Dynamic Memory Allocation

Gerson Robboy
Portland State University

class20.ppt

Harsh Reality

Memory is not unbounded

- It must be allocated and managed
- Many applications are memory dominated
  - Especially those based on complex, graph algorithms

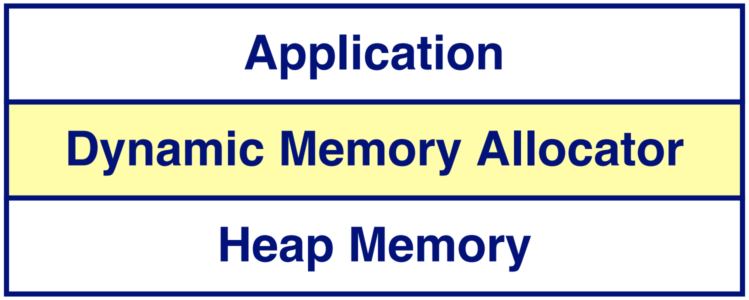
Memory referencing bugs especially pernicious

- Effects are distant in both time and space

Memory performance is not uniform

- Cache and virtual memory effects can greatly affect program performance
- Adapting program to characteristics of memory system can lead to major speed improvements

Dynamic Memory Allocation



Explicit vs. Implicit Memory Allocator

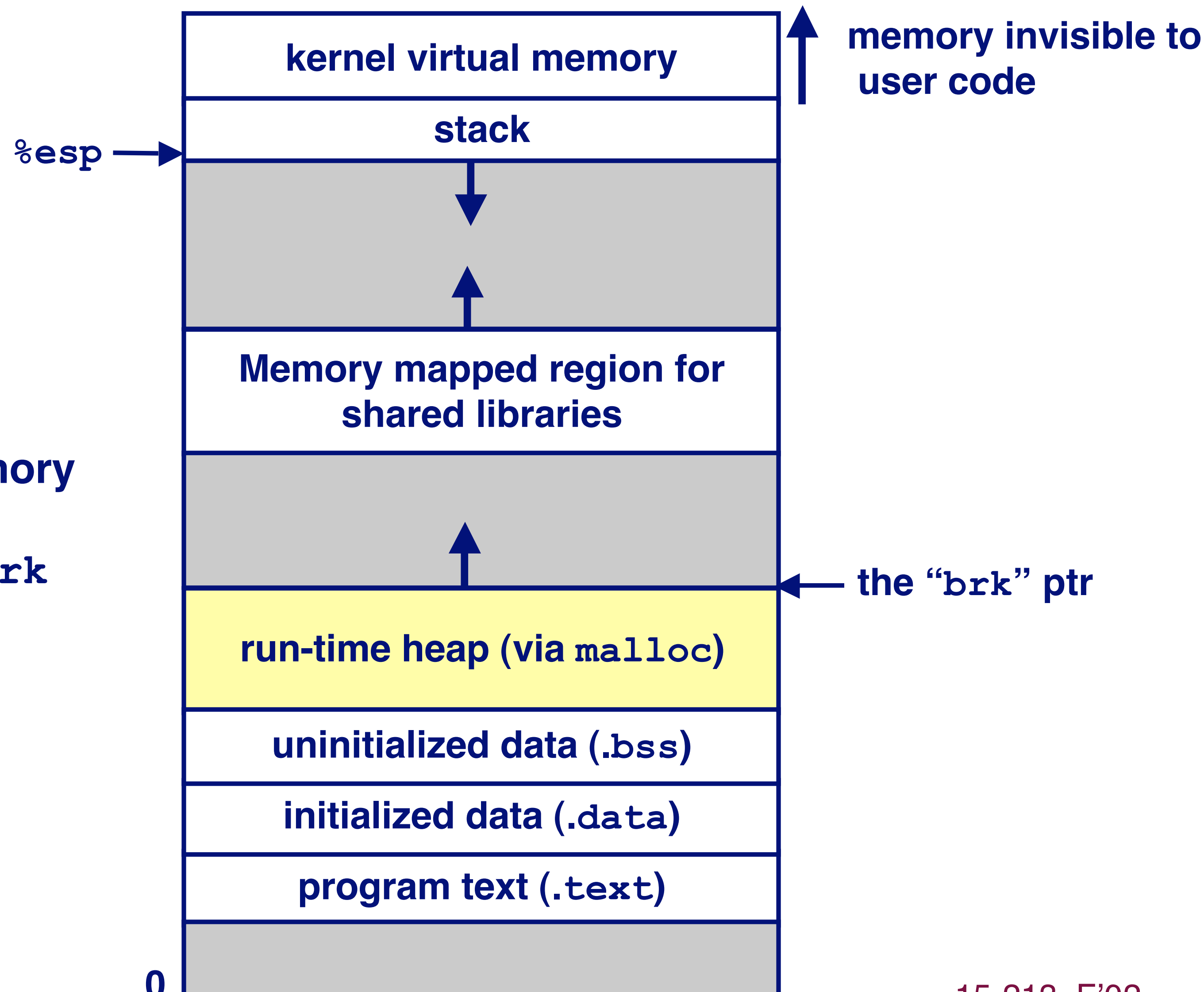
- Explicit: application allocates and frees space
  - E.g., `malloc` and `free` in C
- Implicit: application allocates, but does not free space
  - E.g. garbage collection in Java, ML or Lisp

Allocation

- In both cases the memory allocator provides an abstraction of memory as a set of blocks
- Doles out free memory blocks to application

Process Memory Image

Allocators request additional heap memory from the operating system using the `sbrk` function.



Malloc Package

`#include <stdlib.h>`

`void *malloc(size_t size)`

- If successful:
  - Returns a pointer to a memory block of at least `size` bytes, (typically) aligned to 8-byte boundary.
  - If `size == 0`, returns NULL
- If unsuccessful: returns NULL (0) and sets `errno`.

`void free(void *p)`

- Returns the block pointed at by `p` to pool of available memory
- `p` must come from a previous call to `malloc` or `realloc`.

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

- Changes size of block `p` and returns pointer to new block.
- Contents of new block unchanged up to min of old and new size.

Malloc Example

```
void foo(int n, int m) {
  int i, *p;

  /* allocate a block of n ints */
  if ((p = (int *) malloc(n * sizeof(int))) == NULL) {
    perror("malloc");
    exit(0);
  }
  for (i=0; i<n; i++)
    p[i] = i;

  /* add m bytes to end of p block */
  if ((p = (int *) realloc(p, (n+m) * sizeof(int))) == NULL)
{
    perror("realloc");
    exit(0);
  }
  for (i=n; i < n+m; i++)
    p[i] = i;

  /* print new array */
  for (i=0; i<n+m; i++)
    printf("%d\n", p[i]);

  free(p); /* return p to available memory pool */
}
```

Question

Suppose a process mallocs many megabytes of memory, uses the memory, and then frees it and continues executing.

