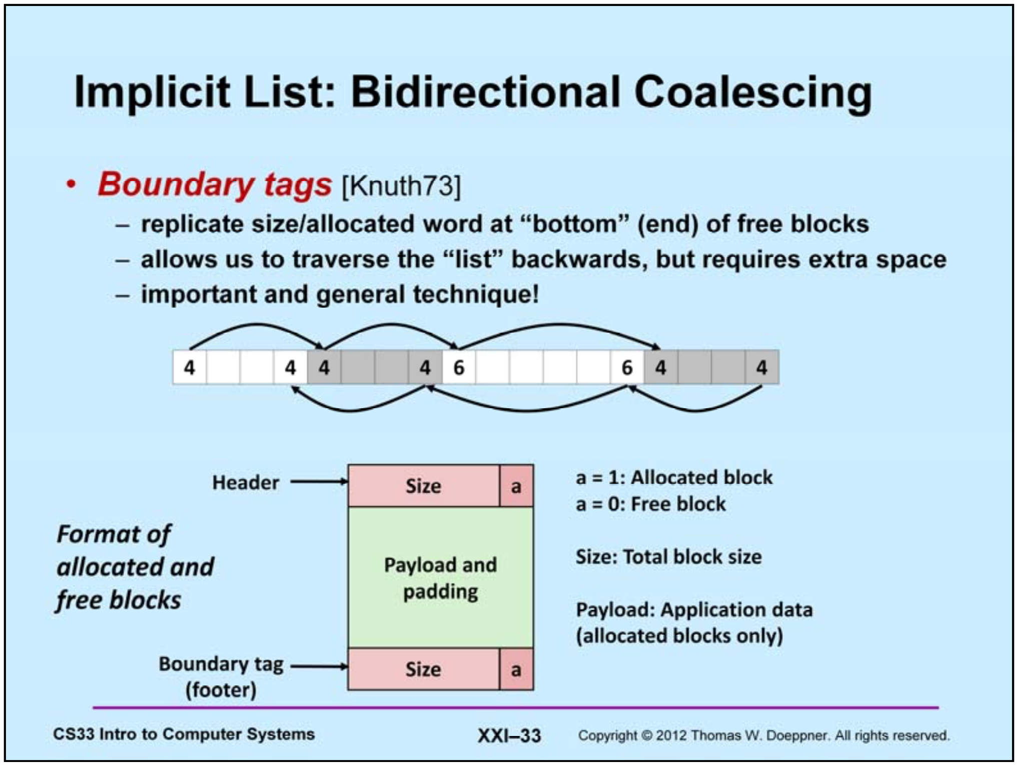

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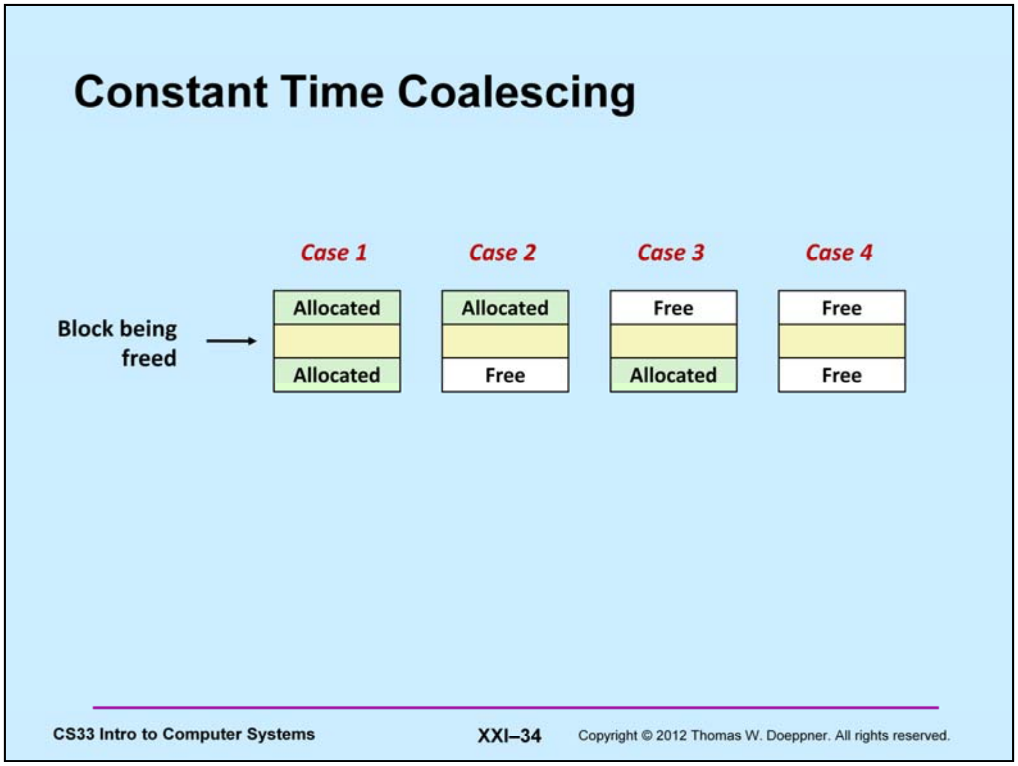

