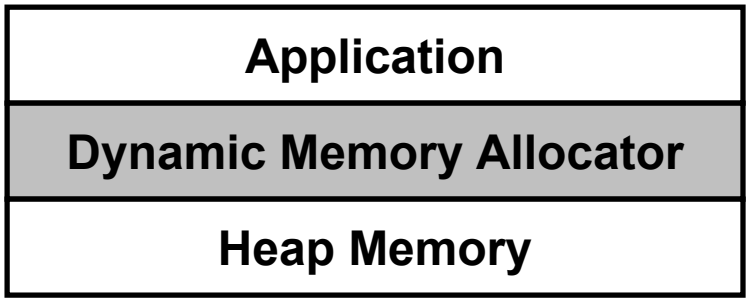
Dynamic Memory Allocation – beyond the stack and globals

- **Stack**
  - **Easy to allocate (decrement esp)**
  - **Easy to deallocate (increment esp)**
  - **Automatic allocation at run-time, including variable size (alloca)**
  - **Can pass values to called procedures, but not up to callers**
- **Global variables**
  - **Statically allocated**
  - **Have to decide at compile time how much space you need**
  - **Can pass values between any procedures**
- **Allocation on the heap**
  - **Dynamically allocated at run-time**
  - **Independent of procedure calls**
  - **But must be carefully managed**
    - Automatically: garbage collection
    - Manually: malloc/free or new/delete

Dynamic Memory Allocation



Explicit vs. Implicit Memory Allocator

- **Explicit: application allocates and frees space**
  - E.g., `malloc` and `free` in C, new/delete/delete[] in C++
- **Implicit: application allocates, but does not free space**
  - E.g. garbage collection in Java, ML or Lisp

