Dynamic Memory Allocation

Today

- Dynamic memory allocation – mechanisms & policies
- Memory bugs

Next time

- Virtual memory

Dynamic memory allocation

- Why? Memory needs may be unknown at runtime
  - A program that orders items in a list – how many items?

- Two basic memory allocator types: explicit & implicit
  - 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

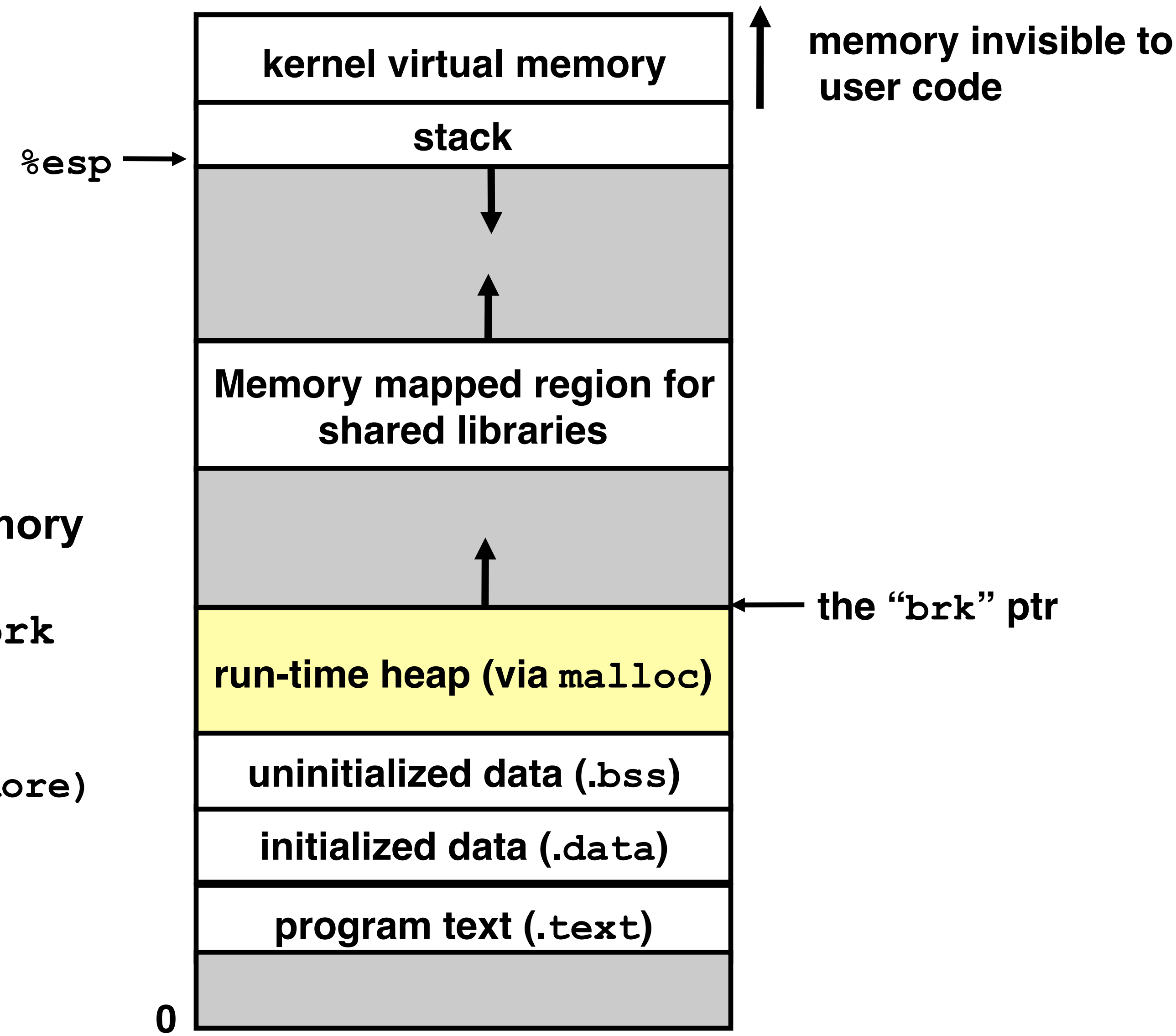
C standard library explicit allocator

- `#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)
```

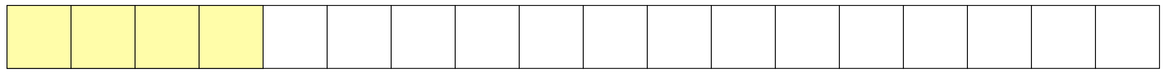


Malloc example

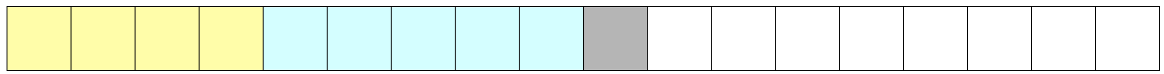
```
void foo(int n, int m) {
  int i, *p;