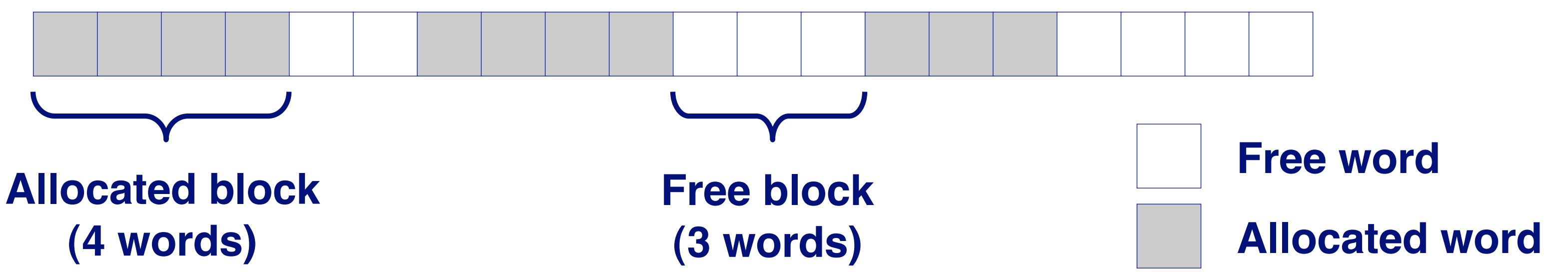
Is the memory returned to the system for re-use?

Does this process hog that memory from then on?

Assumptions

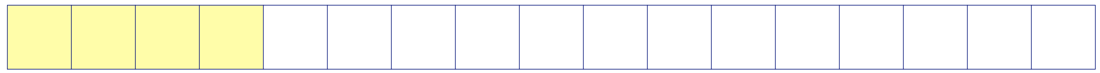
Assumptions made in this lecture

- Memory is word addressed (each word can hold a pointer)

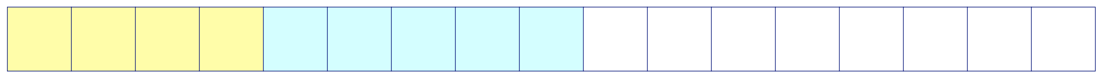


Allocation Examples

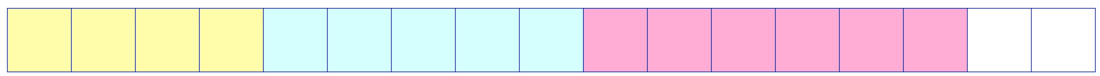
```
p1 = malloc(4)
```



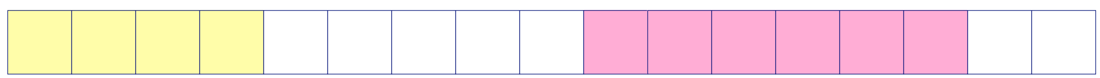
```
p2 = malloc(5)
```



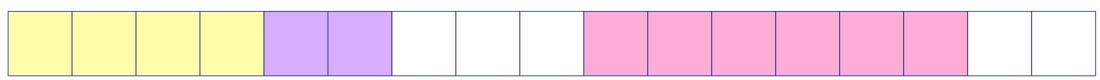
```
p3 = malloc(6)
```



```
free(p2)
```



```
p4 = malloc(2)
```



Constraints

Applications:

- Can issue arbitrary sequence of allocation and free requests
- Free requests must correspond to an allocated block

Allocators

- Can't control number or size of allocated blocks
- Must respond immediately to all allocation 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 only manipulate and modify free memory
- Can't move the allocated blocks once they are allocated
  - *i.e.*, compaction is not allowed

Goals of Good malloc/free

Primary goals

- Good time performance for `malloc` and `free`
  - Ideally should take constant time (not always possible)
  - Should certainly not take linear time in the number of blocks
- Good space utilization
  - User allocated structures should be large fraction of the heap.
  - Want to minimize “fragmentation”.

Some other goals

- Good locality properties
  - Structures allocated close in time should be close in space
  - “Similar” objects should be allocated close in space
- Robust
  - Can check that `free(p1)` is on a valid allocated object `p1`
  - Can check that memory references are to allocated space

Performance Goals: Throughput

Given some sequence of malloc and free requests:

- $R_0, R_1, ..., R_k, ... , R_{n-1}$

Want to maximize throughput and peak memory utilization.

- These goals are often conflicting

Throughput:

- Number of completed requests per unit time
- Example:
  - 5,000 malloc calls and 5,000 free calls in 10 seconds
  - Throughput is 1,000 operations/second.

Performance Goals: Peak Memory Utilization

Given some sequence of malloc and free requests:

- $R_0, R_1, \ldots, R_k, \ldots , R_{n-1}$

Def: Aggregate payload P_k:

- `malloc(p)` results in a block with a *payload* of `p` bytes..
- After request R_k has completed, the *aggregate payload* P_k is the sum of currently allocated payloads.

Def: Current heap size is denoted by H_k

- Assume that H_k is monotonically nondecreasing

Def: Peak memory utilization:

- After k requests, *peak memory utilization* is:
  - $U_k = (\max_{i<k} P_i) / H_k$

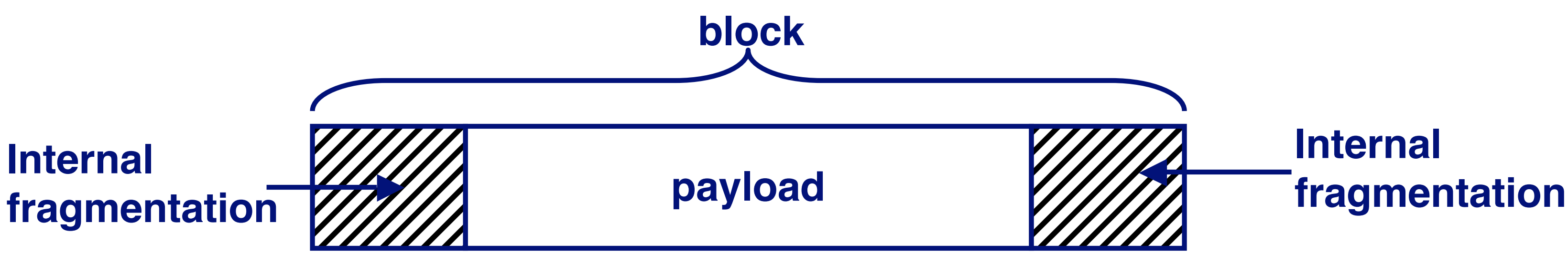
Internal Fragmentation

Poor memory utilization caused by *fragmentation*.

- Comes in two forms: internal and external fragmentation

Internal fragmentation

- For some block, internal fragmentation is the difference between the block size and the payload size.

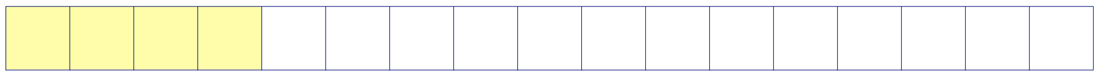


- Caused by overhead of maintaining heap data structures, padding for alignment purposes, or explicit policy decisions (e.g., not to split the block).
- Depends only on the pattern of *previous* requests, and thus is easy to measure.