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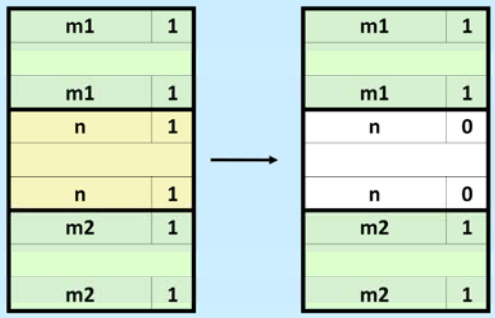
Constant Time Coalescing (Case 1)



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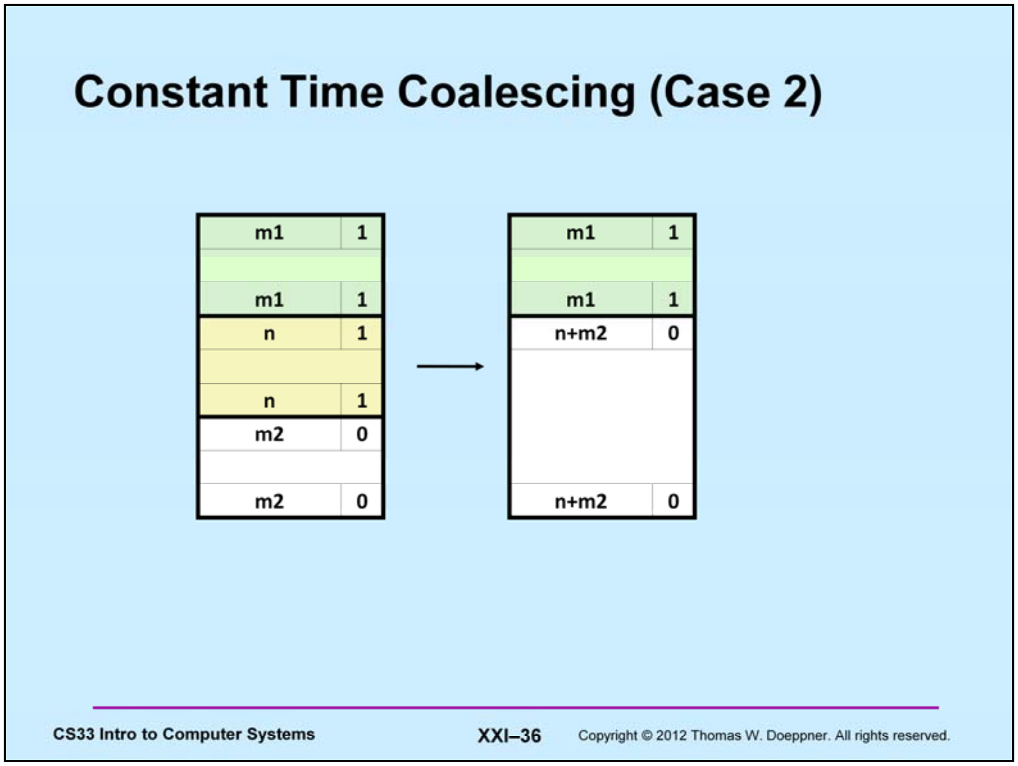

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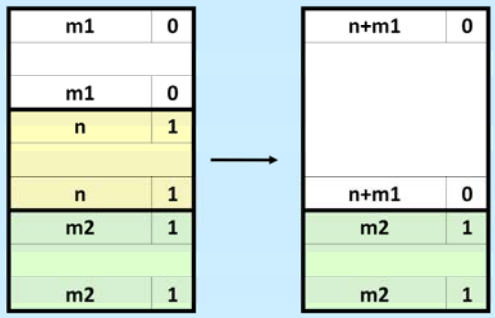
Constant Time Coalescing (Case 3)



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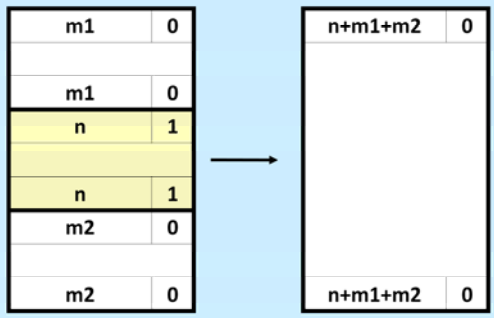
Constant Time Coalescing (Case 4)



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Disadvantages of Boundary Tags

- Internal fragmentation
- Can it be optimized?