  /* 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

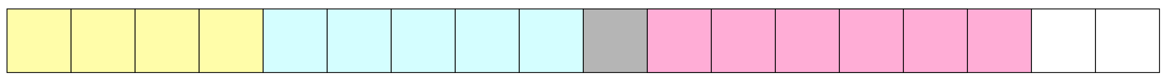
```
p1 = malloc(4)
```



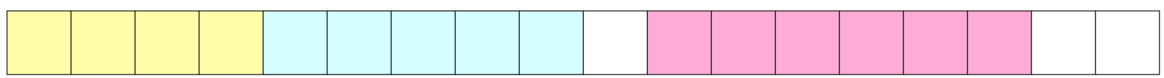
```
p2 = malloc(5)
```



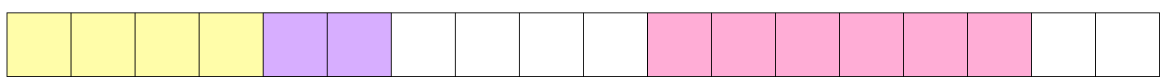
```
p3 = malloc(6)
```



```
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
  - 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 others
  - 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

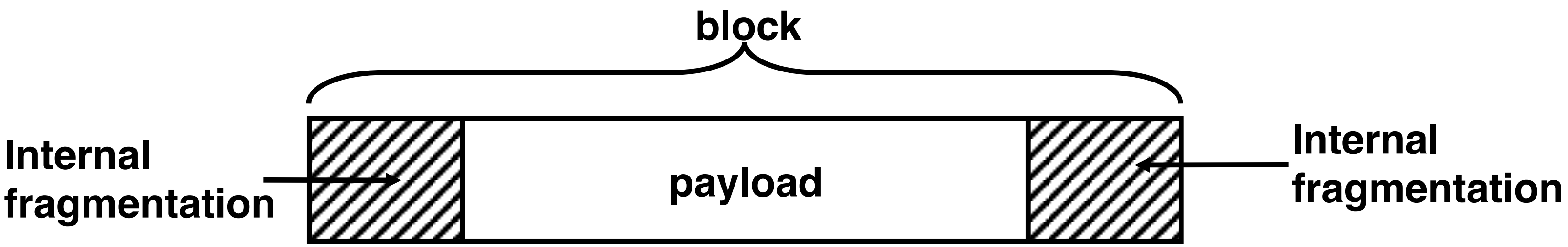
- Given some sequence of malloc and free requests:
- Want to maximize throughput and peak memory utilization
  - These goals are often in conflict
- Throughput:
  - Number of completed requests per unit time
  - Example:
    - 5,000 malloc calls and 5,000 free calls in 10 seconds
    - Throughput is 1,000 operations/second

Performance goals: Peak mem utilization

- Given some sequence of malloc and free requests
  - $R_0, R_1, ..., R_k, ... , R_{n-1}$
- 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
- Current heap size is denoted by H_k
  - Assume that H_k is monotonically nondecreasing
- Peak memory utilization:
  - After *k* requests, *peak memory utilization* is:
    - $U_k = (\max_{i \le k} P_i) \; / \; H_k$

Internal fragmentation

- Poor memory utilization caused by *fragmentation*
  - Comes in two forms: internal and external fragmentation
- Internal fragmentation
  - The difference between the block size and the payload size

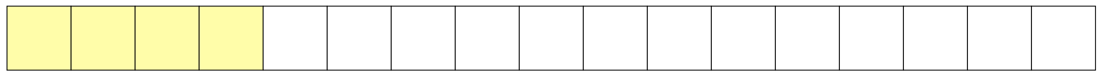


  - Due to overhead of maintaining heap data structures, padding for alignment purposes, or explicit policy decisions (e.g., not to split the block).
  - Depends only on the pattern of *previous* requests, so easy to measure

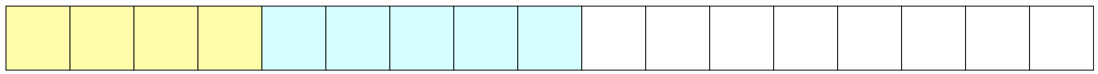
External fragmentation

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

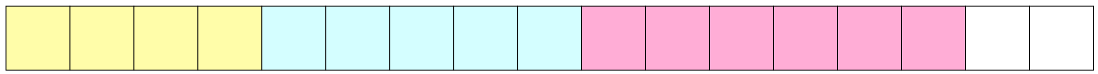
```
p1 = malloc(4)
```



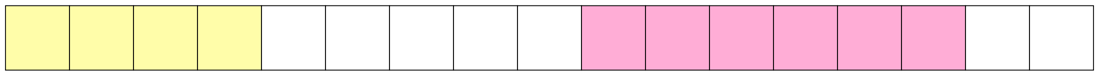
```
p2 = malloc(5)
```



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



