Dynamic Memory Allocation

NORTHWESTERN UNIVERSITY 1851

Today

- Dynamic memory allocation – mechanisms & policies
- Memory bugs

Next time

- Exceptional control flow

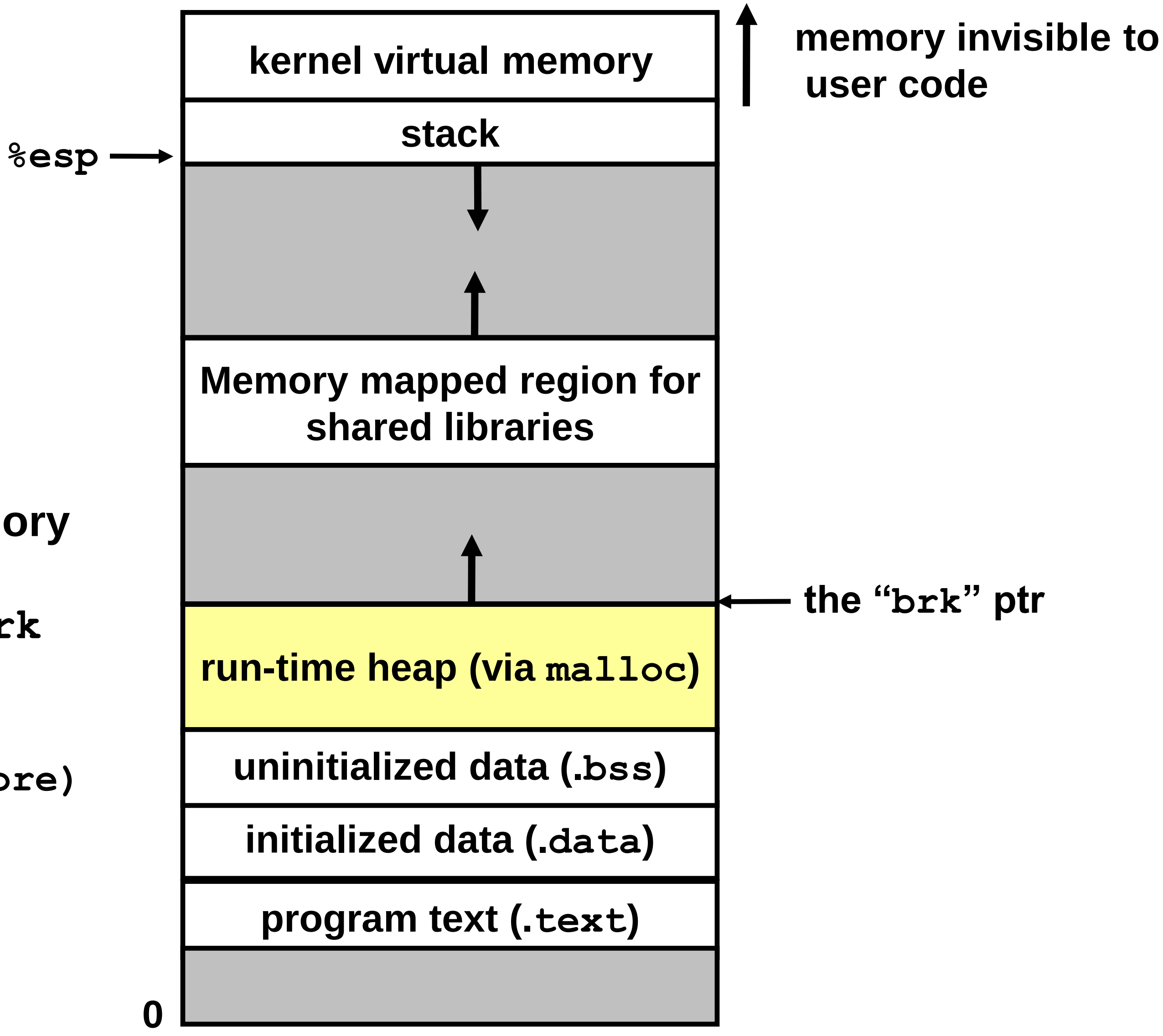
Dynamic memory allocation

- Why you need it? Memory needs may be unknown at runtime
- 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

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 *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.
- `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`.