External Fragmentation

Occurs when there is enough aggregate heap memory, but no single free block is large enough

```
p1 = malloc(4)
```



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p2 = malloc(5)
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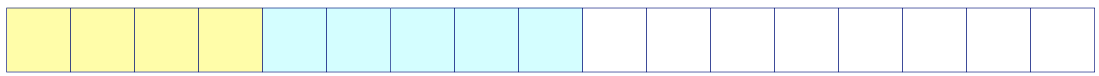

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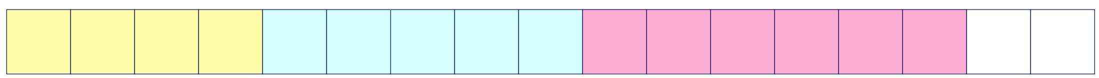
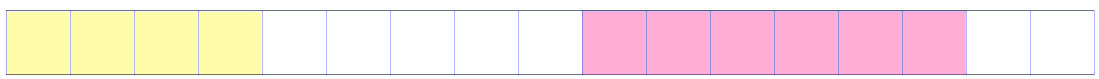


```
free(p2)
```



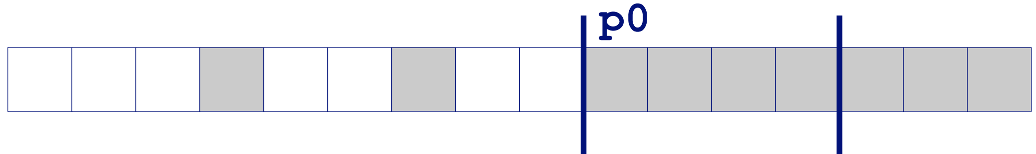
```
p4 = malloc(6)
```

oops!

External fragmentation depends on the pattern of *future* requests, and thus is difficult to measure.

Implementation Issues

- How do we know how much memory to free just given 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?



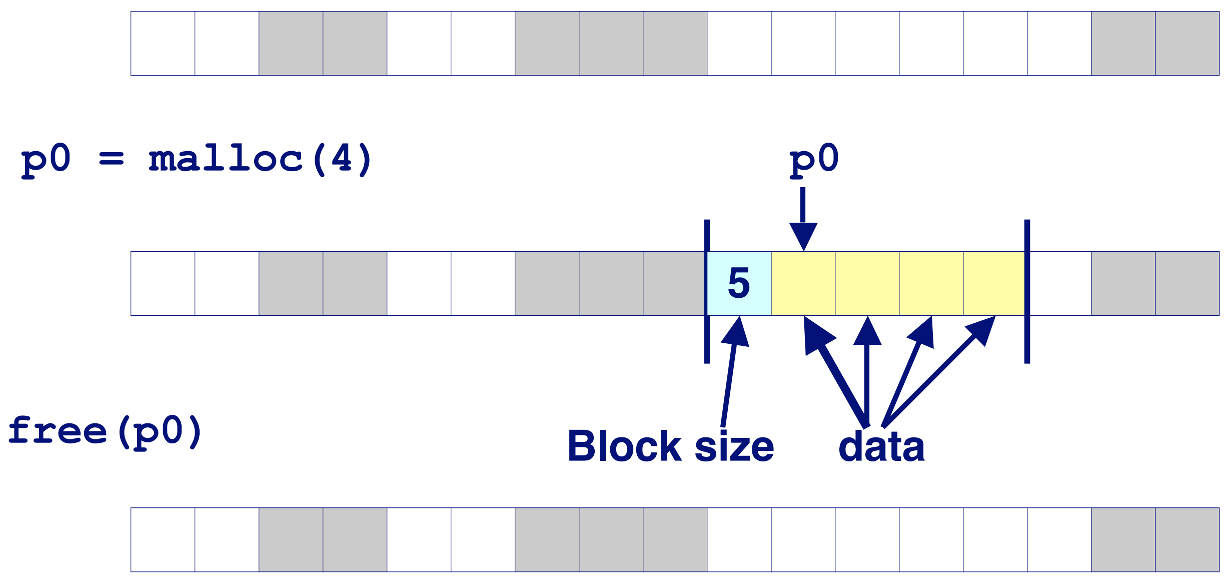

```
free(p0)

p1 = malloc(1)
```

Knowing How Much to Free

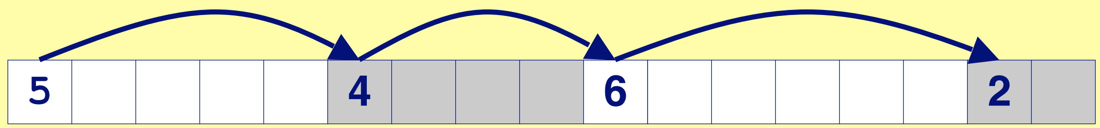
Standard method

- 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

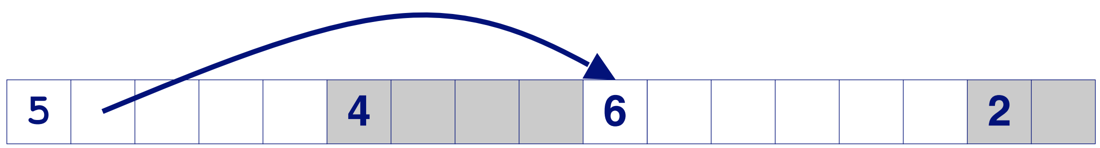


Keeping Track of Free Blocks

Method 1: ***Implicit list*** **using lengths -- links all blocks**



Method 2: ***Explicit list*** **among the free blocks using pointers within the free blocks**



Method 3: ***Segregated free list***

- Different free lists for different size classes

Method 4: **Blocks sorted by size**

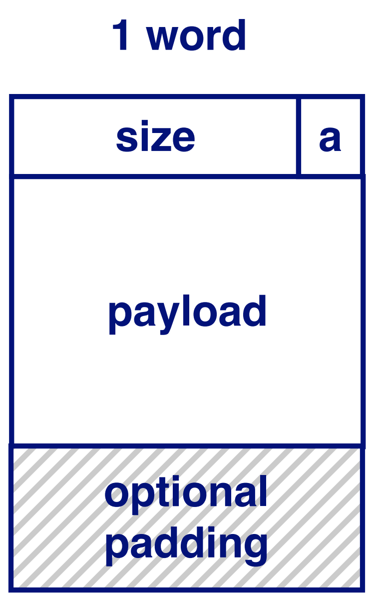
- Can use a balanced tree (e.g. Red-Black tree) with pointers within each free block, and the length used as a key

Method 1: Implicit List

Need to identify whether each block is free or allocated

- Can use extra bit
- Bit can be put in the same word as the size if block sizes are always multiples of two (mask out low order bit when reading size).