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Summary of Key Allocator Policies

- **Placement policy:**
  - first-fit, next-fit, best-fit, etc.
  - trades off lower throughput for less fragmentation
  - *interesting observation*: segregated free lists (next lecture) approximate a best fit placement policy without having to search entire free list
- **Splitting policy:**
  - when do we go ahead and split free blocks?
  - how much internal fragmentation are we willing to tolerate?
- **Coalescing policy:**
  - *immediate coalescing:* coalesce each time `free` is called
  - *deferred coalescing:* try to improve performance of `free` by deferring coalescing until needed. Examples:
    - » coalesce as you scan the free list for `malloc`
    - » coalesce when the amount of external fragmentation reaches some threshold

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Implicit Lists: Summary

- **Implementation: very simple**
- **Allocate cost:**
  - linear time worst case
- **Free cost:**
  - constant time worst case
  - even with coalescing
- **Memory usage:**
  - will depend on placement policy
  - first-fit, next-fit or best-fit
- **Not used in practice for `malloc/free` because of linear-time allocation**
  - used in many special purpose applications
- **However, the concepts of splitting and boundary tag coalescing are general to *all* allocators**

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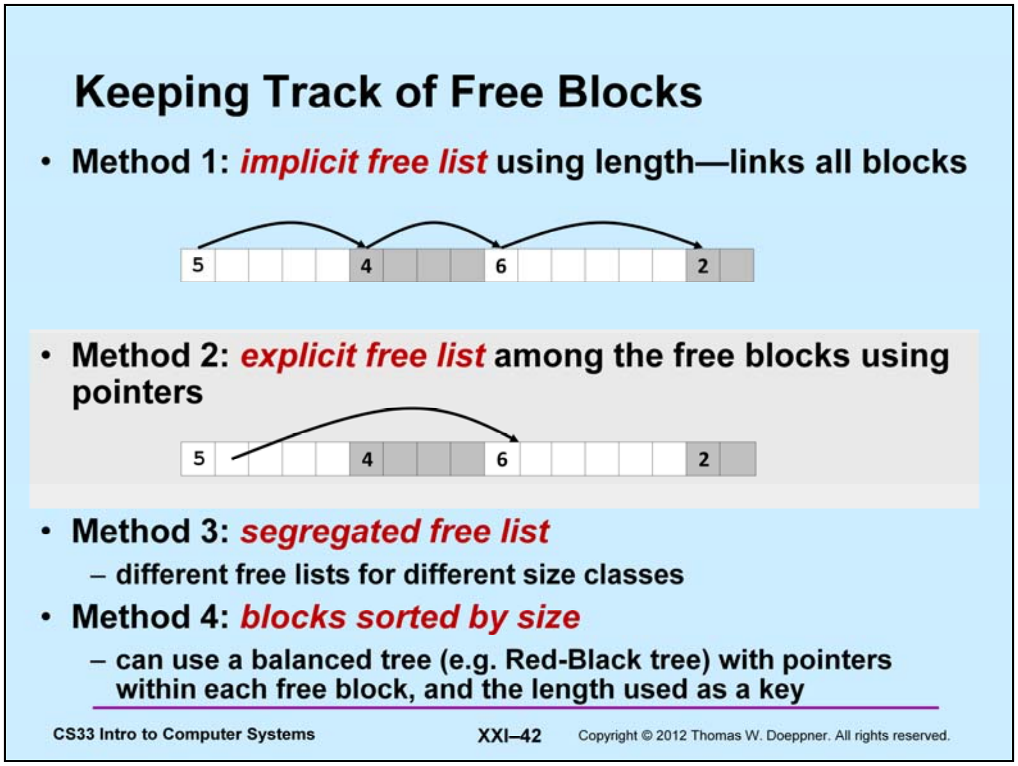