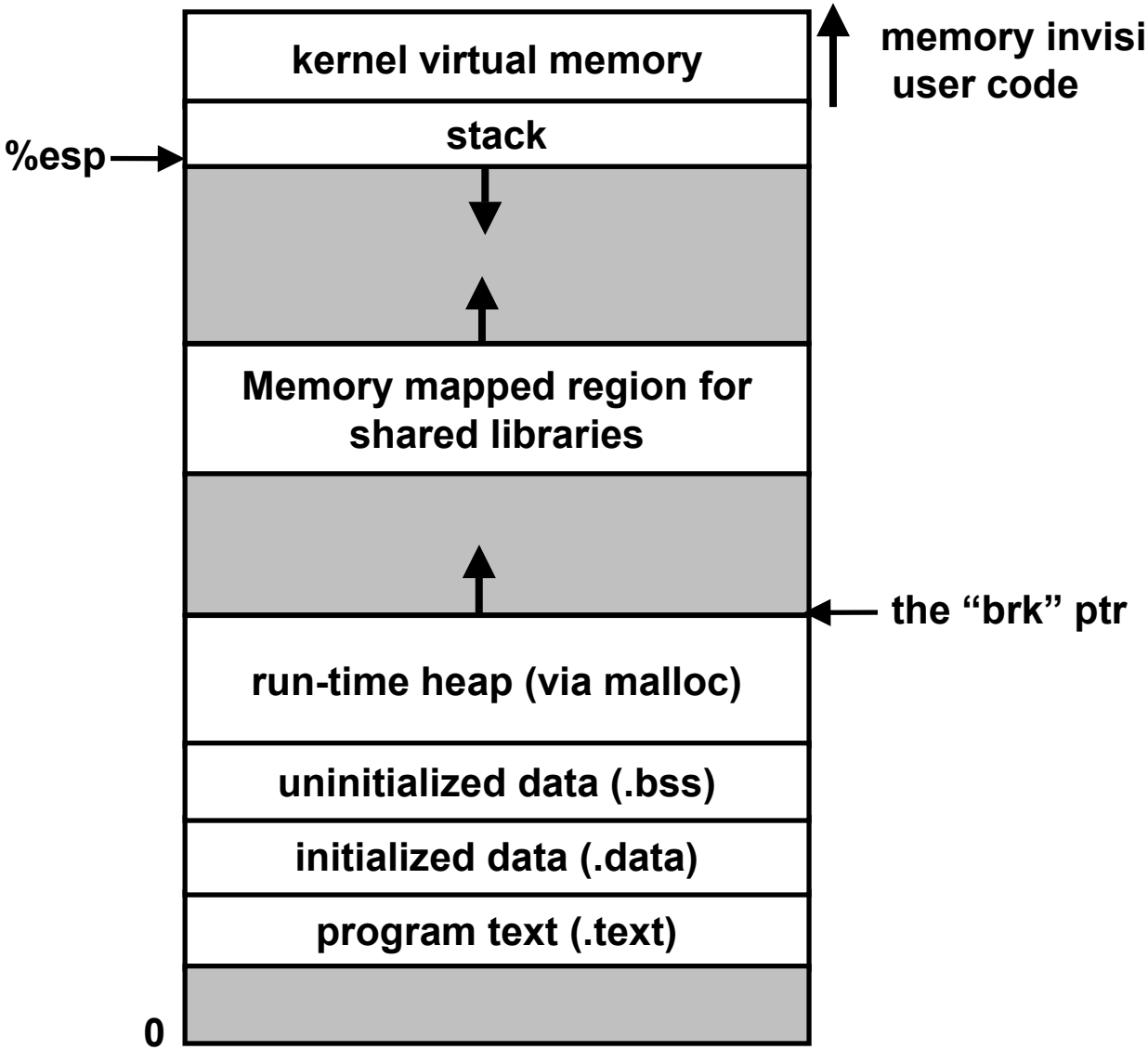
Allocation

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

Allocator is typically a system or language library

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, aligned to 8-byte boundary.
  - if `size==0`, returns NULL
- **if unsuccessful:** returns NULL

```
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 ptr to new block.**
- **contents of new block unchanged up to min of old and new size.**

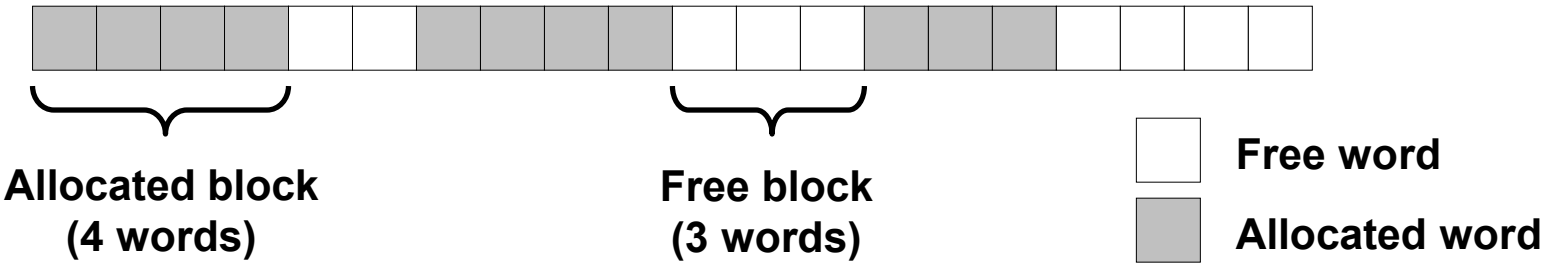
Malloc example

```
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 */
}
```

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**
  - usually 8 byte alignment
- **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**
  - blocks allocated close in time should be close in space
  - Similar-sized blocks 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:

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

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.

Want to maximize throughput and peak memory utilization.

- **These goals are often conflicting**

Performance goals: peak memory utilization

Given some sequence of malloc and free requests:

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

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. (increases with malloc, decreases with free)**

Def: current heap size is denoted by H_k

- **Note that H_k is monotonically increasing (generally)**

Def: peak memory utilization:

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

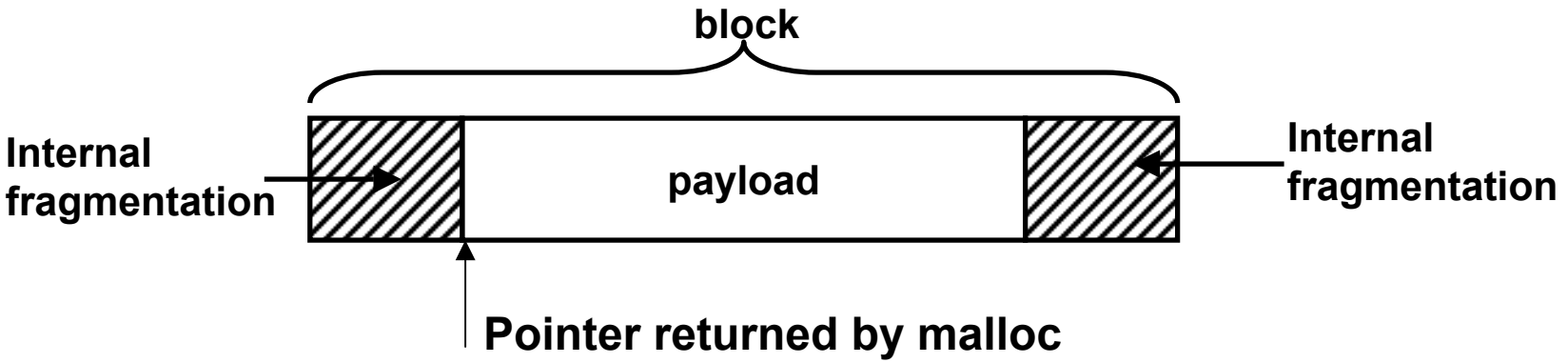
Internal Fragmentation

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)
```

