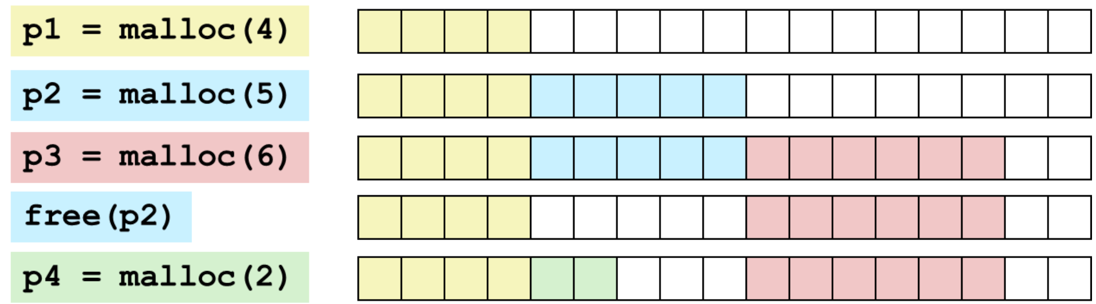
Running Programs on a System

Dynamic Memory Allocation II

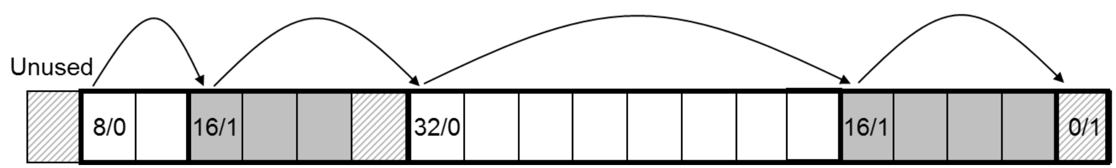
Recap: Dynamic Memory Allocation Basics