Format of allocated and free blocks



a = 1: allocated block
a = 0: free block

size: block size

payload: application data (allocated blocks only)

Implicit List: Finding a Free Block

First fit:

- Search list from beginning, choose first free block that fits

```
p = start;
while ((p < end) &&           // not past end
       ((*p & 1) ||           // already allocated
       (*p & ~1 <= len)))     // too small
    p += (len + 1);
```

- 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 from location of end of previous search
- Research suggests that fragmentation is worse

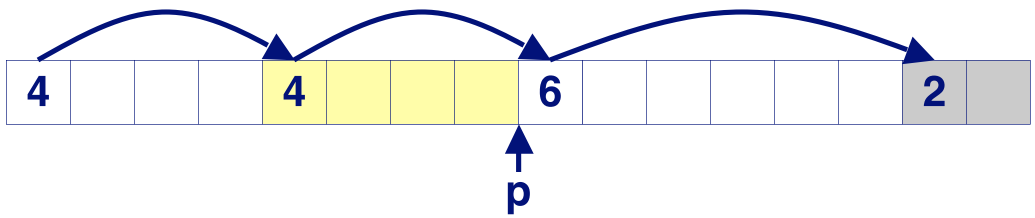
Best fit:

- Search the list, choose the free block with the closest size that fits
- Keeps fragments small --- usually helps fragmentation
- Will typically run slower than first-fit

Implicit List: Allocating in Free Block

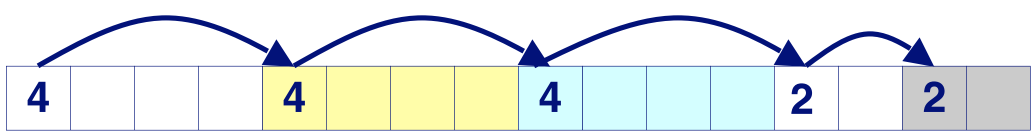
Allocating in a free block - *splitting*

- Since allocated space might be smaller than free space, we might want to split the block




```
void addblock(ptr p, int len) {
  int newsize = ((len + 1) >> 1) << 1;  // add 1 and round up
  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
```

`addblock(p, 2)`



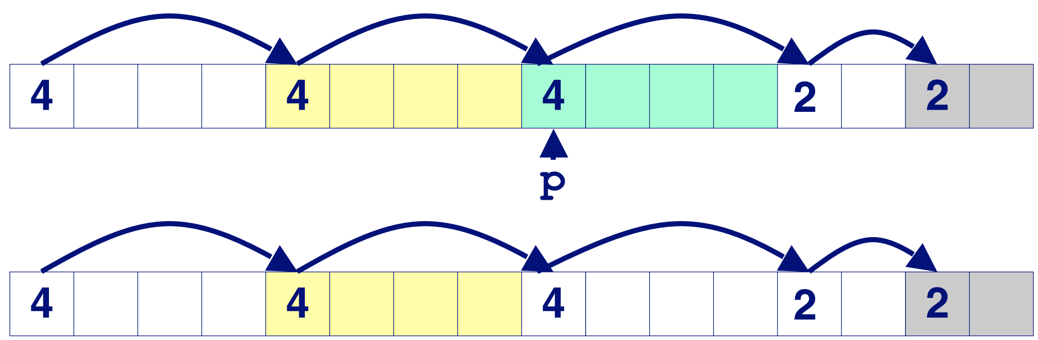
Implicit List: Freeing a Block

Simplest implementation:

- Only need to clear allocated flag

```
void free_block(ptr p) { *p = *p & -2}
```

- But can lead to "false fragmentation"



`free(p)`

`malloc(5)` **Oops!**

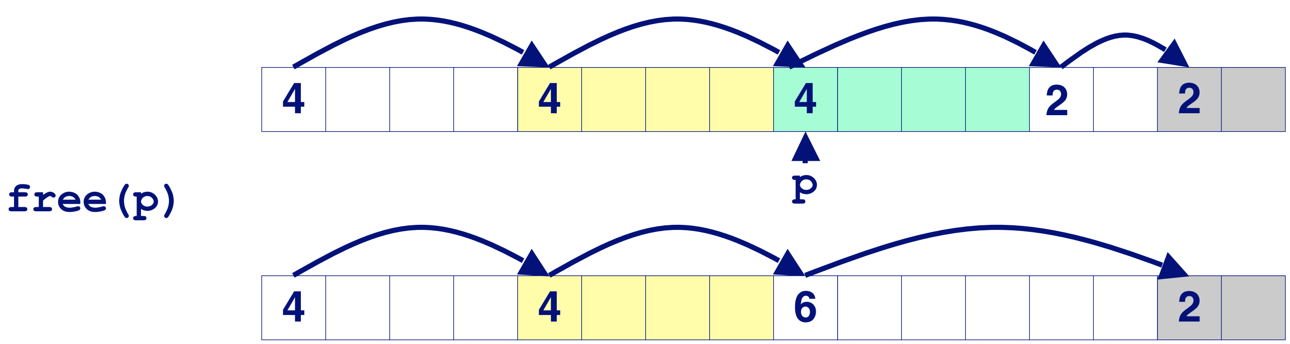
There is enough free space, but the allocator won't be able to find it