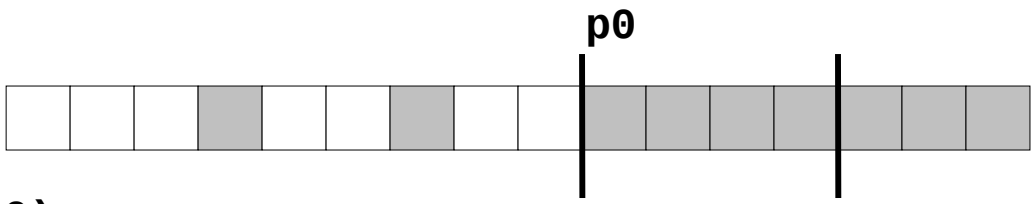
```
p4 = malloc(6)
```

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?

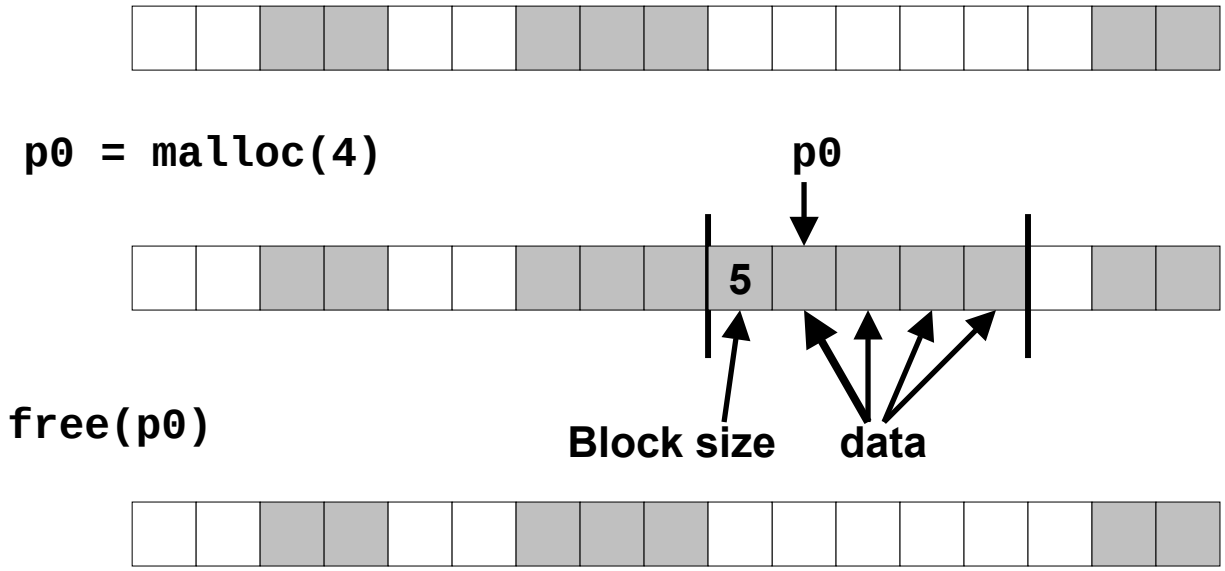



```
free(p0)

p1 = malloc(1)
```

Knowing how much to free

Standard method

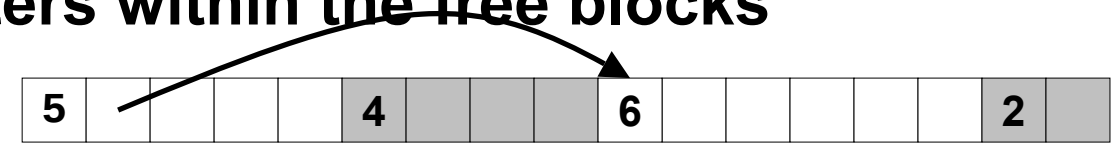
- **keep the length of a structure in the word preceding the structure**
  - This word is often called the *header field* or *header*
- **requires an extra word for every allocated structure**