```
free(p2)
```



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

oops!

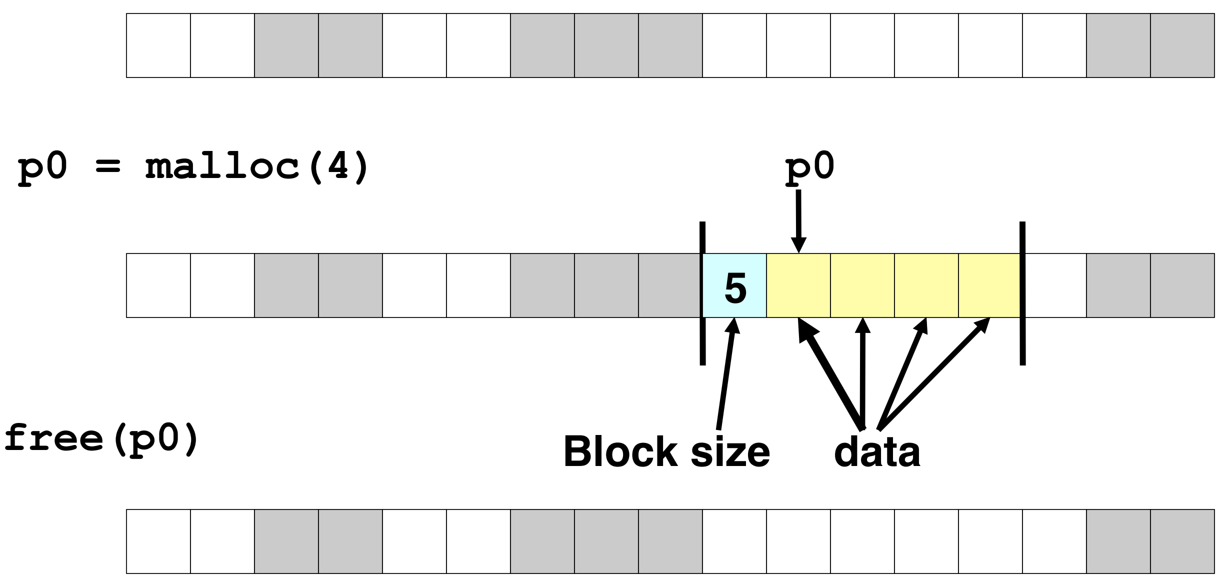
Depends on the pattern of *future* requests, so it's difficult to measure

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?

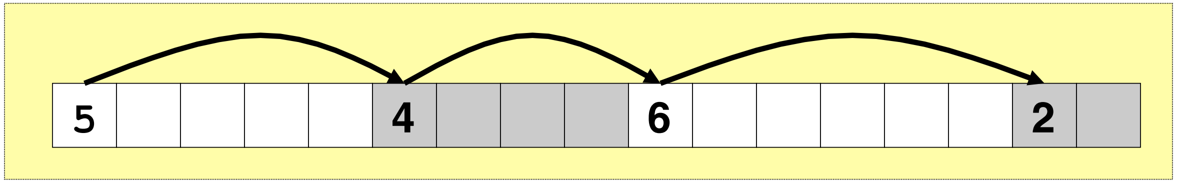
Knowing how much to free

- Standard method
  - Keep 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

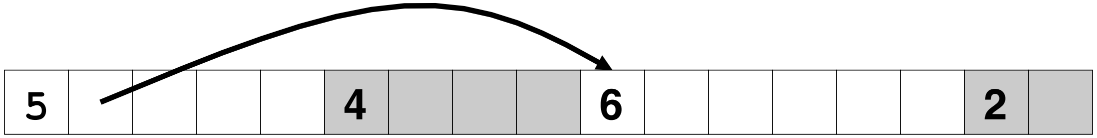


Keeping track of free blocks

- **Implicit list** using lengths -- links all blocks



- **Explicit list** among the free blocks using pointers within the free blocks



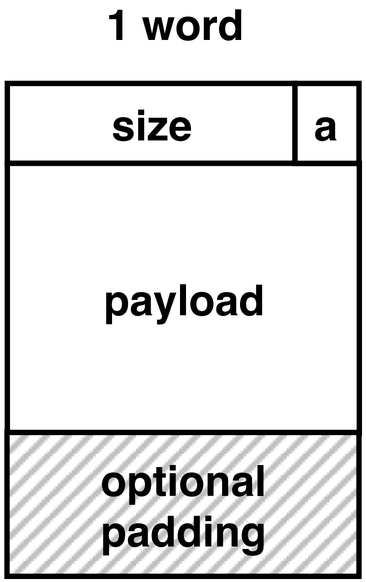
- **Segregated free list** – different free lists for different size classes

- Blocks sorted by size
  - Can use a balanced 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 2/4/8 (for alignment) – 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

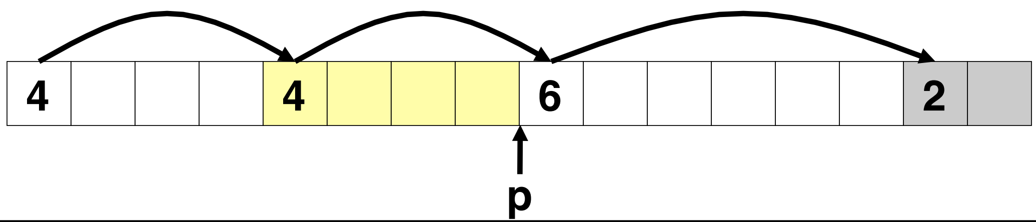
payload: application data (allocated blocks only)

Implicit list: Finding a free block

- First fit:
  - Search list from beginning, select first free block that fits
  - Can take linear time in num. of blocks (allocated and free)
  - In practice it can cause "splinters" at beginning of list
- Next fit:
  - Like first-fit, but start from end of previous search
  - Research suggests that fragmentation is worse
- Best fit:
  - Search the list, select free block with closest size that fits
  - Keeps fragments small --- usually helps fragmentation
  - Will typically run slower than first-fit

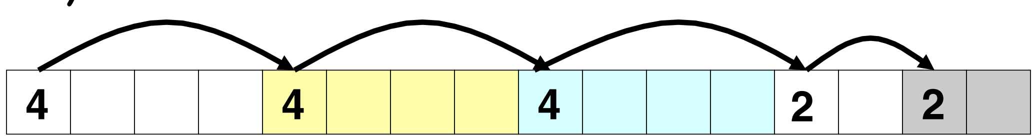
Implicit list: Allocating in free block

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



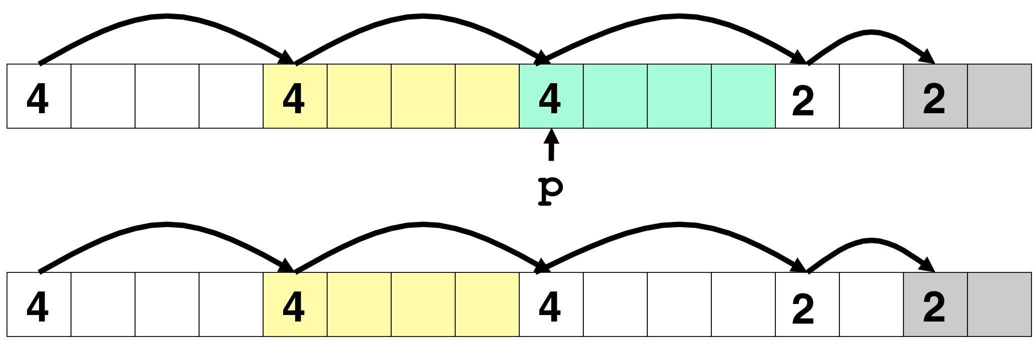