- Dynamic Memory Allocation
  - by user-space allocator
  - for data structures whose size is unknown at compile time



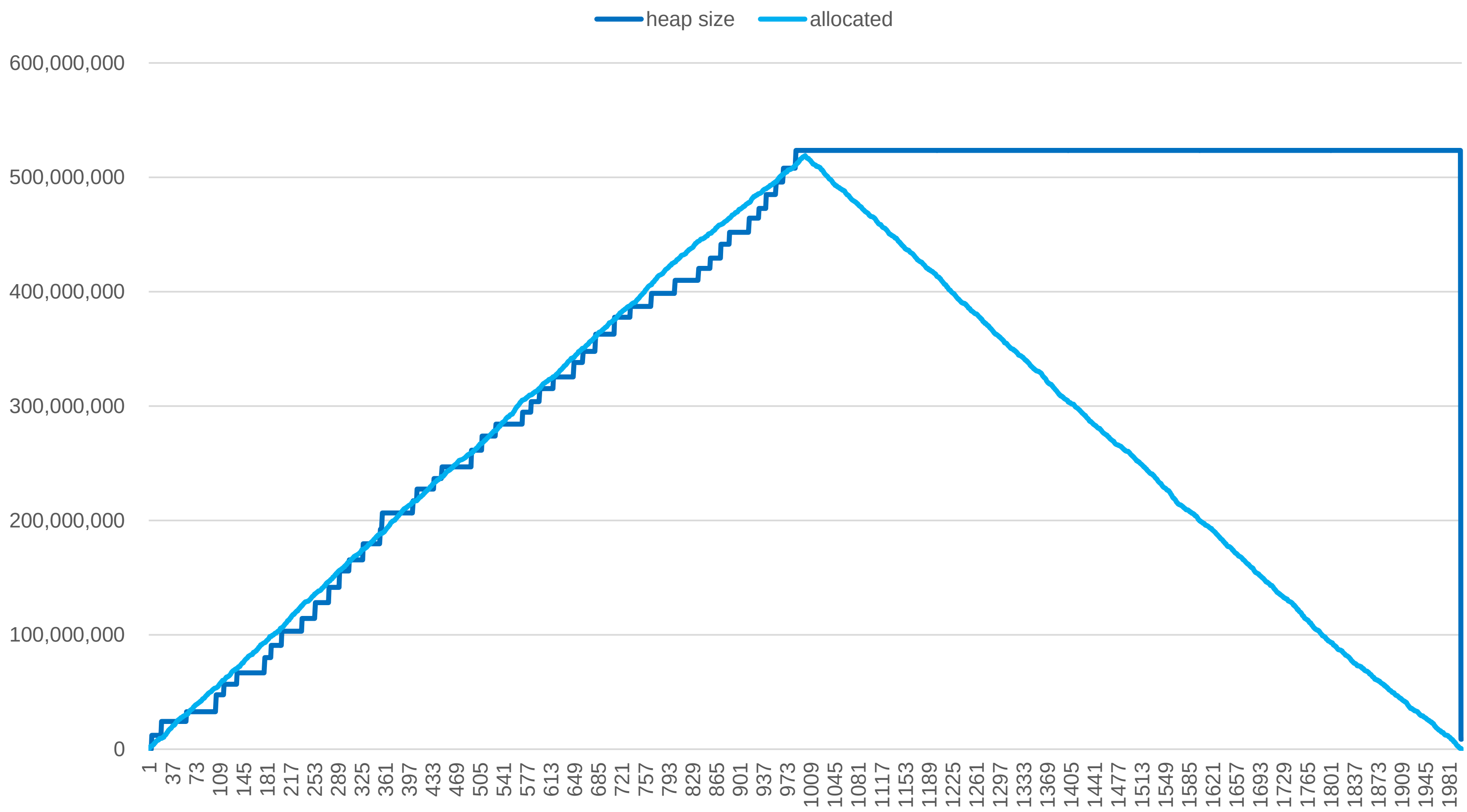
- Fragmentation
  - internal
  - external