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**



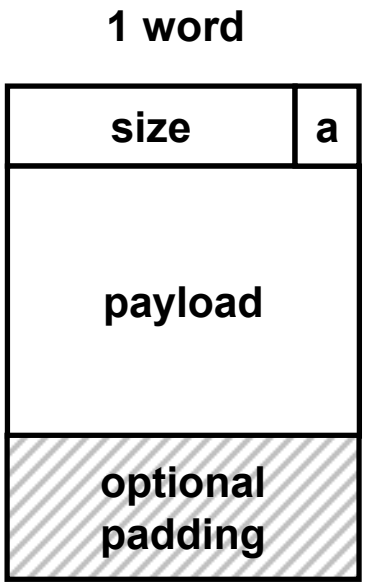
- ***Method 3***: **segregated free lists**
  - Different free lists for different size classes
- ***Method 4***: **blocks sorted by size**
  - Can use a balanced tree (e.g. Red-Black tree) with pointers within each free block, and the length used as a key

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 passed end
       (*p & 1) ||      // already allocated
       (*p <= len))     // too small
   p+=*p;               // goto next block
```

- 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

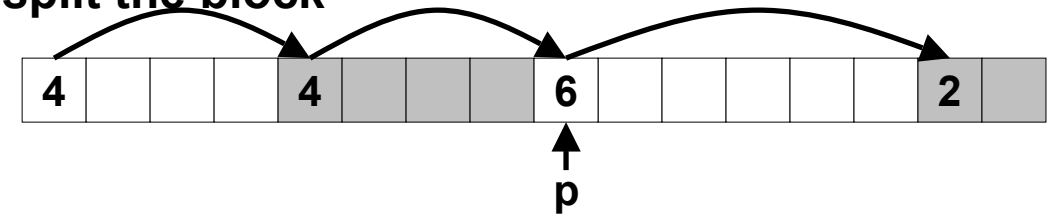
Best fit:

- 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

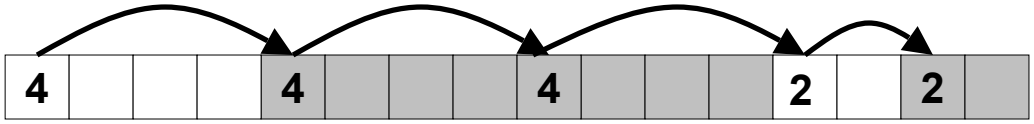
Implicit list: allocating in a free block

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);
```



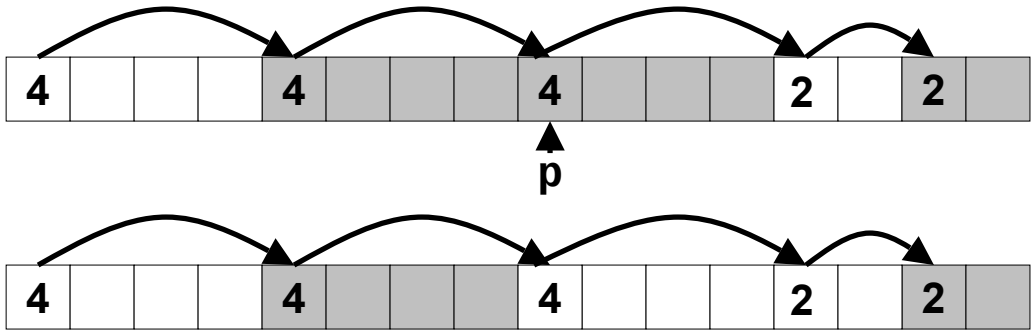
Implicit list: freeing a block

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!