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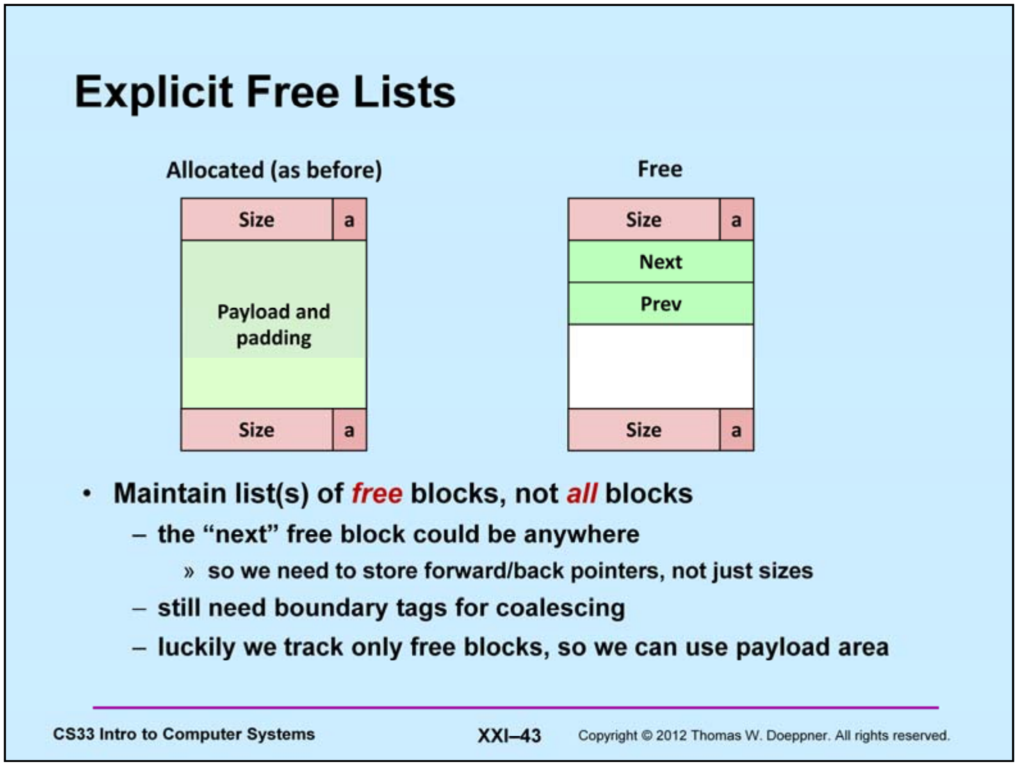

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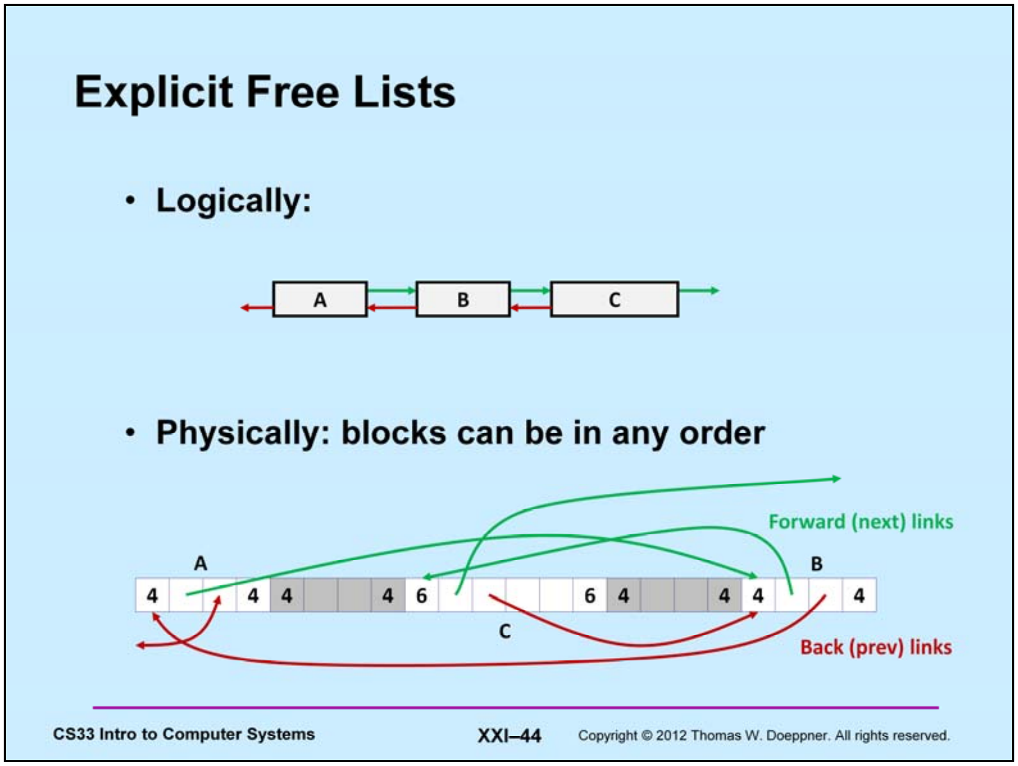