- Allocation Methods:
  - Implicit free lists
    - allocation: O(n)
    - free: O(1), even with coalescing



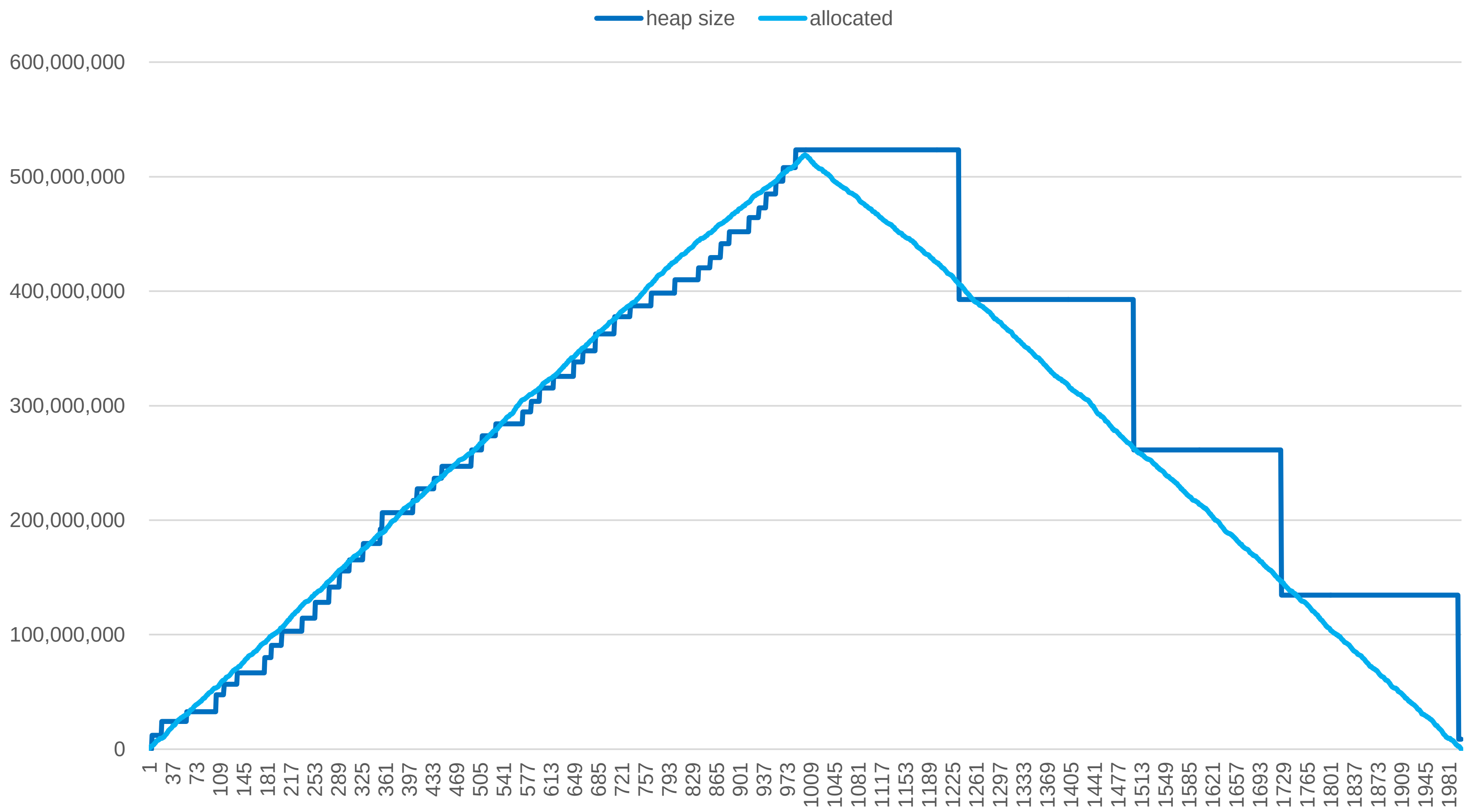
Recap: Allocation and brk

- 1000 random allocations, followed by in-order 1000 deallocations



Recap: Allocation and brk

- 1000 random allocations, followed by reverse order 1000 deallocations



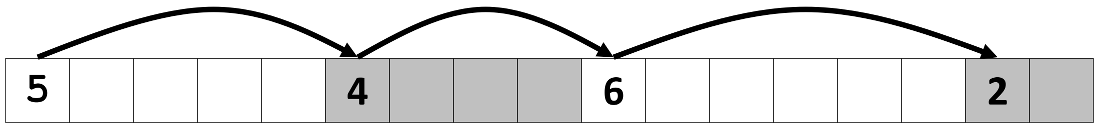
Dynamic Memory Allocation - Advanced Concepts

- **Dynamic memory allocation**
  - Implicit free lists
  - **Explicit free lists**
  - Segregated free lists
- Garbage collection
- Memory-related perils and pitfalls

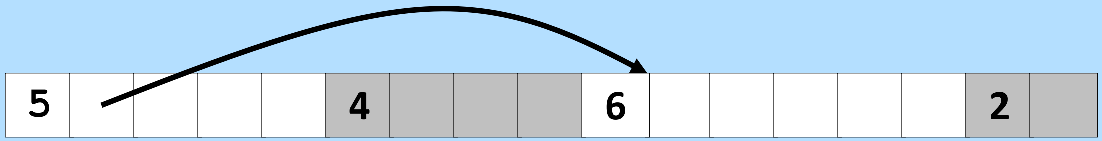
Acknowledgement: slides based on the cs:app2e material