Process memory image



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

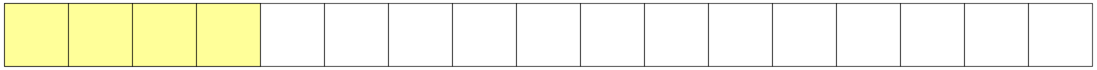
```
error = sbrk(amt_more)
```

Malloc example

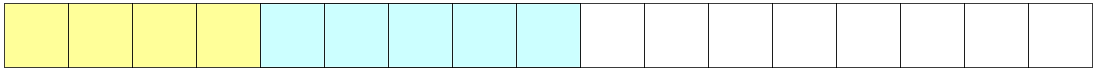
```
void foo(int n, int m) {
  int i, *p;

  /* 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 */
}
```

Allocation examples

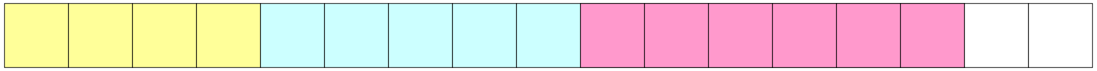
```
p1 = malloc(4)
```



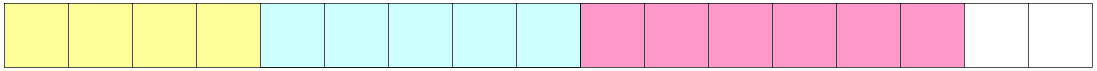
```
p2 = malloc(5)
```



```
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

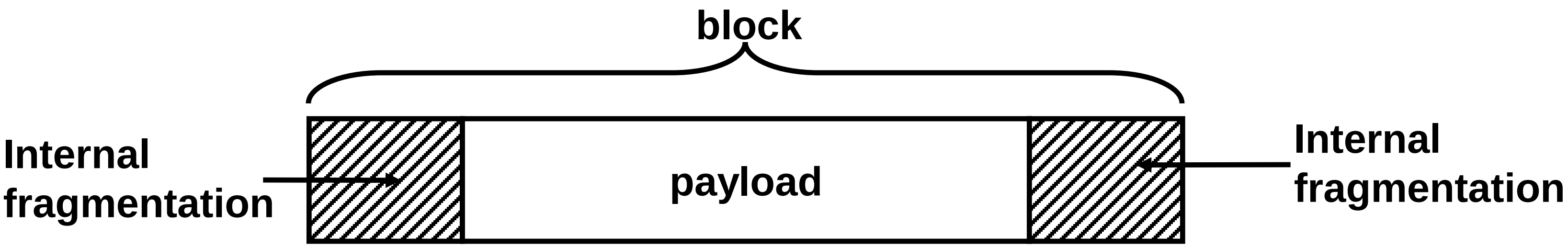
- Given some sequence of malloc and free requests:
  - $R_0, R_1, \ldots, R_k, \ldots, R_{n-1}$
- Want to maximize throughput and peak memory utilization.
  - These goals are often conflicting
- Throughput:
  - Number of completed requests per unit time
  - Example:
    - 5,000 malloc calls and 5,000 free calls in 10 seconds
    - Throughput is 10,000 operations/second.

Performance goals: Peak mem 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.

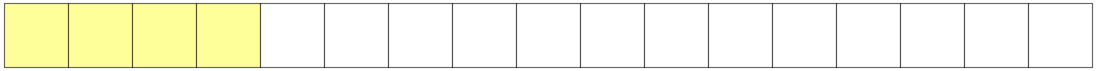


  - Caused by overhead of maintaining heap data structures, padding for alignment purposes, or explicit policy decisions (e.g., not to split the block).
  - Depends only on the pattern of *previous* requests, and thus is easy to measure.

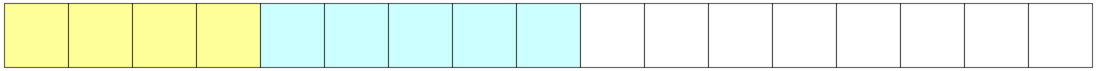
External fragmentation

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

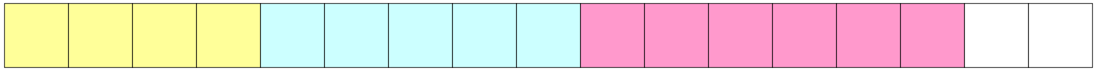
```
p1 = malloc(4)
```



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



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