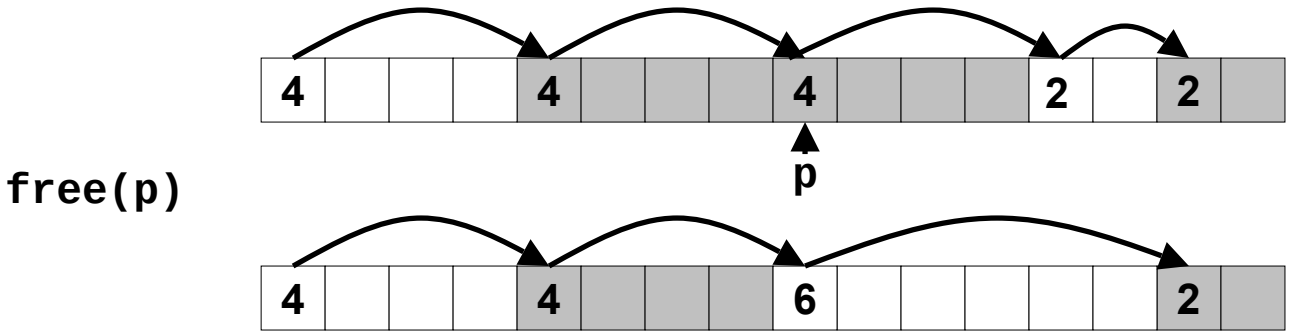
There is enough free space, but the allocator won’t be able to find it