Implicit List: Coalescing

Join (*coelesce*) with next and/or previous block 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
```

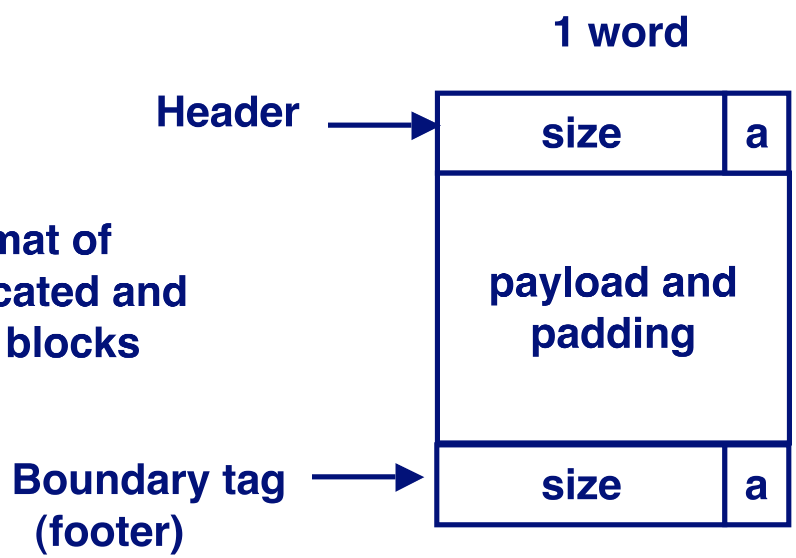


- But how do we coalesce with previous block?

Implicit List: Bidirectional Coalescing

Boundary tags **[Knuth73]**

- Replicate size/allocated word at bottom of free blocks
- Allows us to traverse the "list" backwards, but requires extra space
- Important and general technique!

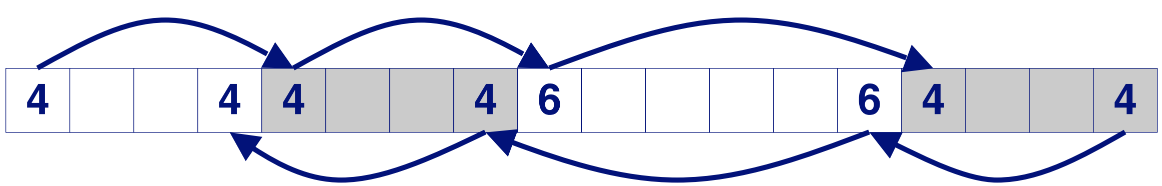


Format of allocated and free blocks

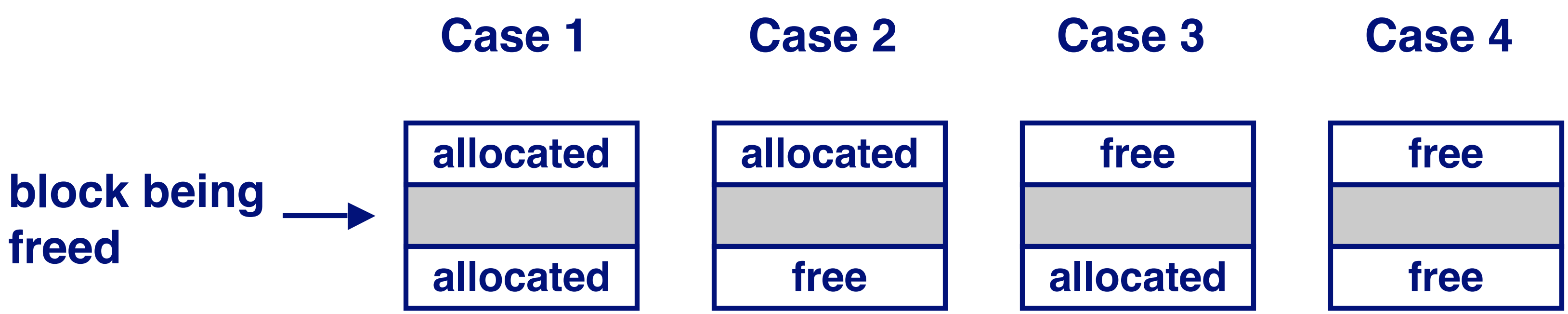
a = 1: allocated block
a = 0: free block

size: total block size

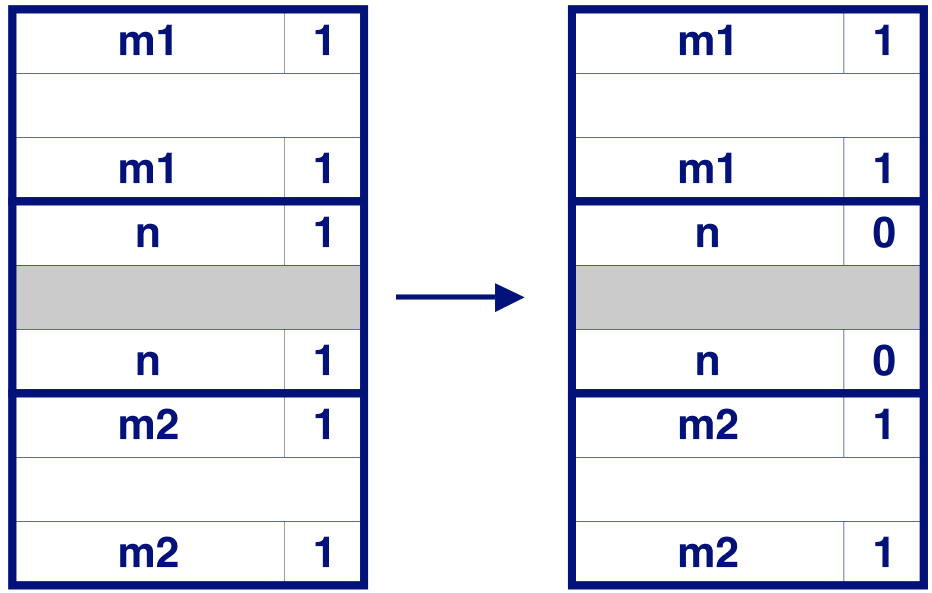
payload: application data (allocated blocks only)



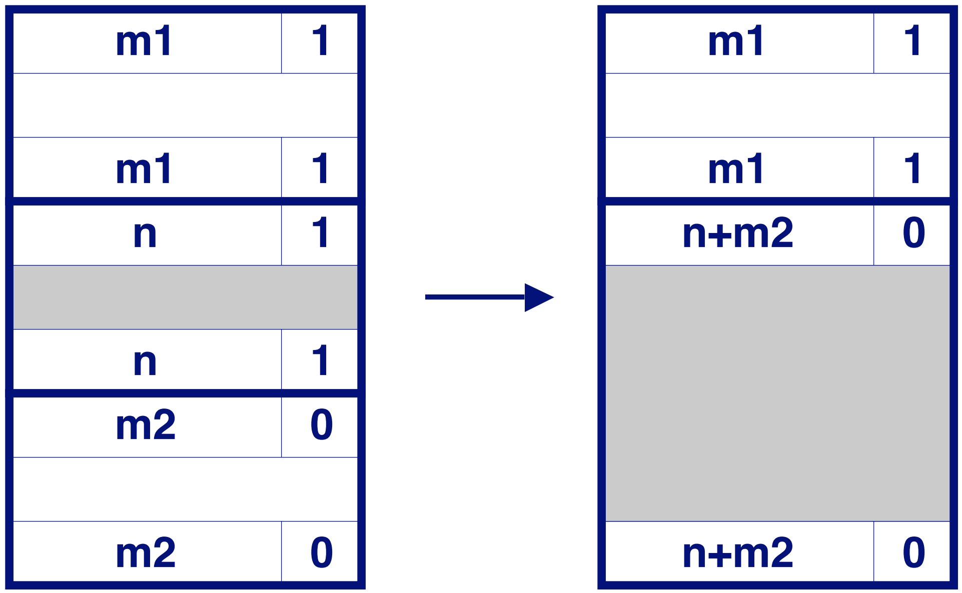
Constant Time Coalescing



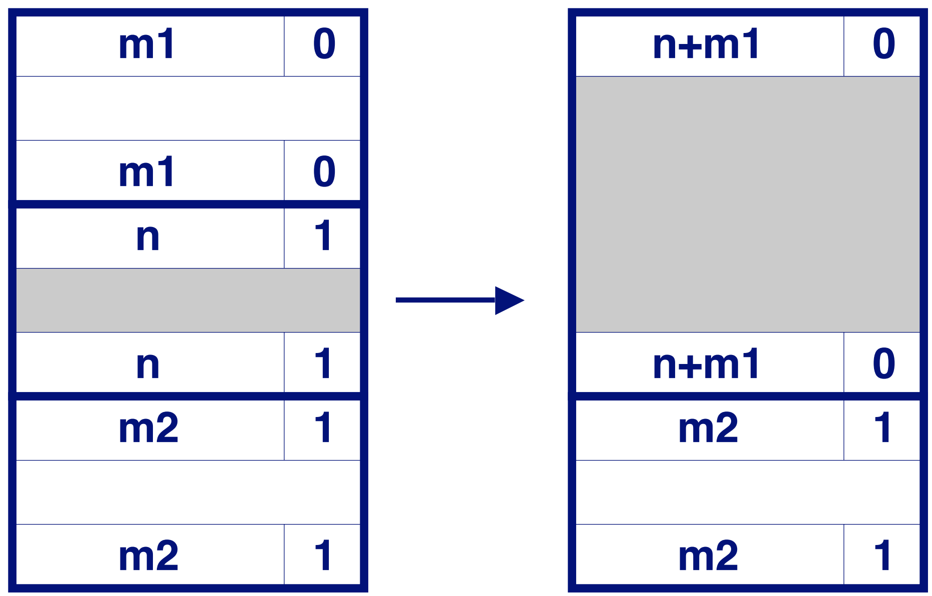
Constant Time Coalescing (Case 1)



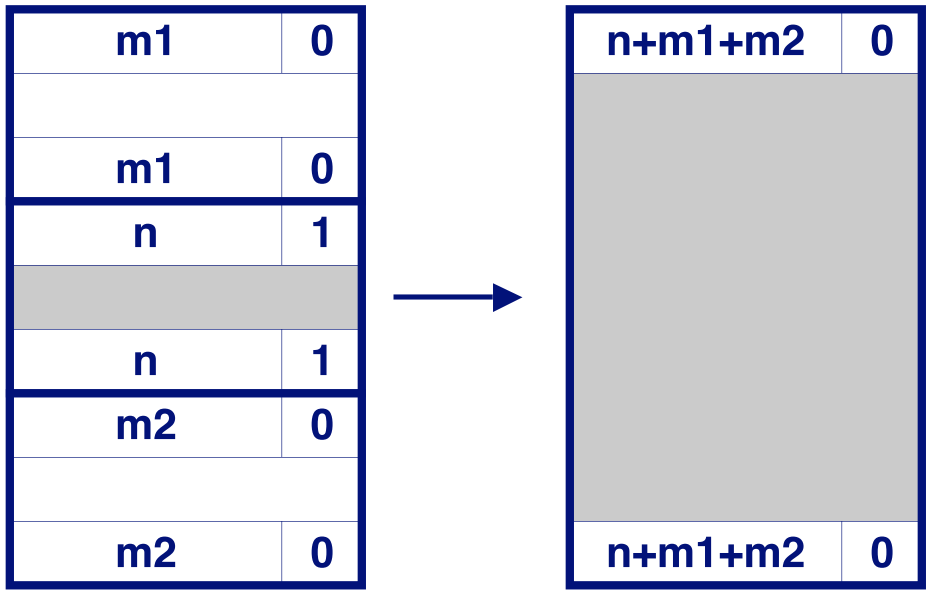
Constant Time Coalescing (Case 2)



Constant Time Coalescing (Case 3)



Constant Time Coalescing (Case 4)



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 the 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 adjacent blocks each time free is called
- Deferred coalescing: try to improve performance of free by deferring coalescing until needed. e.g.,
  - Coalesce as you scan the free list for malloc.
  - Coalesce when the amount of external fragmentation reaches some threshold.

Implicit Lists: Summary

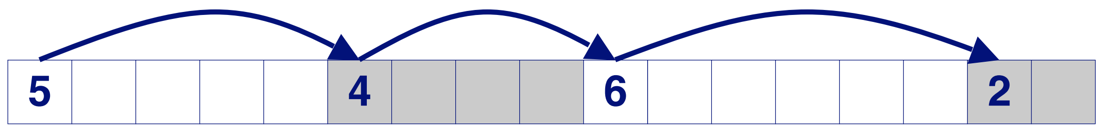
- **Implementation:** very simple