```
free(p2)
```

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

oops!

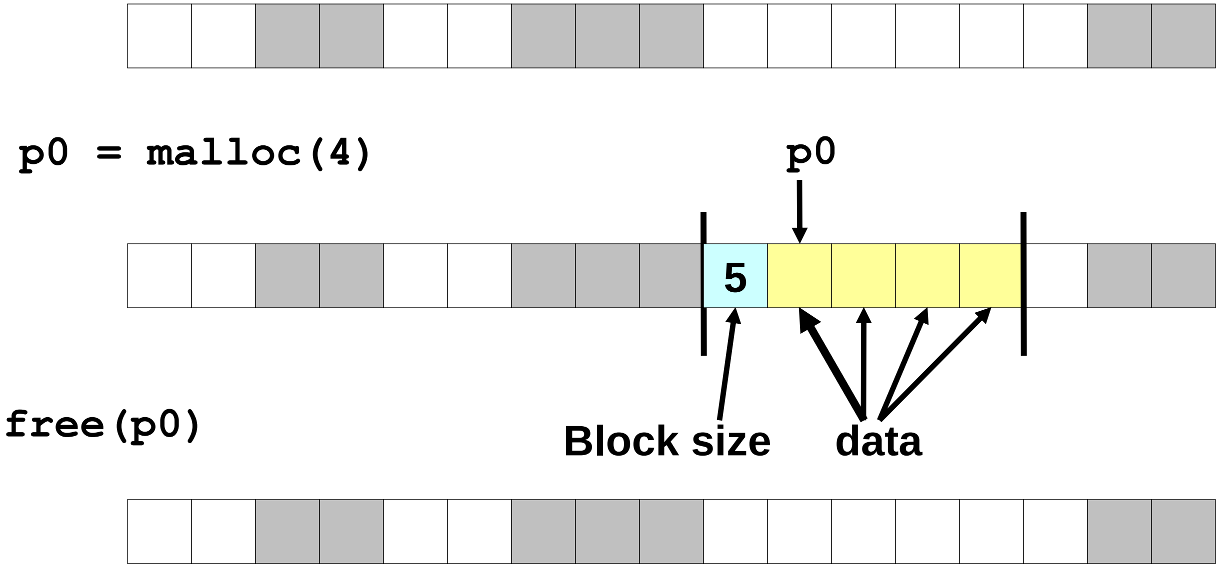
External fragmentation depends on the pattern of *future* requests, and thus is difficult to measure.

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?

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

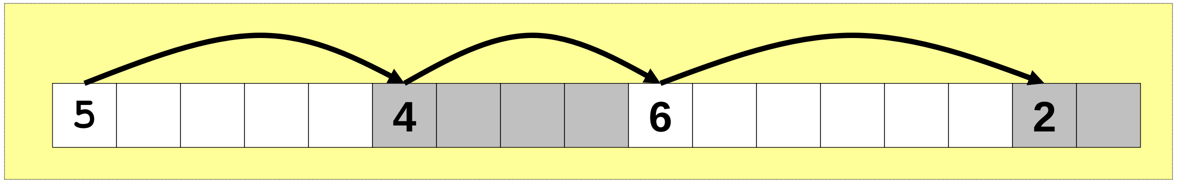


`p0 = malloc(4)`

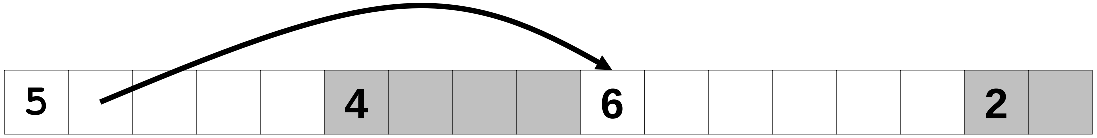
`free(p0)`

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



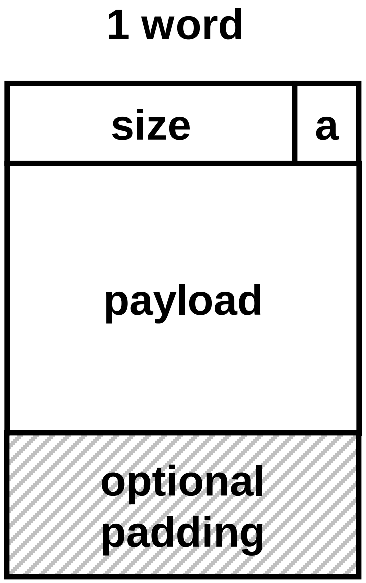
- *Method 3*: *Segregated free list*

  - 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

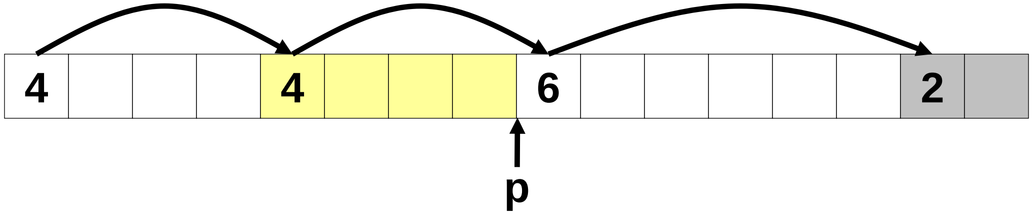
payload: application data (allocated blocks only)

Implicit list: Finding a free block

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

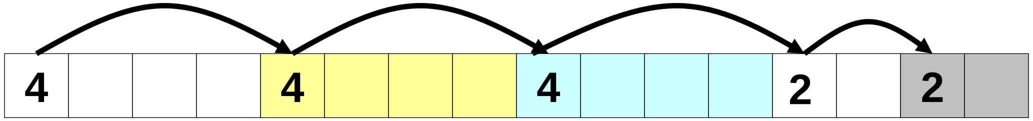
Implicit list: Allocating in free block

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



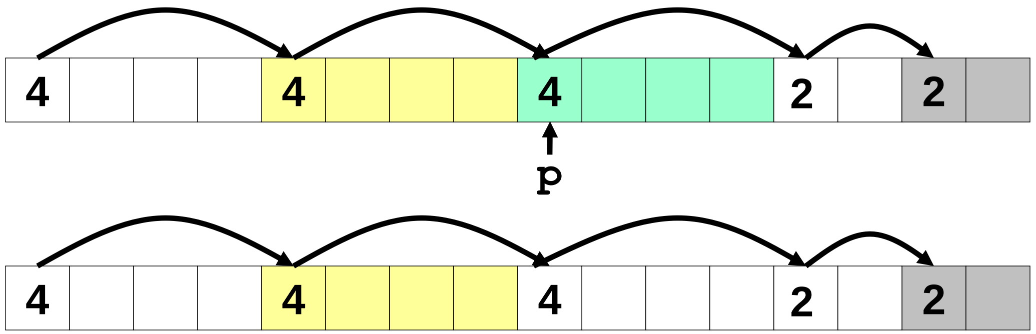
```
void addblock(ptr p, int len) {
  int newsize = ((len + 1) >> 1) << 1;  // add 1 and round up
  int oldsize = *p & -2;                // mask out low bit
  *p = newsize | 1;                     // set new length
  if (newsize < oldsize)
    *(p+newsize) = oldsize - newsize;   // set length in remaining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