Implicit list: coalescing

Join 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
```

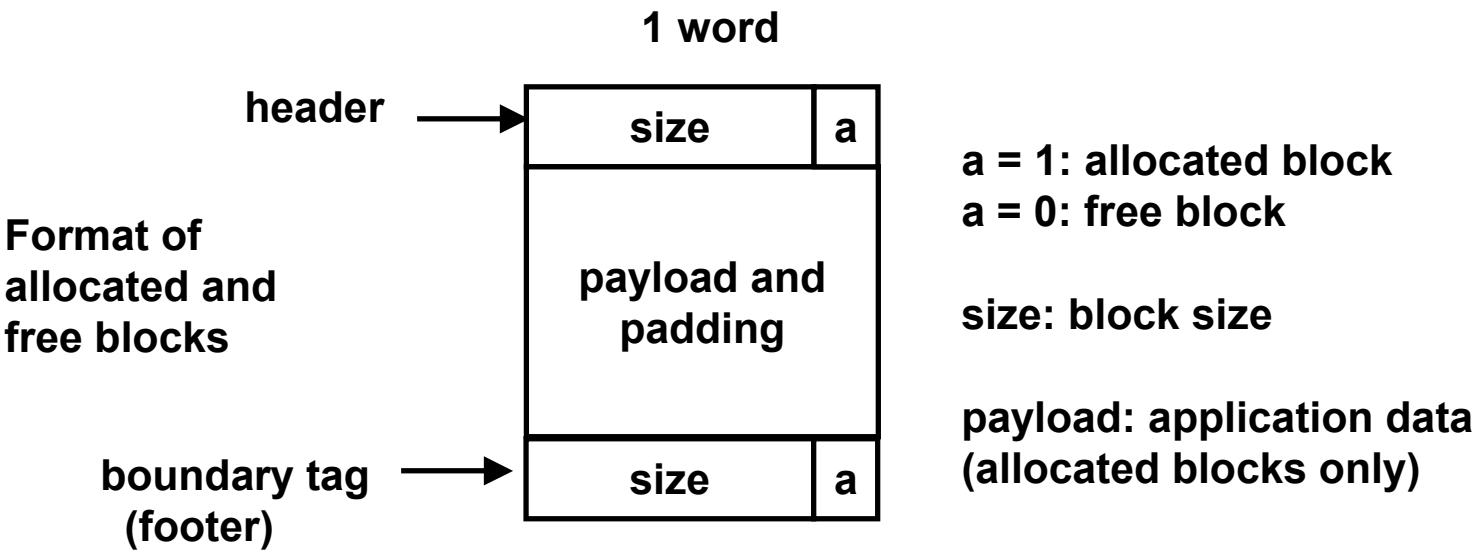


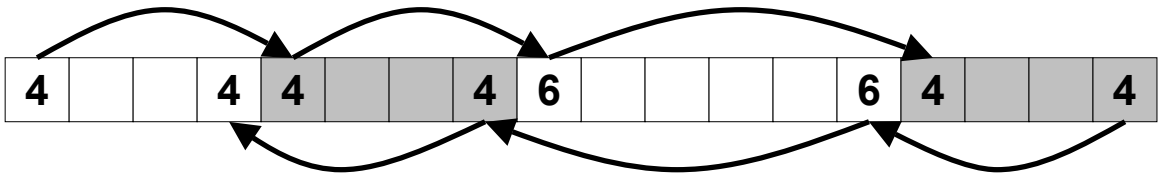
- But how do we coalesce with previous block?

Implicit list: bidirectional

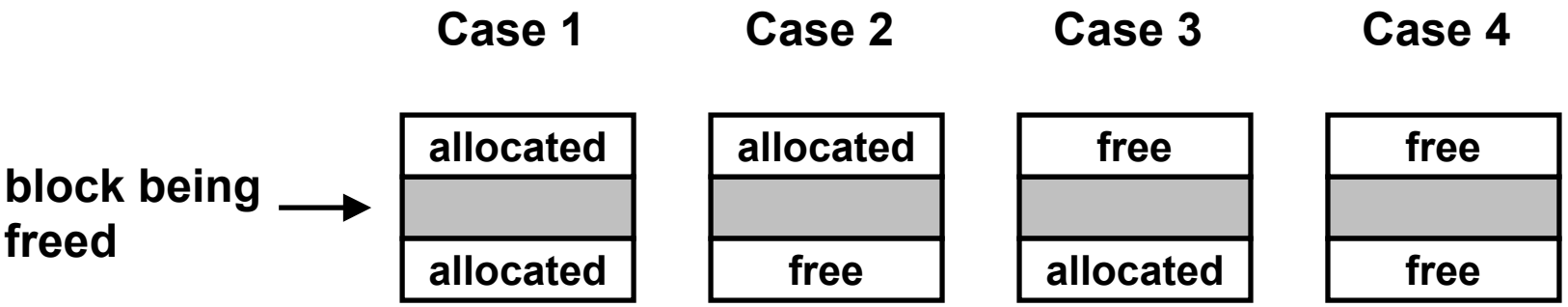
Boundary tags [Knuth73]

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

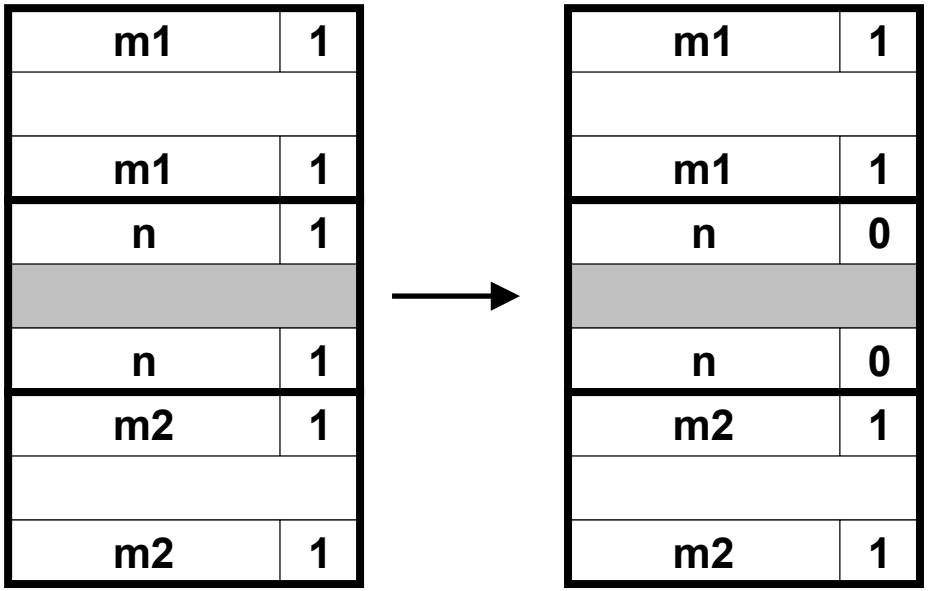




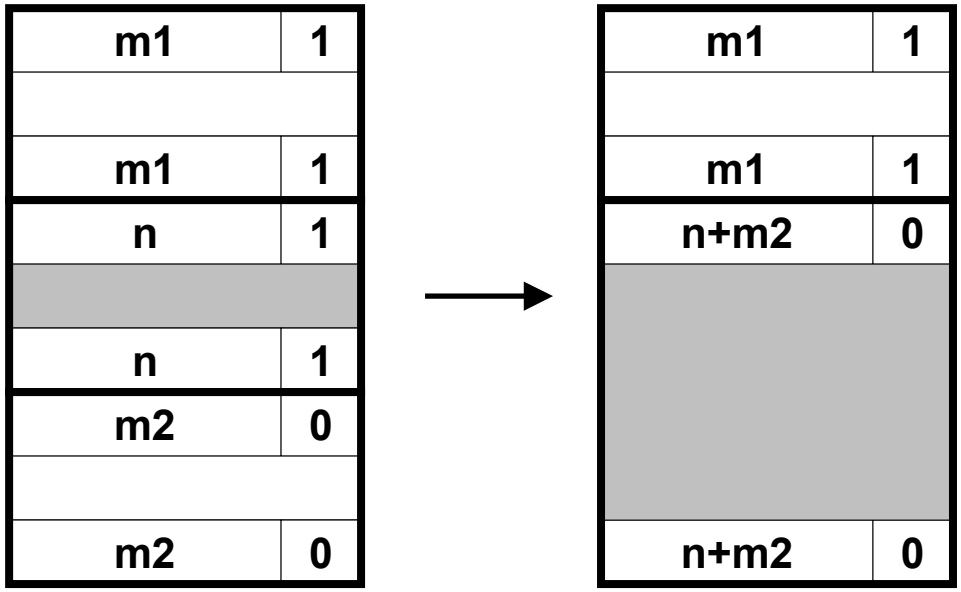
Constant time coalescing



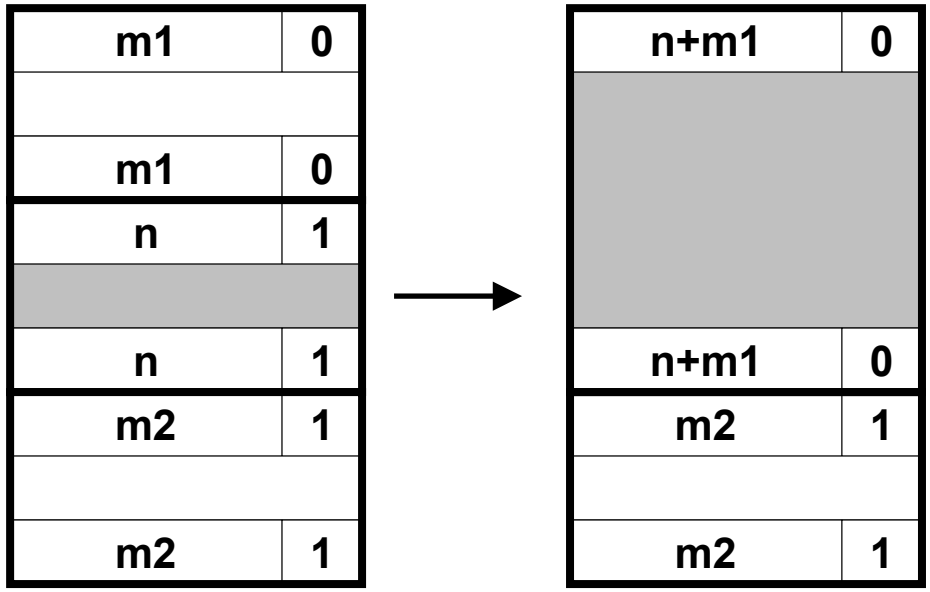
Constant time coalescing (case 1)



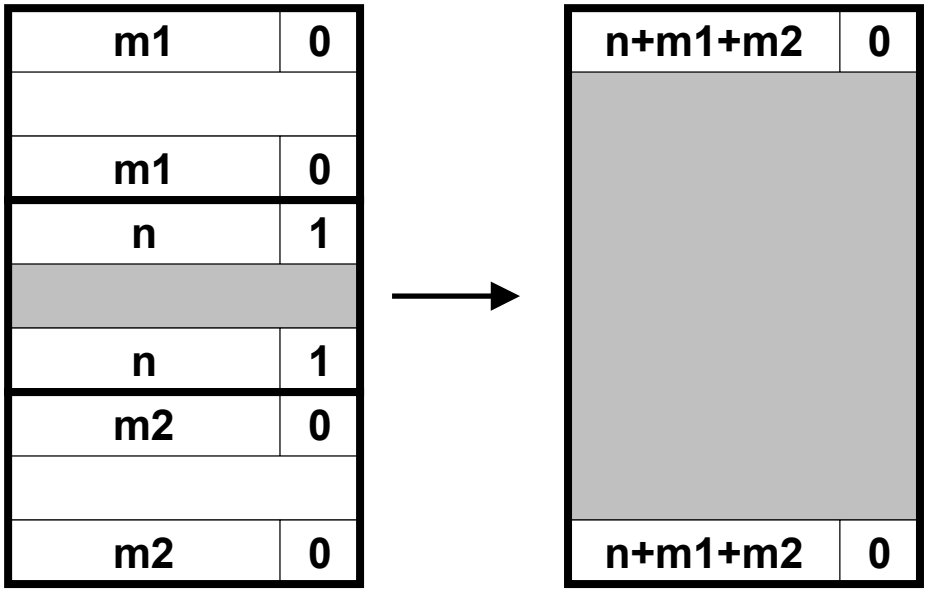
Constant time coalescing (case 2)



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.

For more information of dynamic storage 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 the course web page (see Documents page)**