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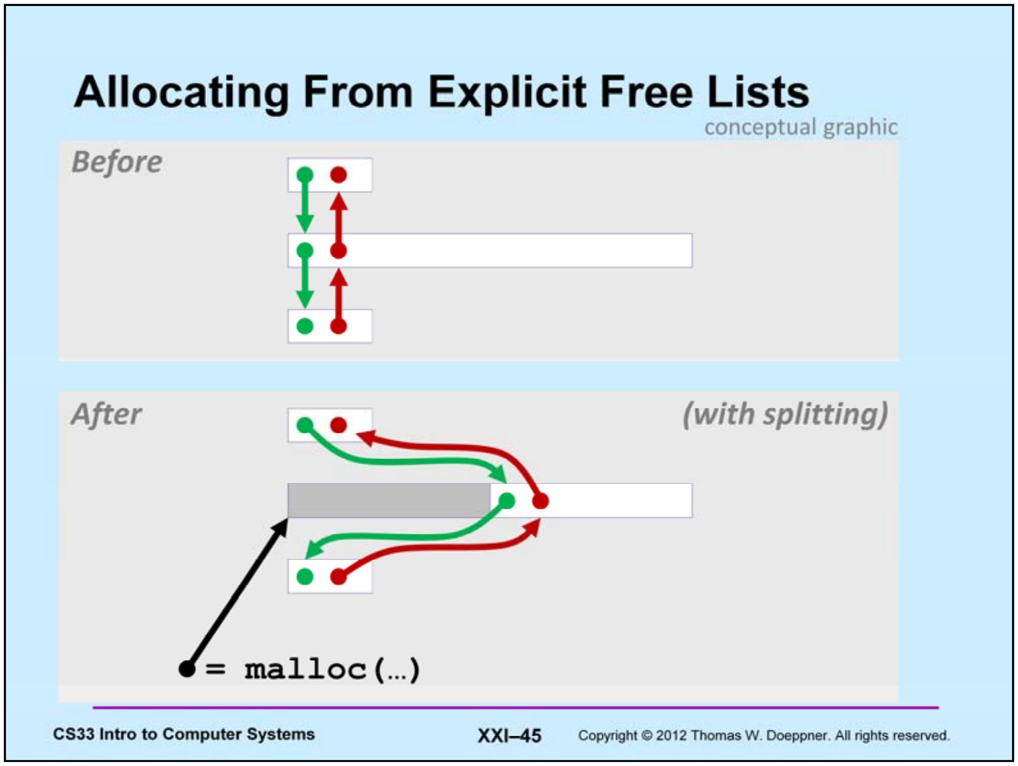

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Freeing With Explicit Free Lists

- ***Insertion policy*: where in the free list do you put a newly freed block?**
  - **LIFO (last-in-first-out) policy**
    - » **insert freed block at the beginning of the free list**
    - » ***pro:* simple and constant time**
    - » ***con:* studies suggest fragmentation is worse than address ordered**
  - **address-ordered policy**
    - » **Insert freed blocks so that free list blocks are always in address order:**

      addr(prev) < addr(curr) < addr(next)
    - » ***con:* requires search**
    - » ***pro:* studies suggest fragmentation is lower than LIFO**

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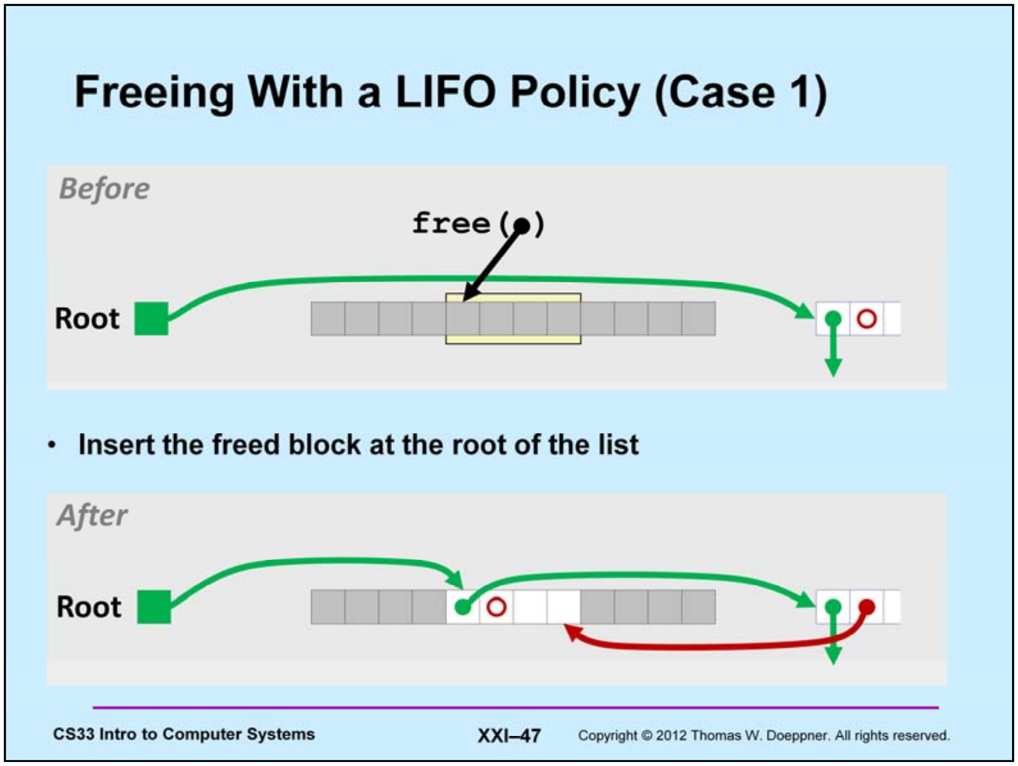