`addblock(p, 2)`



Implicit list: Freeing a block

- Simplest implementation:
  - Only need to clear allocated flag
  - But can lead to "false fragmentation"



`free(p)`

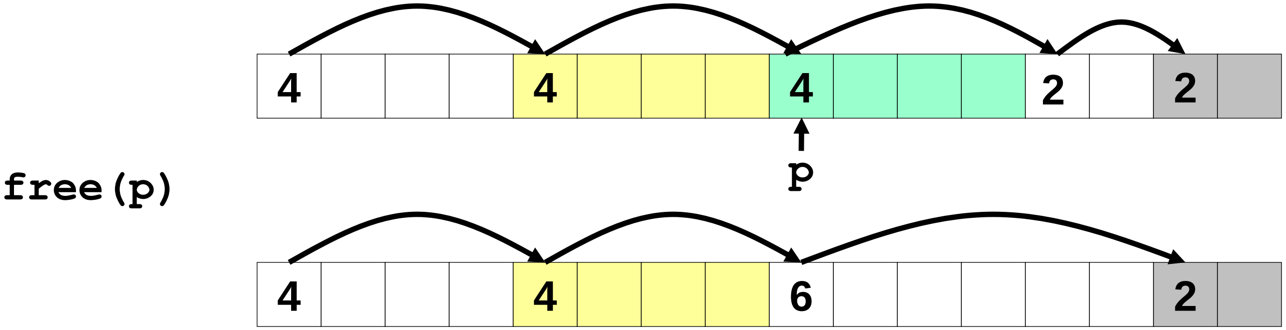
`malloc(5)` **Oops!**

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

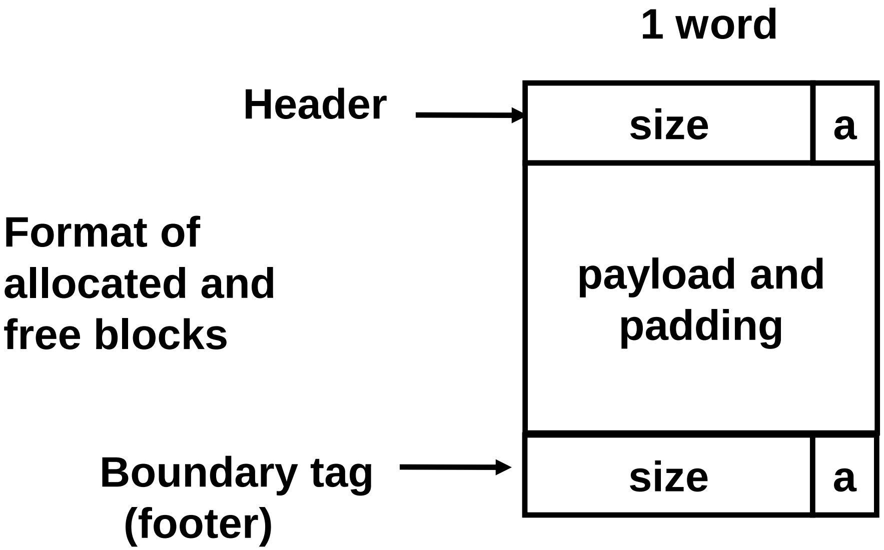
```
void free_block(ptr p) {
    *p = *p & -2;            // clear allocated flag
    next = p + *p;           // find next block
    if ((*next & 1) == 0)
      *p = *p + *next;      // add to this block if
}                           //     not allocated
```



  - But how do we coalesce with previous block?