Keeping Track of Free Blocks

- Method 1: Implicit free list using length—links all blocks



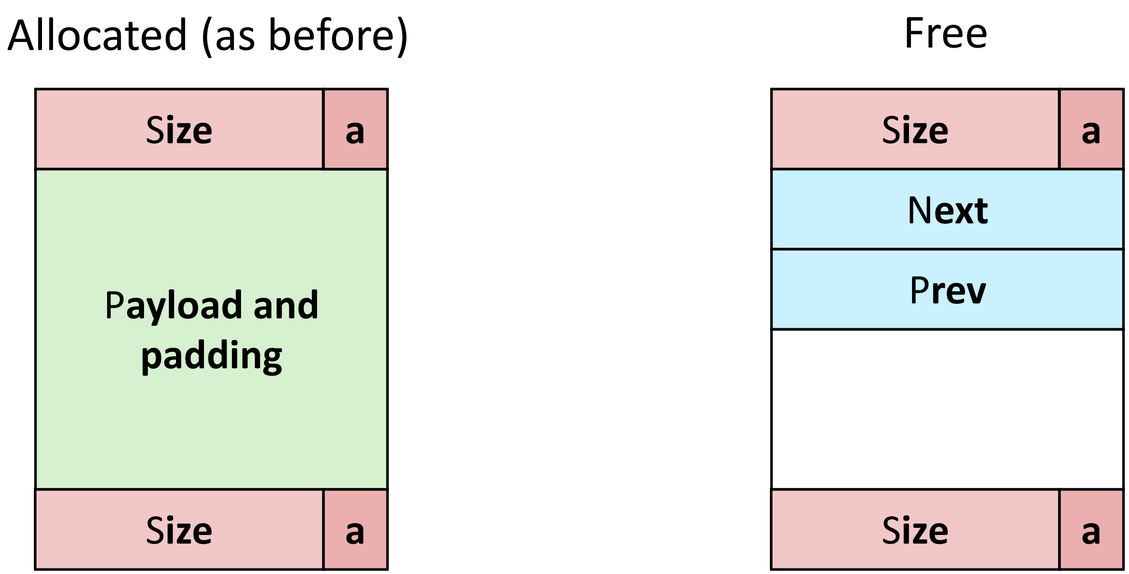
- Method 2: Explicit free list among the free blocks using pointers



- 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 b lock, and the length used as a key

Explicit Free Lists

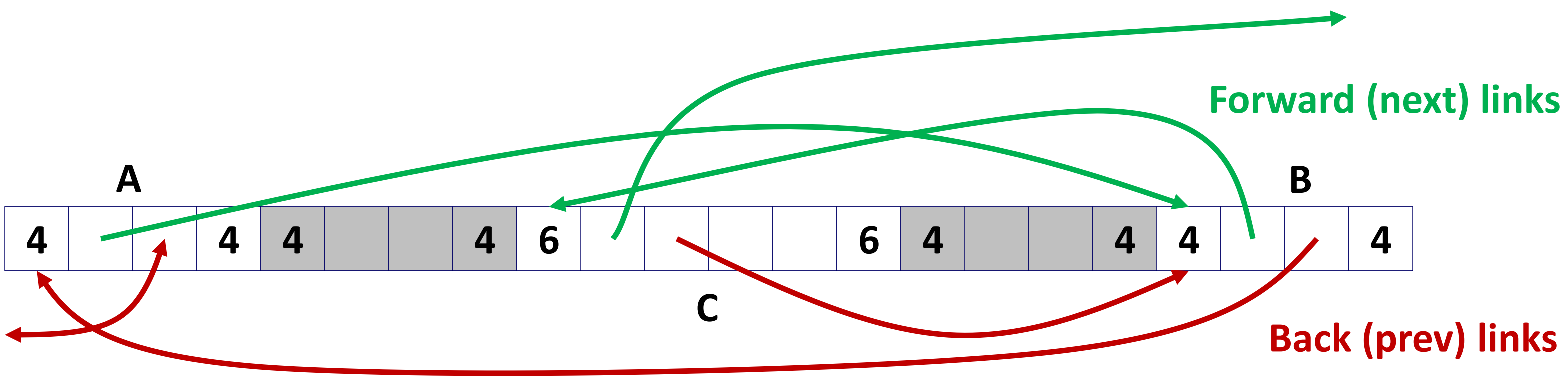


- Maintain list(s) of **free** blocks, not **all** blocks
  - The “next” free block could be anywhere
    - So we need to store forward/back pointers, not just sizes
  - Still need boundary tags for coalescing
  - Luckily we track only free blocks, so we can use payload area