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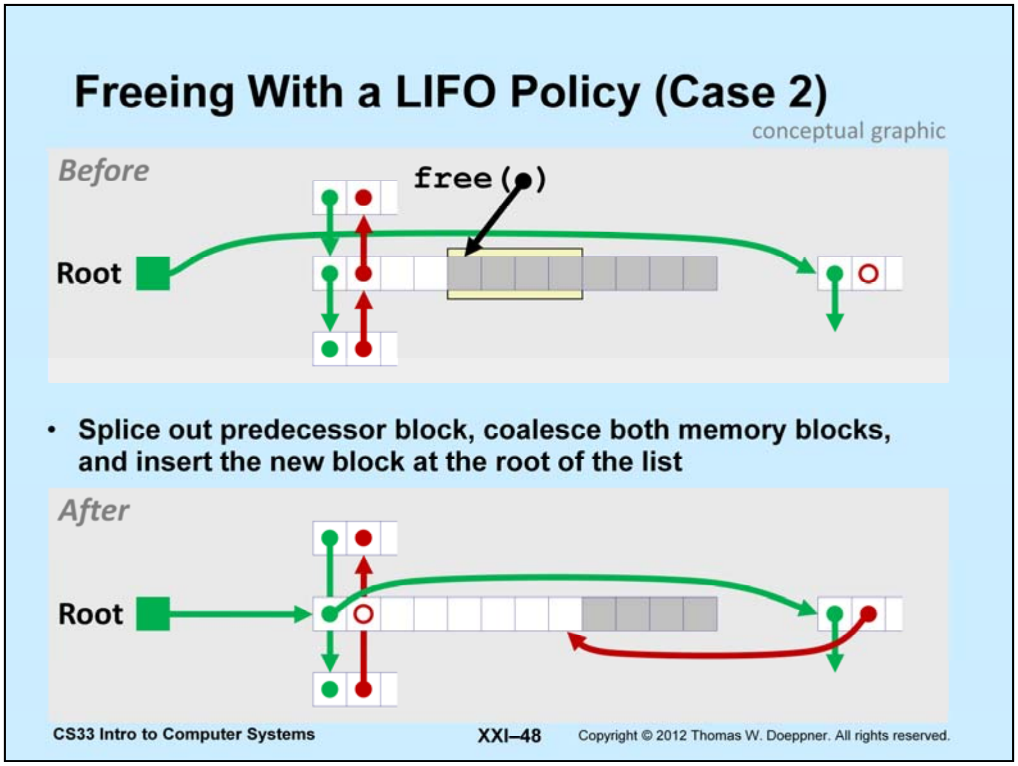