Implicit list: Bidirectional coalescing

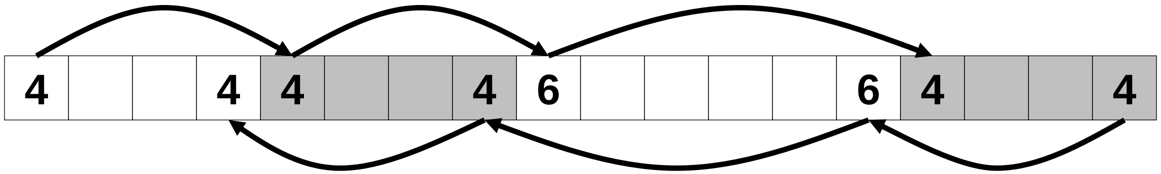
- *Boundary tags* [Knuth73]
  - Replicate size/allocated word at bottom of free blocks
  - Allows us to traverse the "list" backwards, but requires extra space
  - Important and general technique!



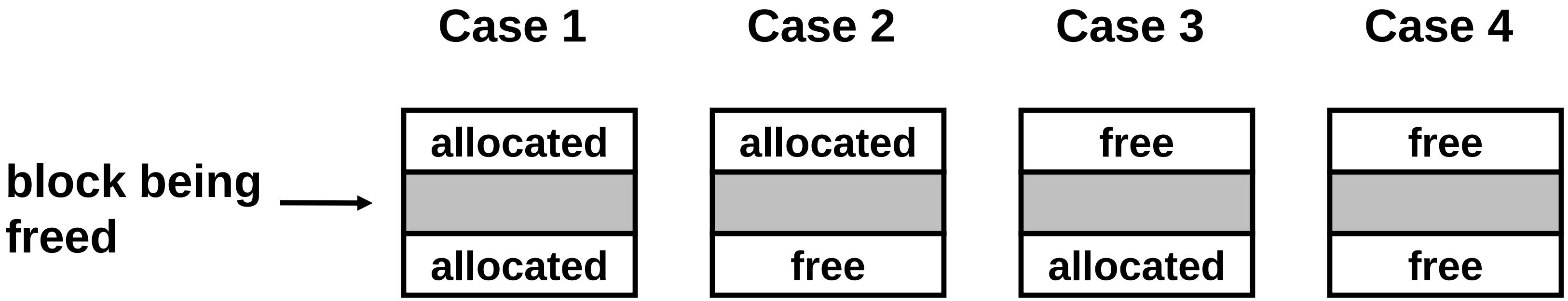
a = 1: allocated block
a = 0: free block

size: total block size

payload: application data (allocated blocks only)