- **Allocate:** linear time worst case
- **Free:** constant time worst case -- even with coalescing
- **Memory usage:** will depend on placement policy
  - First fit, next fit or best fit

Not used in practice for malloc/free because of linear time allocate. Used in many special purpose applications.

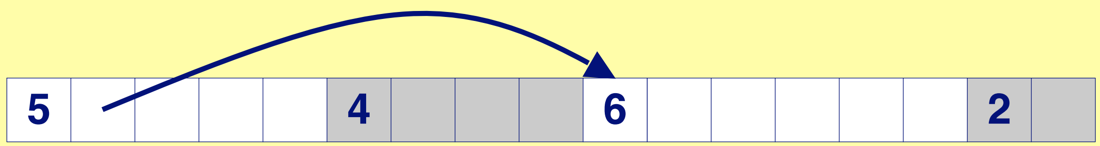
However, the concepts of splitting and boundary tag coalescing are general to *all* allocators.

Keeping Track of Free Blocks

- ***Method 1***: Implicit list using lengths -- links all blocks



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

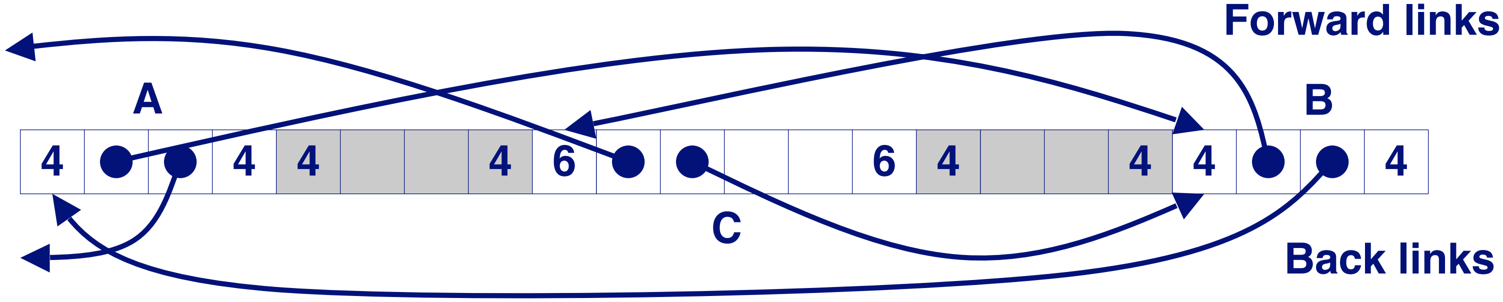


- ***Method 3***: Segregated free lists
  - Different free lists for different size classes
- ***Method 4***: Blocks sorted by size (not discussed)
  - Can use a balanced tree (e.g. Red-Black tree) with pointers within each free block, and the length used as a key

Explicit Free Lists

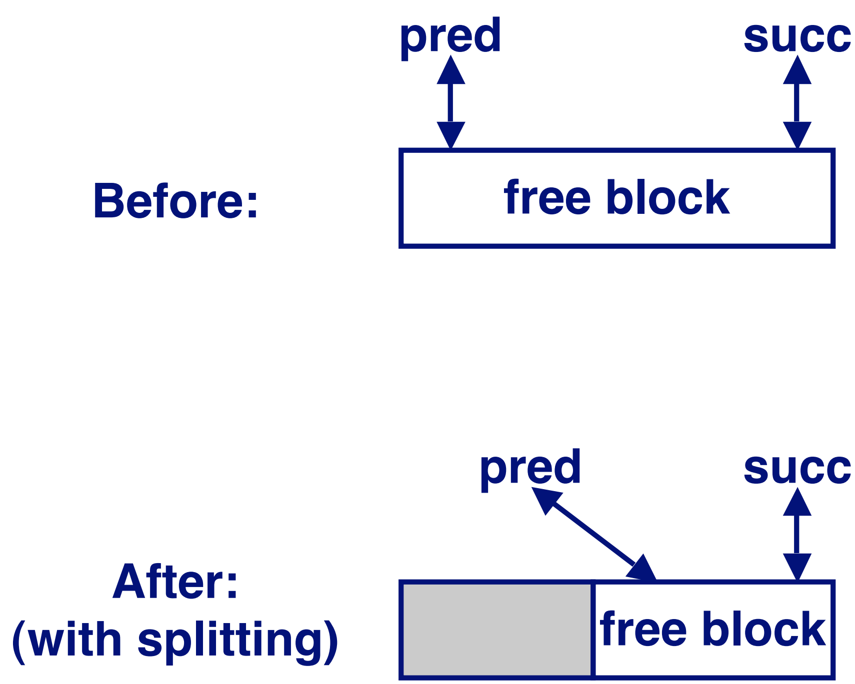
Use data space for link pointers

- Typically doubly linked
- Still need boundary tags for coalescing



- It is important to realize that links are not necessarily in the same order as the blocks

Allocating From Explicit Free Lists



Freeing With Explicit Free Lists

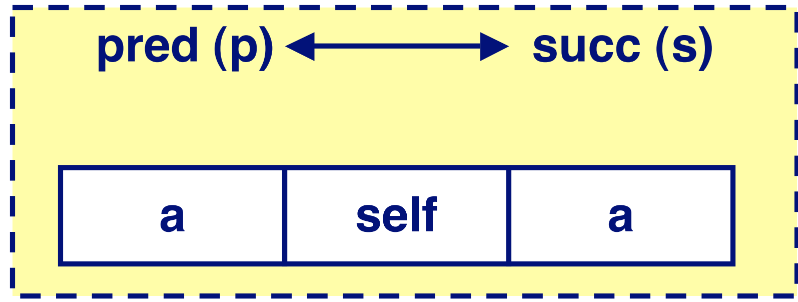
Insertion policy: Where in the free list do you put a newly freed block?

- 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
    - » i.e. addr(pred) < addr(curr) < addr(succ)
  - Con: requires search