```
void addblock(ptr p, int len) {
  int newsize = ((len + 1) >> 1) << 1;  // add 1 and round up
  int oldsize = *p & -2;                // mask out low bit
  *p = newsize | 1;                     // set new length
  if (newsize < oldsize)
    *(p+newsize) = oldsize - newsize;   // set length in remaining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

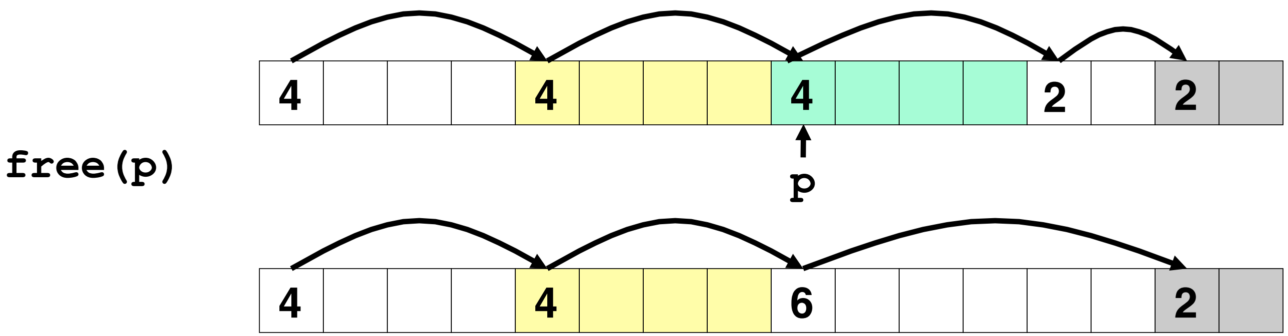
There is enough free space, but the allocator won't be able to find it