Explicit Free Lists

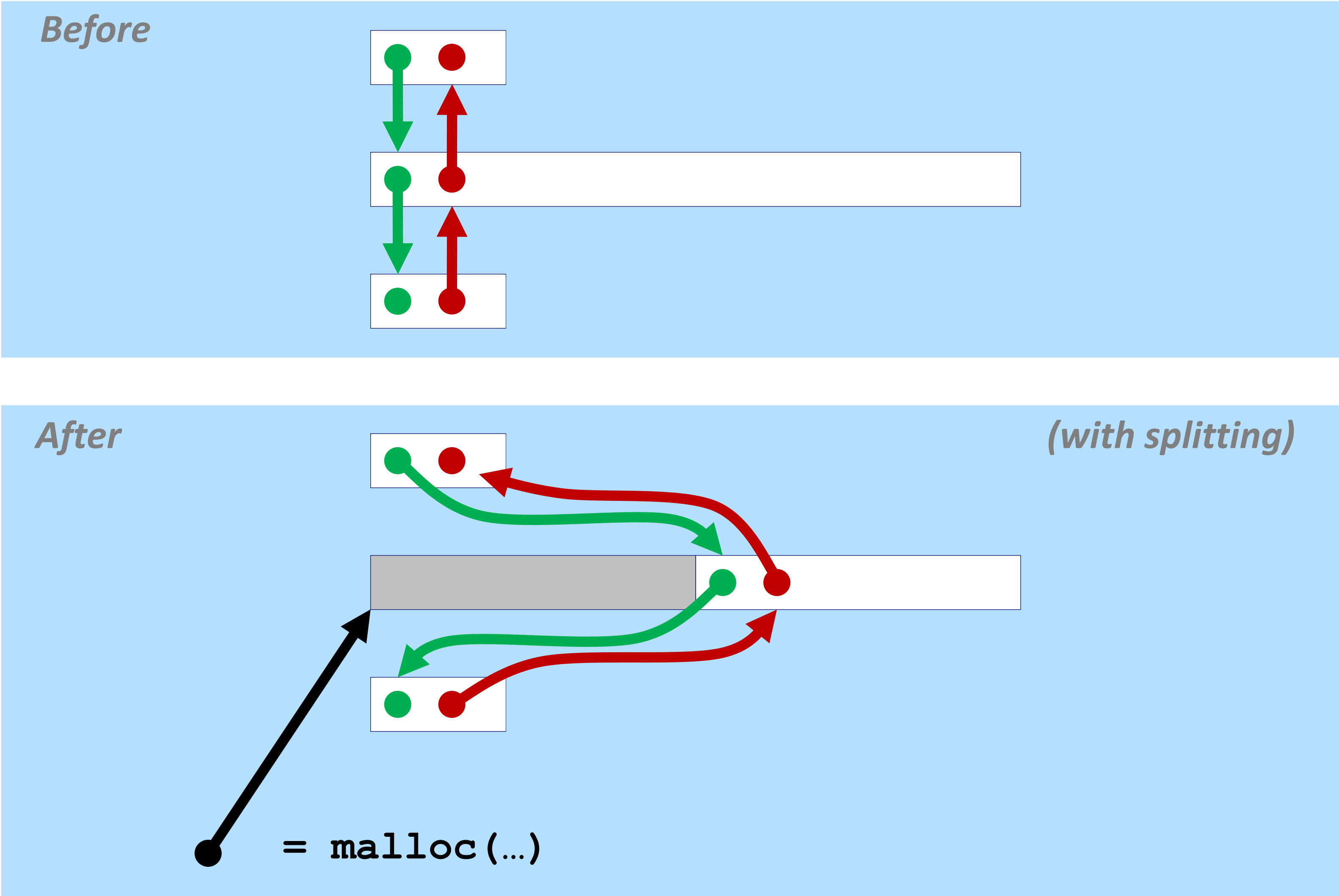
- Logically:

- Physically: blocks can be in any order



Allocating From Explicit Free Lists

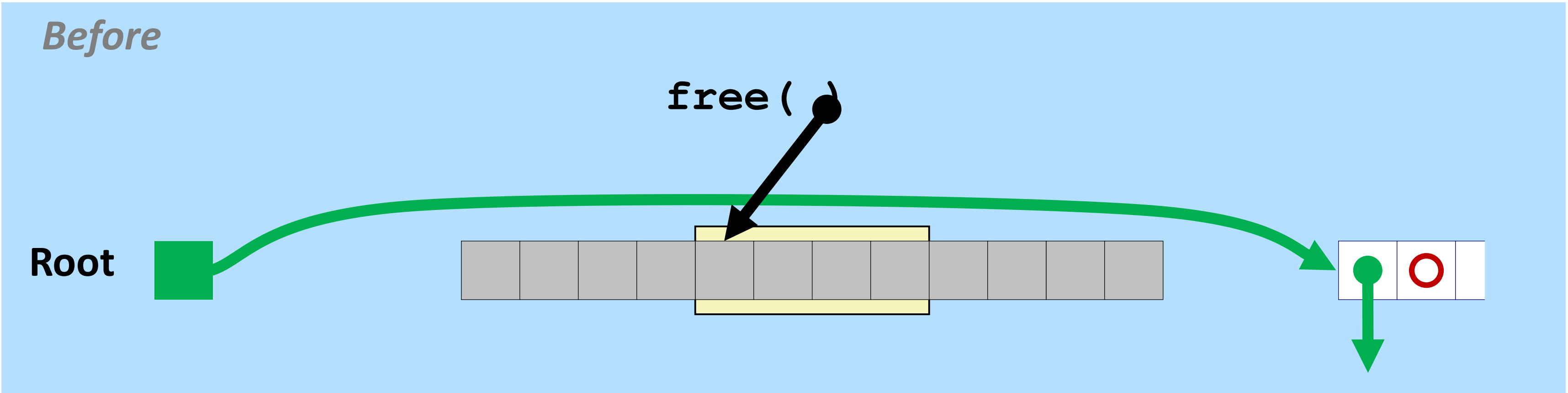
conceptual graphic



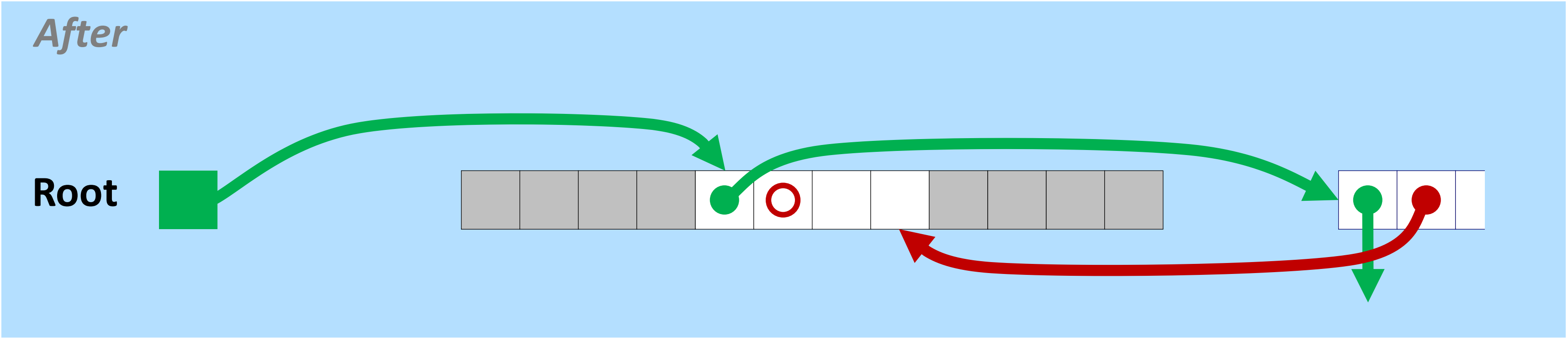
Freeing With Explicit Free Lists