Implicit Memory Management Garbage collector

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
- Cannot hide pointers (e.g. by coercing them to an int, and then back again)

Classical GC algorithms

Mark and sweep collection (McCarthy, 1960)

- **Does not move blocks (unless you also "compact")**

Reference counting (Collins, 1960)

- **Does not move blocks (not discussed)**

Copying collection (Minsky, 1963)

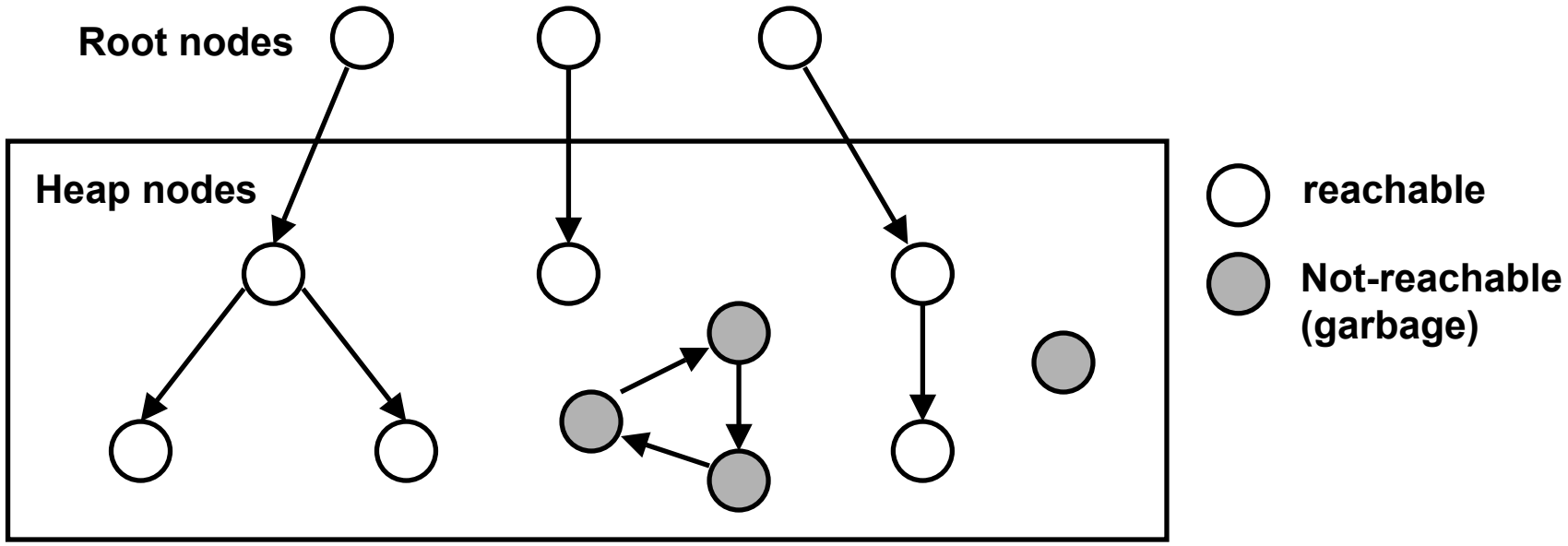
- **Moves blocks (not discussed)**

For more information see *Jones and Lin, "Garbage Collection: Algorithms for Automatic Dynamic Memory", John Wiley & Sons, 1996.*

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)

Memory-related bugs

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);
```

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;
}
```

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));
}
```

Overwriting memory

Off-by-one

```
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**
- **AOL/Microsoft IM war**

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;
}
```

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;
}
```

Dealing with memory bugs

Conventional debugger (gdb)

- **good for finding bad pointer dereferences**
- **hard to detect the other memory bugs**

Debugging malloc (CSRI UToronto 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

Dealing with memory bugs (cont.)

Binary translator (Atom, 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

Garbage collection (Boehm-Weiser Conservative GC)

- **let the system free blocks instead of the programmer.**