Implicit list: Coalescing

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

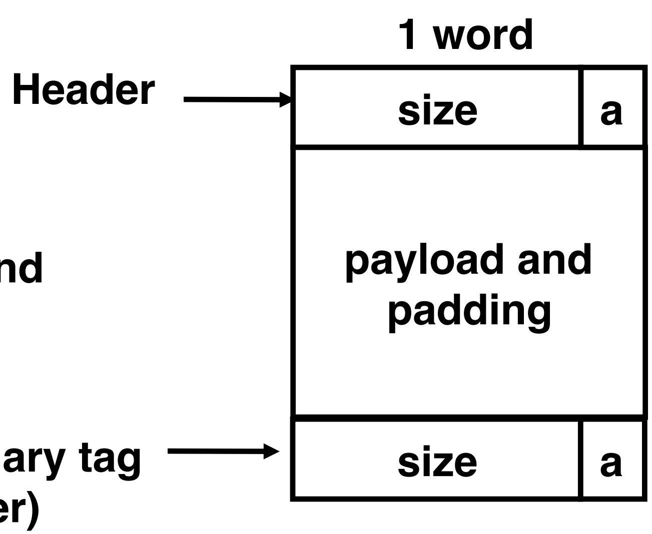


- But how do we coalesce with previous block?

Implicit list: Bidirectional coalescing

- *Boundary tags* [Knuth73]
  - Replicate size/allocated word at bottom of free blocks
  - Allows traversing a “list” backwards, but requires extra space
  - Important and general technique!

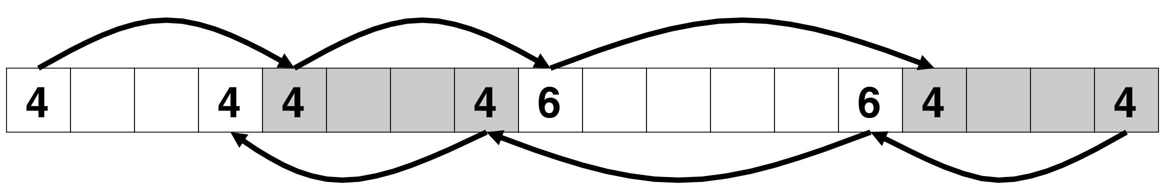
Format of allocated and free blocks



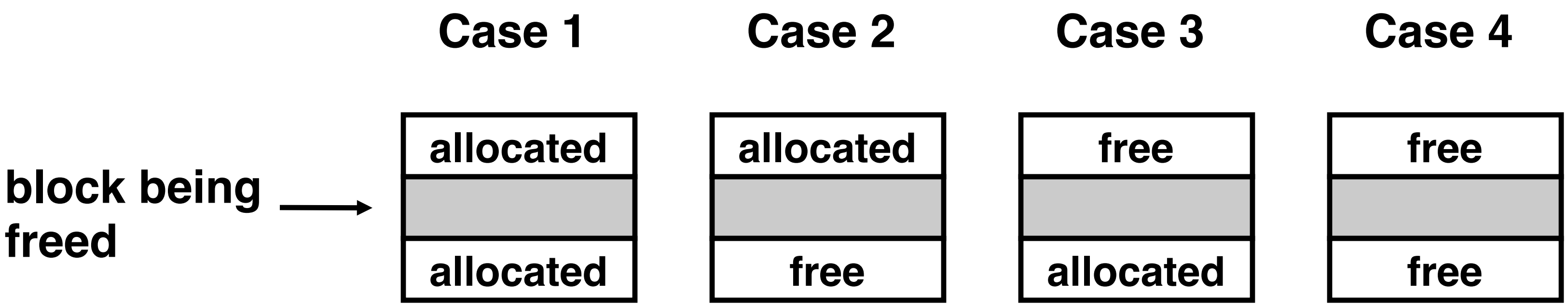
a = 1: allocated block
a = 0: free block

size: total block size

payload: application data (allocated blocks only)