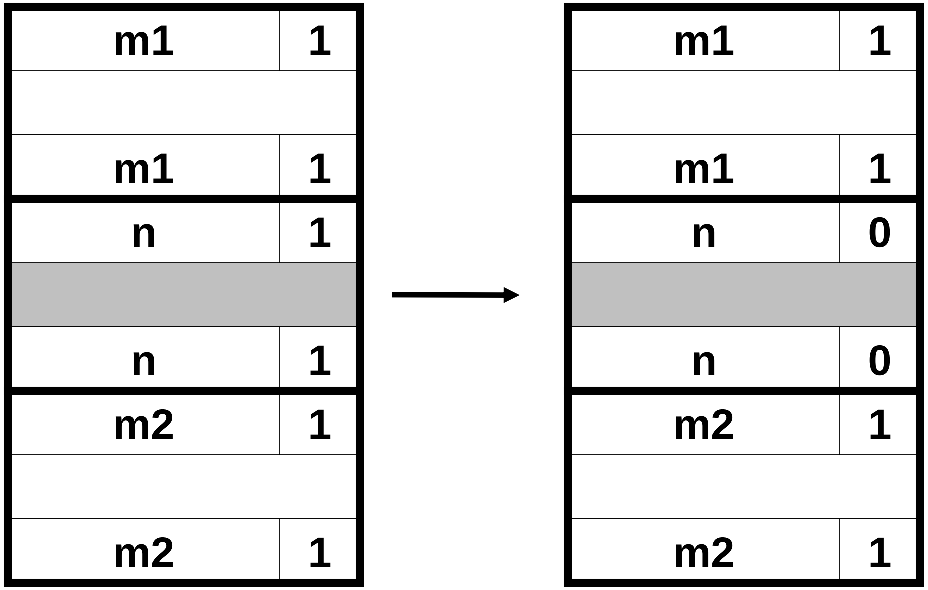
Constant time coalescing


Case 1
Case 2
Case 3
Case 4

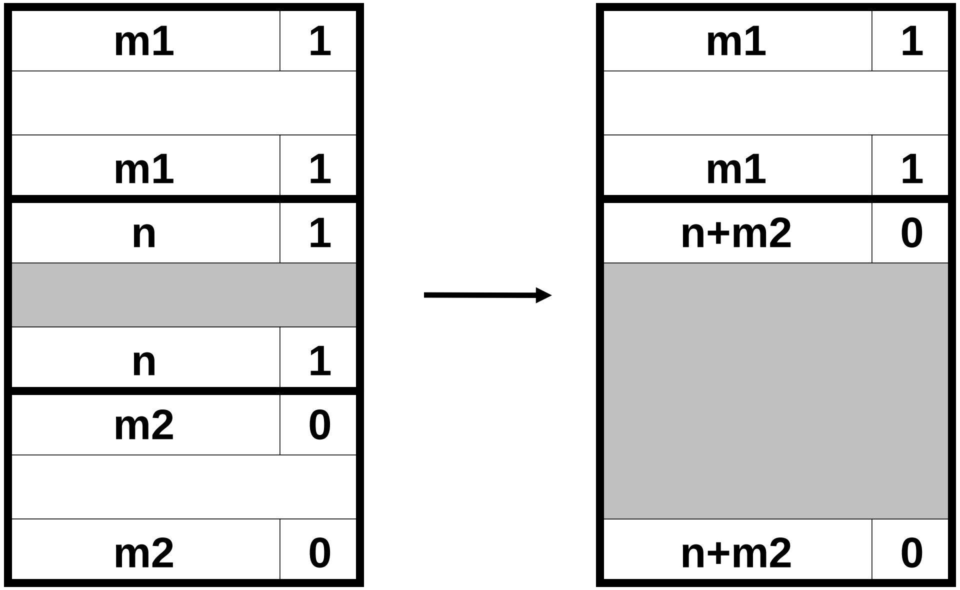
block being freed

Case 1	Case 2	Case 3	Case 4
allocated	allocated	free	free
allocated	free	allocated	free

Constant time coalescing (Case 1)



Constant time coalescing (Case 2)