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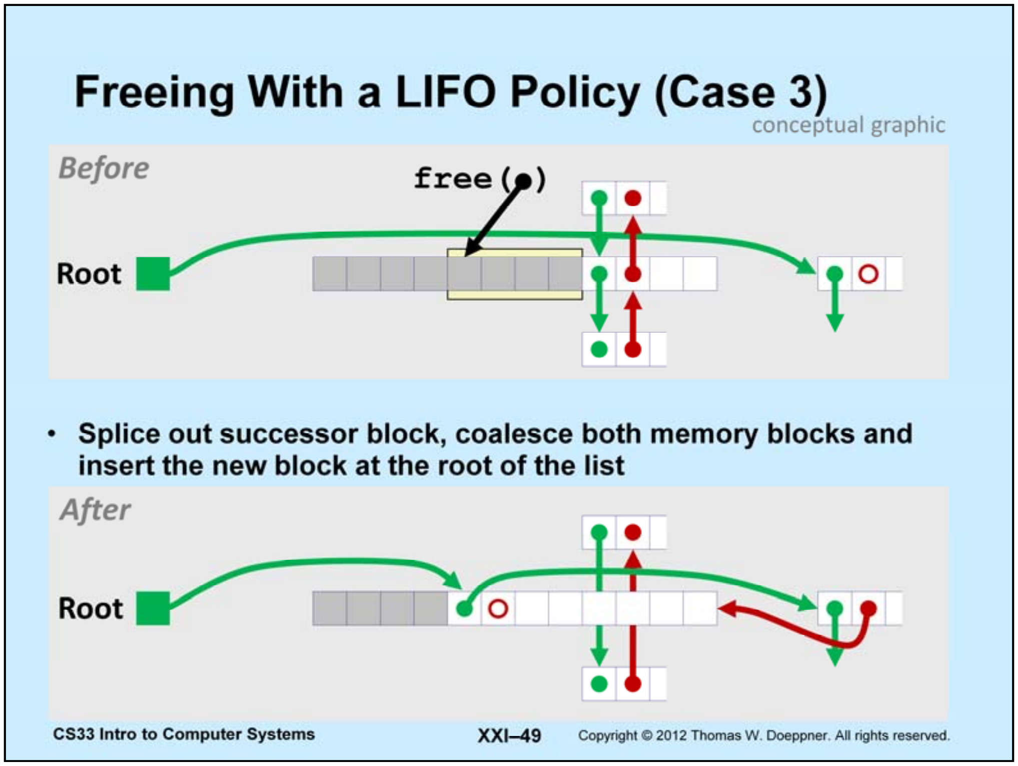

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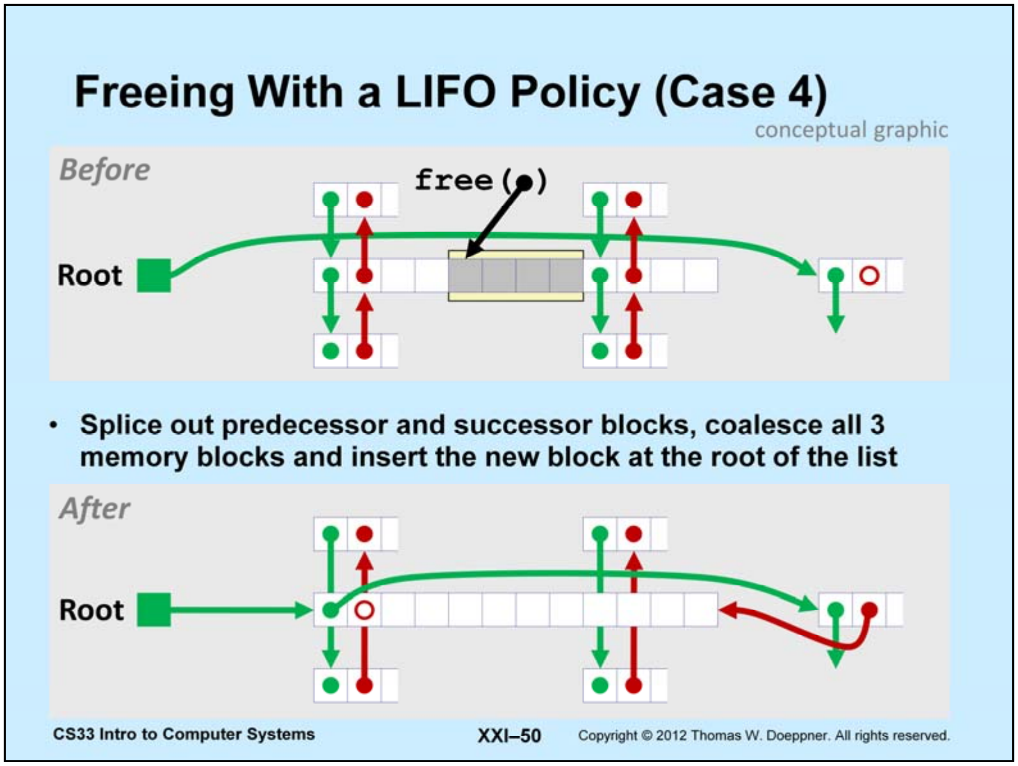

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Explicit List Summary

- **Comparison to implicit list:**
  - allocate is linear time in number of ***free*** blocks instead of ***all*** blocks
    - » ***much faster*** when most of the memory is full
  - slightly more complicated allocate and free since needs to splice blocks in and out of the list
  - some extra space for the links (2 extra words needed for each block)
    - » does this increase internal fragmentation?
- **Most common use of linked lists is in conjunction with segregated free lists**
  - keep multiple linked lists of different size classes, or possibly for different types of objects