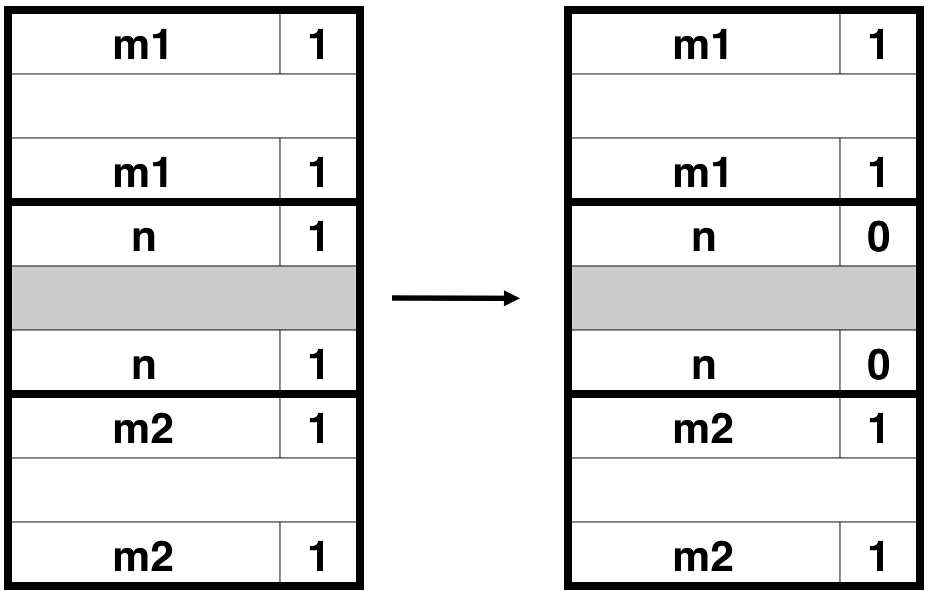


Constant time coalescing



Constant time coalescing (Case 1)

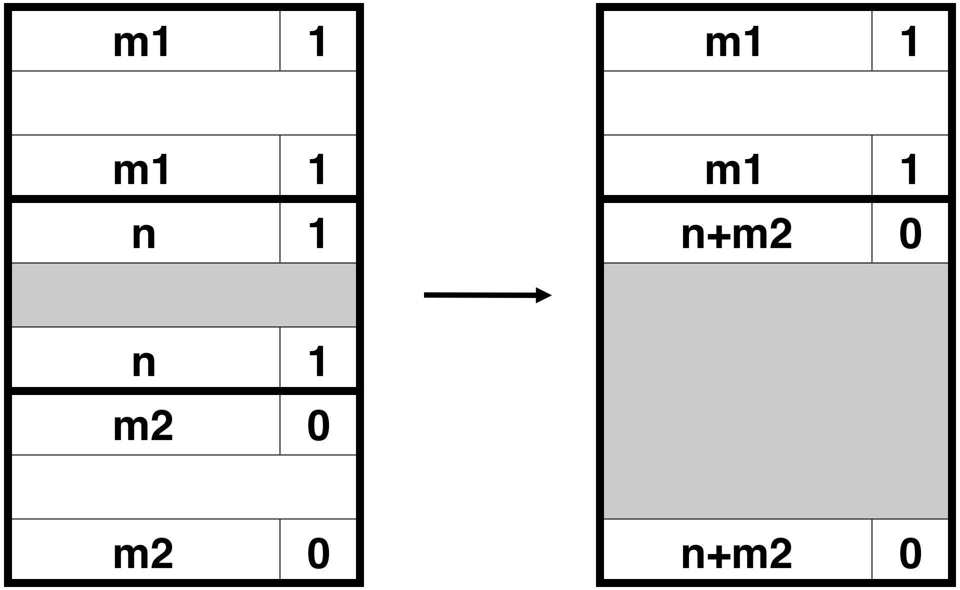
- Both adjacent blocks are allocated
  - No coalescing is possible
  - Simple mark block free




```
static void *coalesce(void *bp)
{
...
if (prev_alloc && next_alloc) {
        return bp;
}
...
```

Constant time coalescing (Case 2)

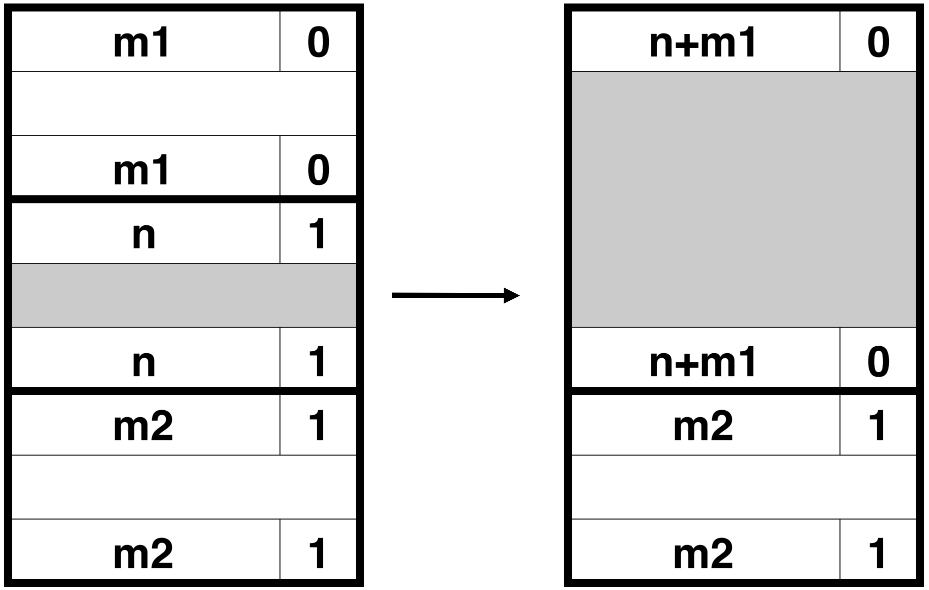
- Merge current and next block
  - Update header of current and footer of next




```
static void *coalesce(void *bp)
{
...
if (prev_alloc && !next_alloc) {
   size += GET_SIZE(HDRP(NEXT_BLKP(bp)));
   PUT(HDRP(bp), PACK(size,0));
   PUT(FTRP(bp), PACK(size,0));
}
...
```