m1 1

m1 1

n 1

n 1

m2 0

m2 0

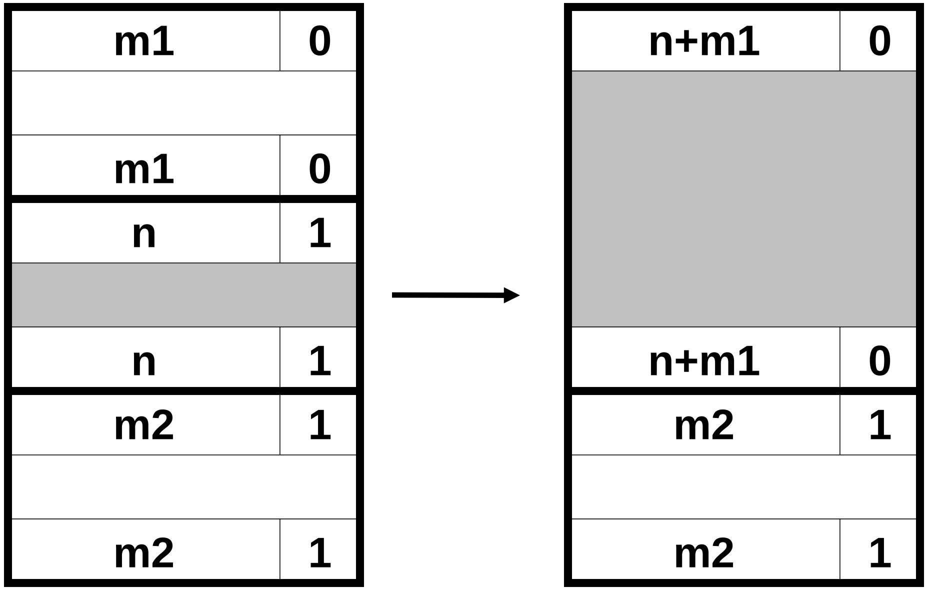
m1 1

m1 1

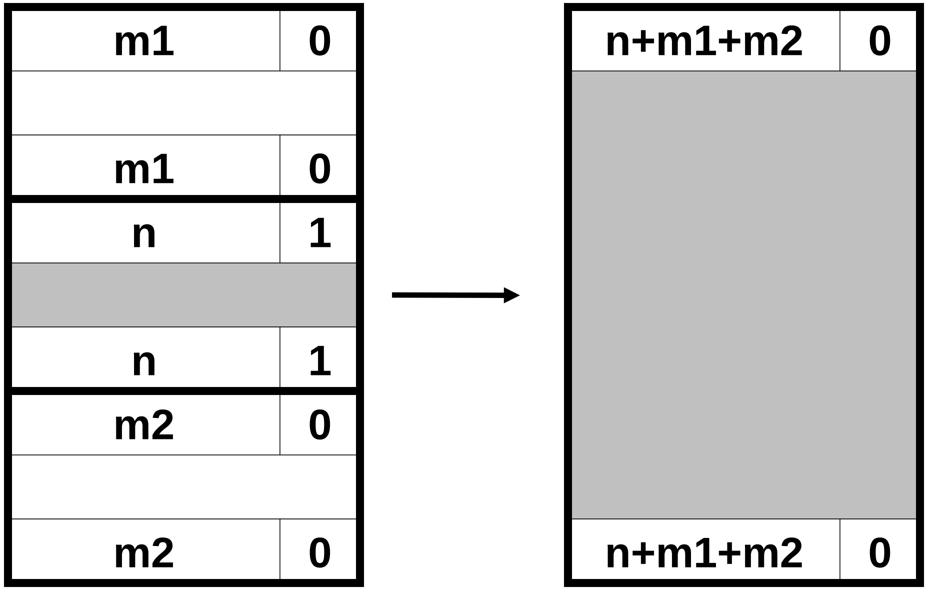
n+m2 0

n+m2 0

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
- 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.

Implicit mem. mgmnt: Garbage collection

- *Garbage collection:* automatic reclamation of heap-allocated storage -- application never has to free

```
void foo() {
   int *p = malloc(128);
   return; /* p block is now garbage */
}
```

- Common in functional languages, scripting languages, and modern object oriented languages:
  - Lisp, ML, Java, Perl, Mathematica,
- Variants (conservative garbage collectors) exist for C and C++
  - Cannot collect all garbage

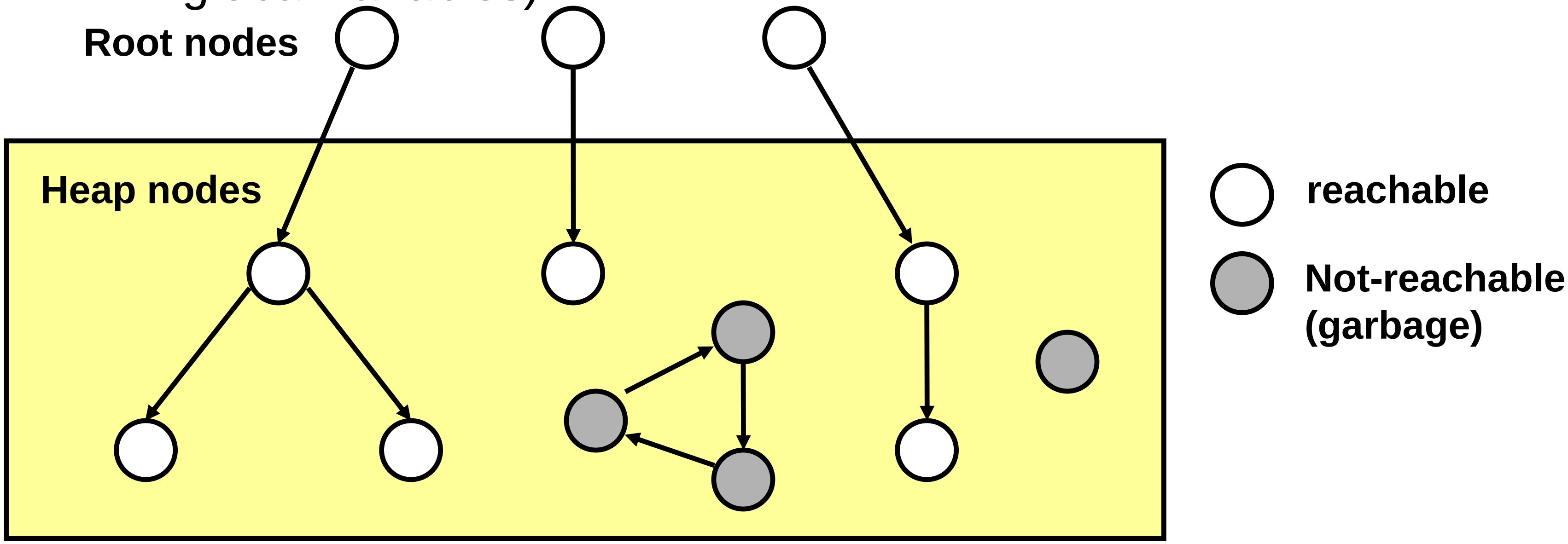
Garbage collection

- How does the memory manager know when memory can be freed?
  - In general we cannot know what is going to be used in the future since it depends on conditionals
  - But we can tell that certain blocks cannot be used if there are no pointers to them

- Need to make certain assumptions about pointers
  - Memory manager can distinguish pointers from non-pointers
  - All pointers point to the start of a block