  - Pro: studies suggest fragmentation is better than LIFO

Freeing With a LIFO Policy

Case 1: a-a-a

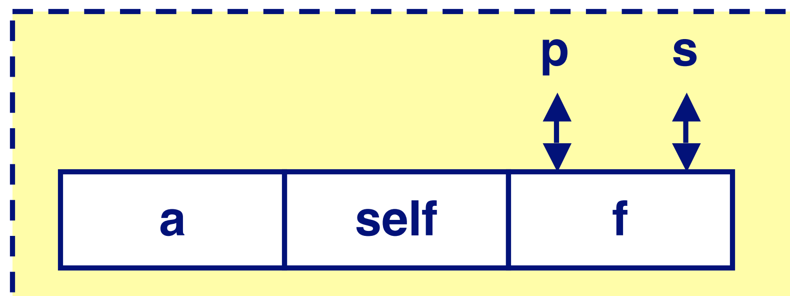
- Insert self at beginning of free list



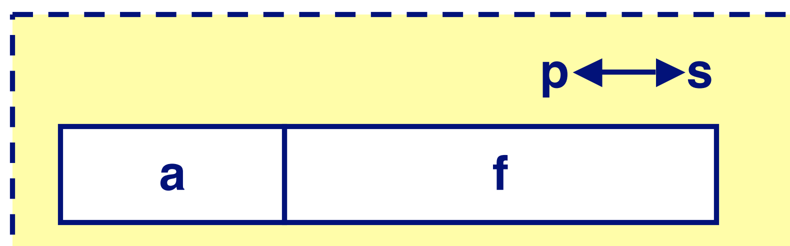
Case 2: a-a-f

- Splice out next, coalesce self and next, and add to beginning of free list

before:



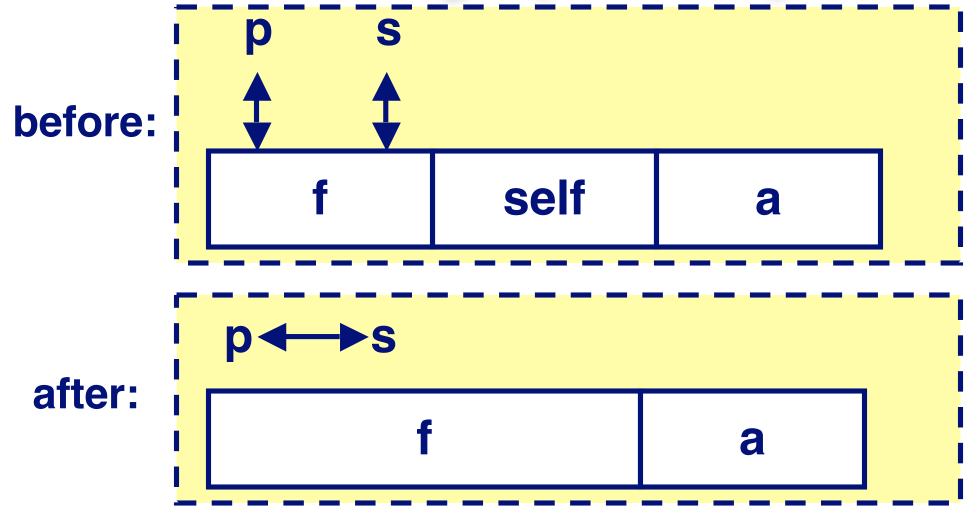
after:



Freeing With a LIFO Policy (cont)

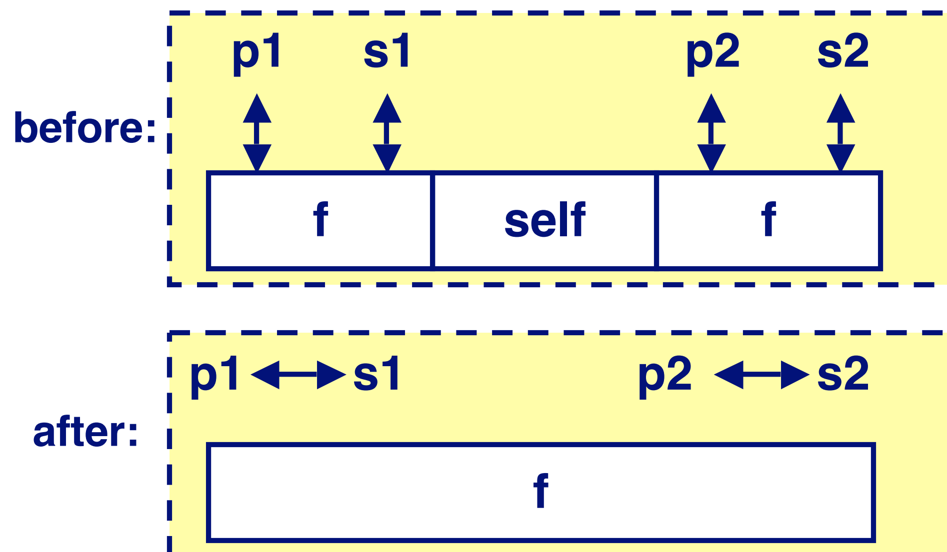
Case 3: f-a-a

- Splice out prev, coalesce with self, and add to beginning of free list



Case 4: f-a-f

- Splice out prev and next, coalesce with self, and add to beginning of list



Explicit List Summary

Comparison to implicit list:

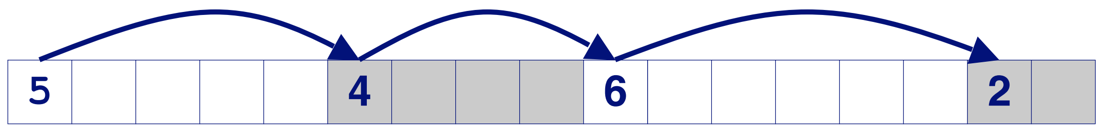
- Allocate is linear time in number of free blocks instead of total blocks -- much faster allocates when most of the memory is full
- Slightly more complicated allocate and free since needs to splice blocks in and out of the list
- Some extra space for the links (2 extra words needed for each block)

Main 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

Keeping Track of Free Blocks

Method 1: ***Implicit list*** **using lengths -- links all blocks**



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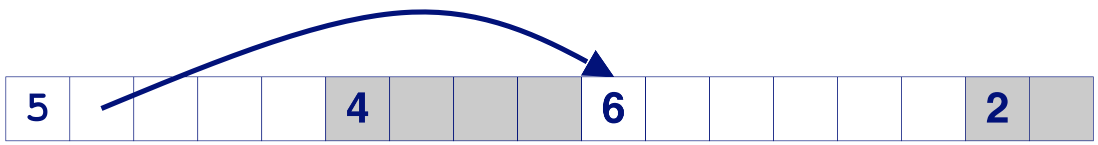


Method 3: ***Segregated free list***

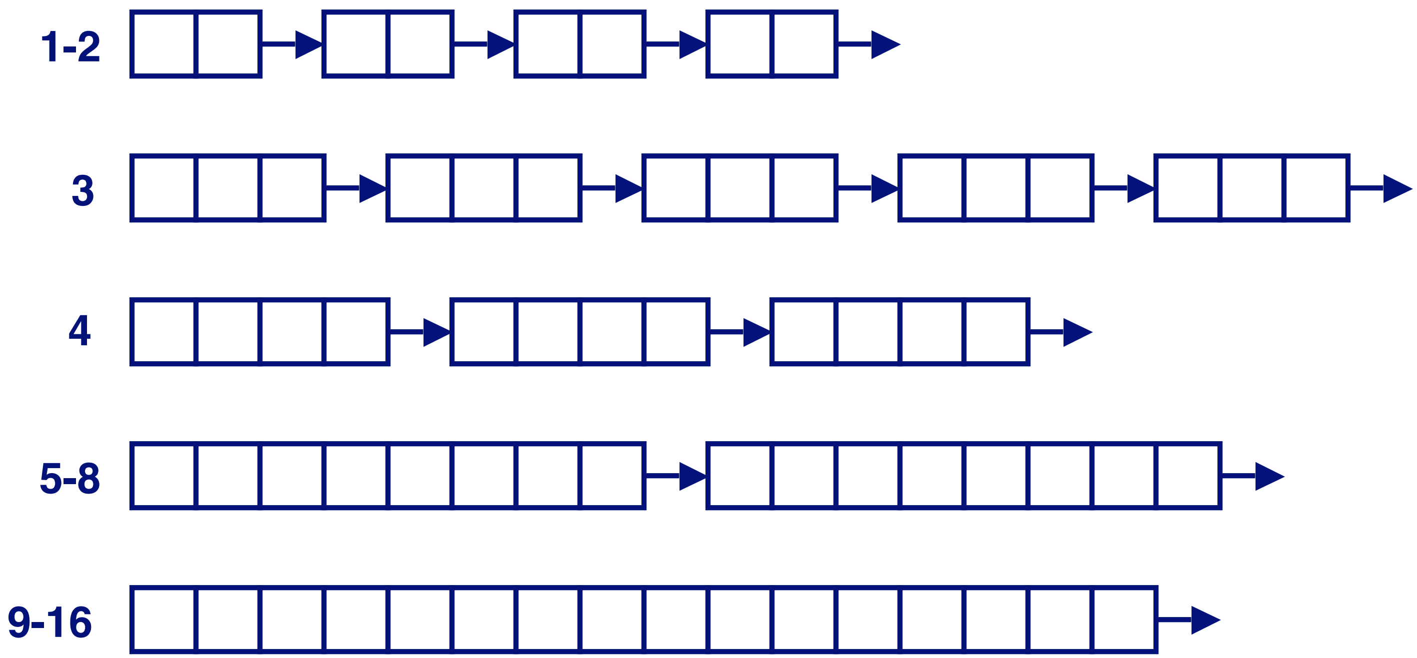
- Different free lists for different size classes

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

Segregated Storage

Each *size class* has its own collection of blocks



- **Often have separate size class for every small size (2,3,4,…)**
- **For larger sizes typically have a size class for each power of 2**

Simple Segregated Storage

Separate heap and free list for each size class

No splitting

To allocate a block of size n:

- If free list for size n is not empty,
  - allocate first block on list (note, list can be implicit or explicit)
- If free list is empty,
  - get a new page
  - create new free list from all blocks in page
  - allocate first block on list
- Constant time

To free a block:

- Add to free list
- If page is empty, return the page for use by another size (optional)

Tradeoffs:

- Fast, but can fragment badly

Segregated Fits

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

To free a block:

- Coalesce and place on appropriate list (optional)

Tradeoffs

- Faster search than sequential fits (i.e., log time for power of two size classes)
- Controls fragmentation of simple segregated storage
- Coalescing can increase search times
  - Deferred coalescing can help

For More Info on Allocators

D. Knuth, "The Art of Computer Programming, Second 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)

Implicit Lists: Summary

- **Implementation:** very simple
- **Allocate:** linear time worst case
- **Free:** 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 allocate. Used in many special purpose applications.

However, the concepts of splitting and boundary tag coalescing are general to *all* allocators.