Constant time coalescing (Case 3)

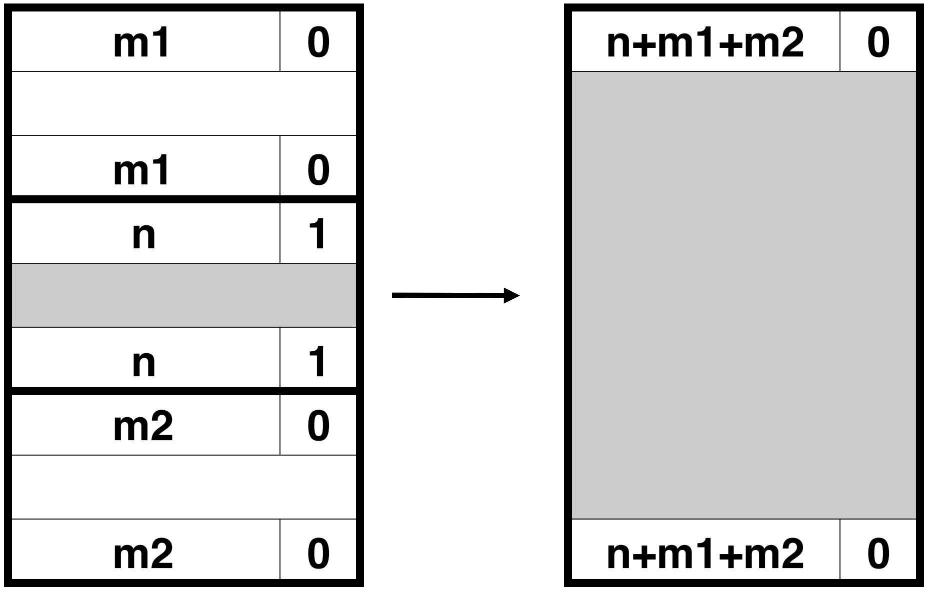
- Previous block is merged with current
  - Update header of previous block and footer of current block




```
static void *coalesce(void *bp)
{
...
if (!prev_alloc && next_alloc) {
    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);
}
...
```

Constant time coalescing (Case 4)

- All three blocks are merged
  - Update header of previous and footer of next block




```
static void *coalesce(void *bp)
{
...
else {
   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);
}
...
```