Memory as a graph

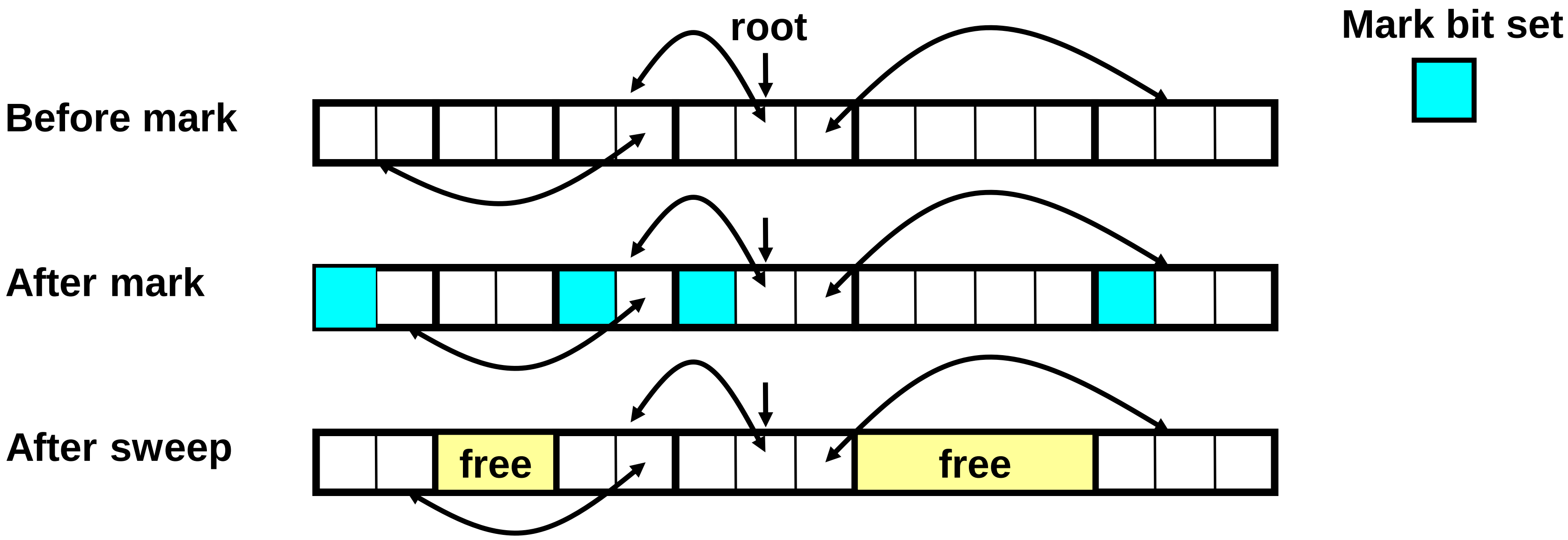
- We view memory as a directed graph
  - Each block is a node in the graph
  - Each pointer is an edge in the graph
  - Locations not in the heap that contain pointers into the heap are called *root* nodes (e.g. registers, locations on the stack, global variables)



- A node (block) is *reachable* if there is a path from any root to that node.
- Non-reachable nodes are *garbage* (never needed by the application)

Mark and sweep collecting

- Can build on top of malloc/free package
  - **Allocate using** malloc **until you “run out of space”**
- When out of space:
  - **Use extra** *mark bit* **in the head of each block**
  - *Mark:* **Start at roots and set** mark bit **on all reachable memory**
  - *Sweep:* **Scan all blocks and** free **blocks that are** not marked



Memory-related bugs

- Why the fear?
  - Symptoms typically appear far, in time and space, from the source
- Some common bugs worth looking at
  - Dereferencing bad pointers
  - Reading uninitialized memory
  - Overwriting memory
  - Referencing nonexistent variables
  - Freeing blocks multiple times
  - Referencing freed blocks
  - Failing to free blocks

Dereferencing bad pointers

- The classic `scanf` bug

```
scanf(“%d”, val);
```

- Should be &val
  - Best case – program terminates with an exception
  - Worst case – contents of val corresponds to a valid r/w area and we overwrite memory ...

Reading uninitialized memory

- While bss memory locations are always initialized to zero, that’s not the case for the heap
- 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;
}
```

Overwriting memory

- Allocating the (possibly) wrong sized object

```
int **p;

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

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

- Should have been

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

Overwriting memory

- Off-by-one errors – allocates N, tries to initialize N+1

```
int **p;

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

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

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
  - 1988 Internet worm
  - Modern attacks on Web servers

Overwriting memory

- Referencing a pointer instead of the object it points to

```
int *binheapDelete(int **binheap, int *size) {
   int *packet;
   packet = binheap[0];
   binheap[0] = binheap[*size - 1];
   *size--;
   heapify(binheap, *size, 0);
   return(packet);
}
```

Overwriting memory

- Misunderstanding pointer arithmetic

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

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

   return p;
}
```

Referencing nonexistent variables

- Forgetting that local variables disappear when a function returns

```
int *foo () {
   int val;
   return &val;
}
```

Freeing blocks multiple times

- Nasty!

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

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

Referencing freed blocks

- Evil!

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

Failing to free blocks (memory leaks)

- Slow, long-term killer

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

Summary

- **Memory matters**
- 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