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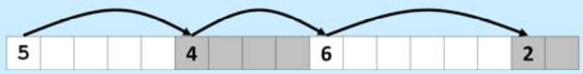
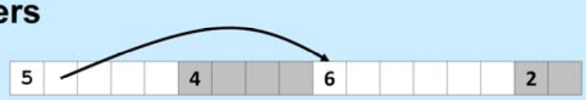
Keeping Track of Free Blocks

- Method 1: ***implicit list*** using length—links all blocks



- Method 2: ***explicit list*** among the free blocks using pointers



- Method 3: ***segregated free list***
  - different free lists for different size classes
- Method 4: ***blocks sorted by size***
  - can use a balanced tree (e.g. red-black tree) with pointers within each free block, and the length used as a key

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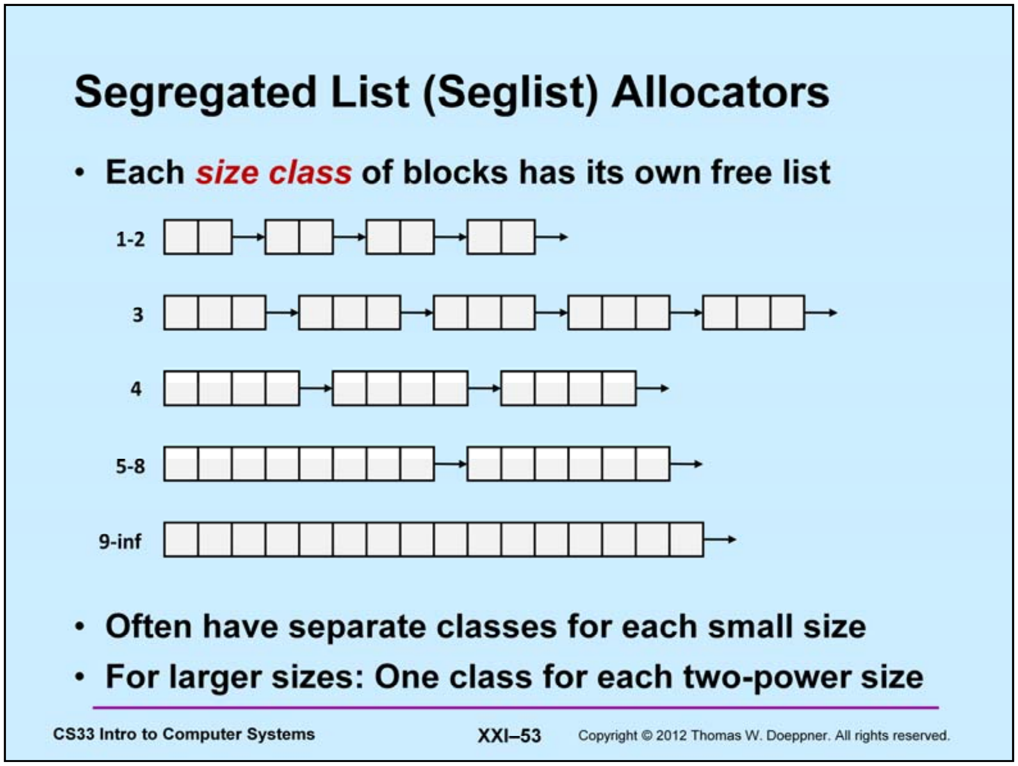

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Seglist Allocator

- Given an array of free lists, each one for some size class
- To allocate a block of size *n*:
  - search appropriate free list for block of size *m* > *n*
  - if an appropriate block is found:
    - split block and place fragment on appropriate list (optional)
  - if no block is found, try next larger class
  - repeat until block is found
- If no block is found:
  - request additional heap memory from OS (using `sbrk()`)
  - allocate block of *n* bytes from this new memory
  - place remainder as a single free block in largest size class

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Seglist Allocator (cont.)

- **To free a block:**
  - coalesce and place on appropriate list (optional)
- **Advantages of seglist allocators**
  - higher throughput
    - » log time for power-of-two size classes
  - better memory utilization
    - » first-fit search of segregated free list approximates a best-fit search of entire heap.
    - » extreme case: giving each block its own size class is equivalent to best-fit

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More Info on Allocators

- D. Knuth, "*The Art of Computer Programming*", 2nd edition, Addison Wesley, 1973
  - the classic reference on dynamic storage allocation
- Wilson et al, "*Dynamic Storage Allocation: A Survey and Critical Review*", Proc. 1995 Int'l Workshop on Memory Management, Kinross, Scotland, Sept, 1995.
  - comprehensive survey
  - available from CS:APP student site (csapp.cs.cmu.edu)

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