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 memory management

- *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

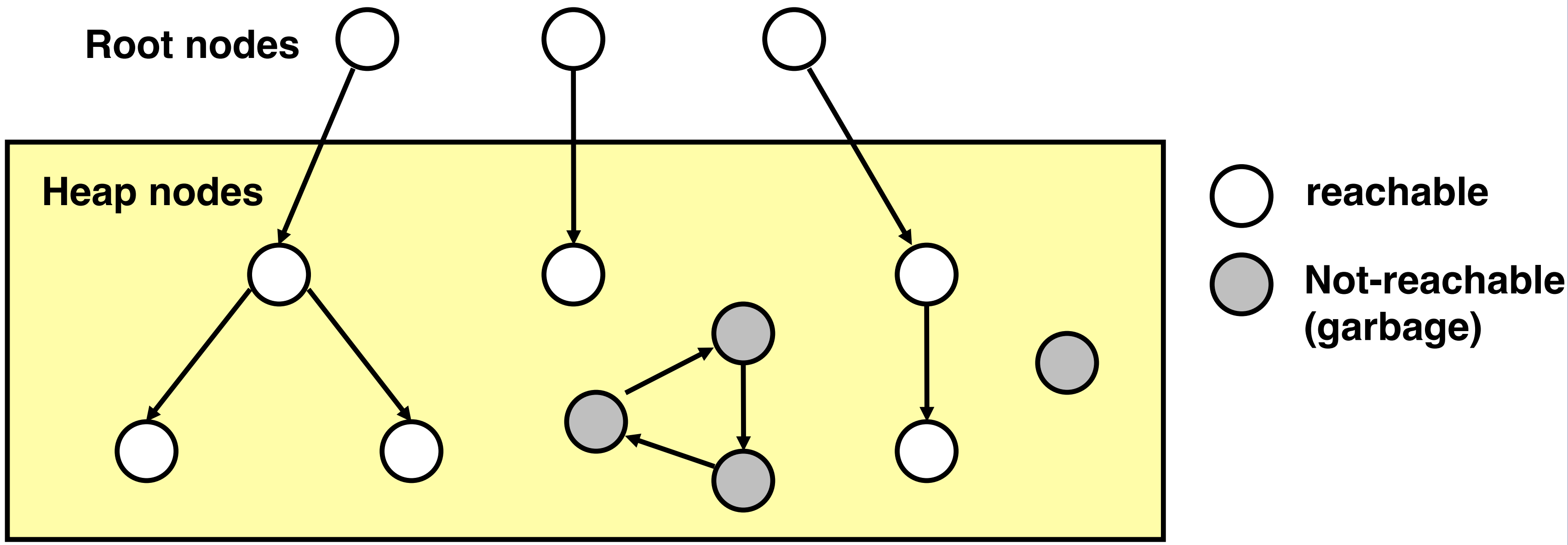
Garbage collection

- 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

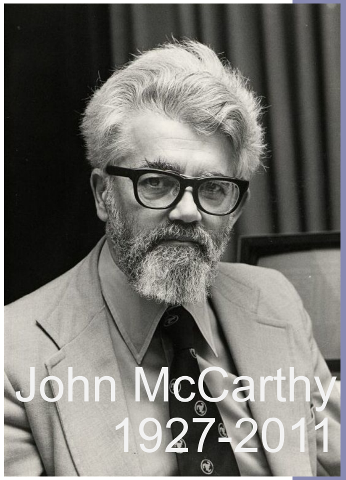
Memory as a graph

- We view memory as a directed graph
  - Each block a node, 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)

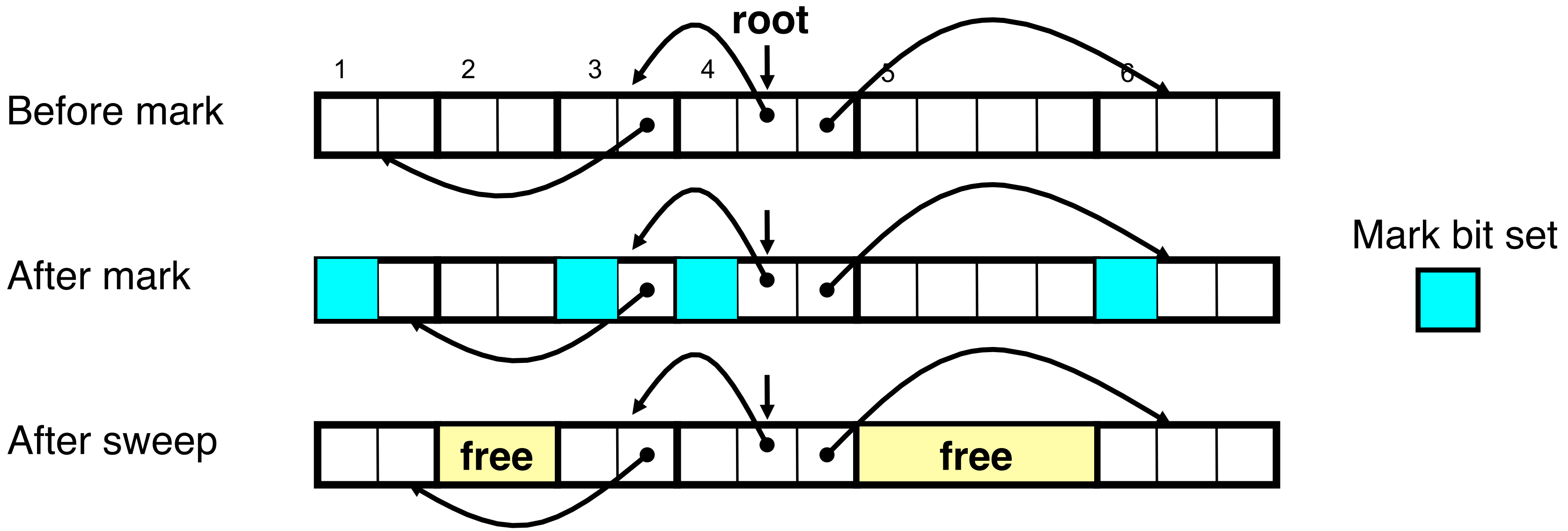


- A node (block) is *reachable* if there is a path from any root to that node.
- Non-reachable nodes are *garbage* (never needed by the application)

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
  - Careful with precedence and associativity!

```
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;
}
```

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
    - Referencing freed blocks
    - …

Dealing with memory bugs

- Some malloc implementations contain checking code
  - Linux glibc malloc: setenv MALLOC_CHECK_ 2
- 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
- Garbage collection (Boehm-Weiser Conservative GC)
  - Let the system free blocks instead of the programmer.

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