- **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

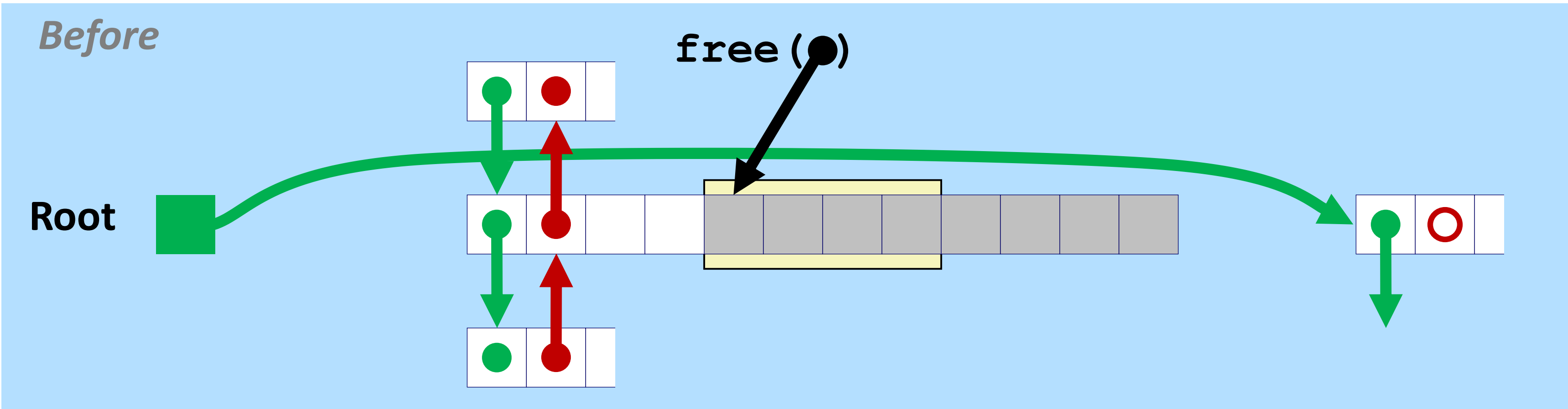
Freeing With a LIFO Policy (Case 1)



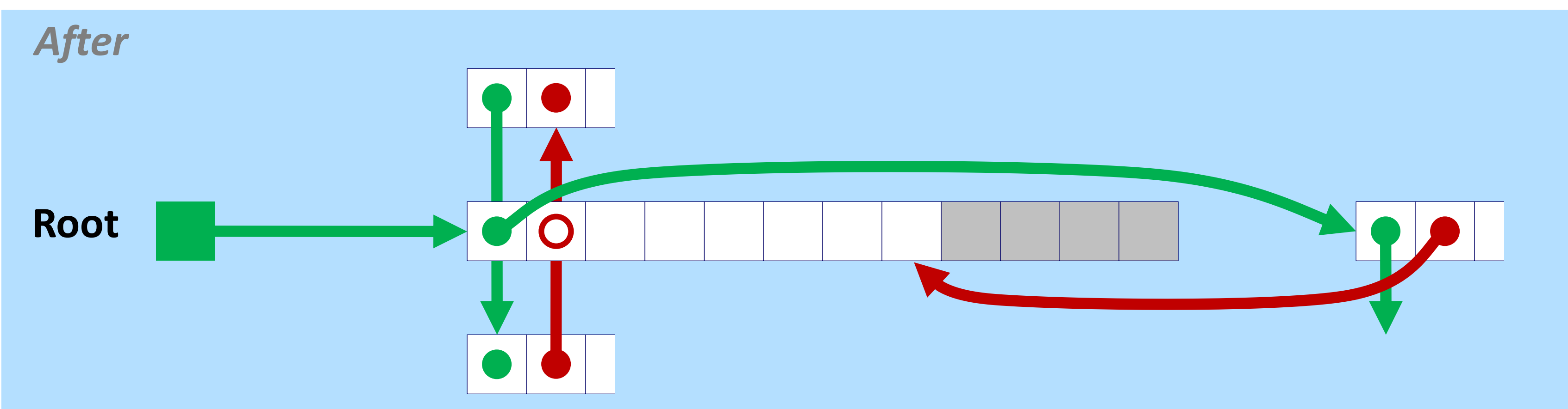
- Insert the freed block at the root of the list



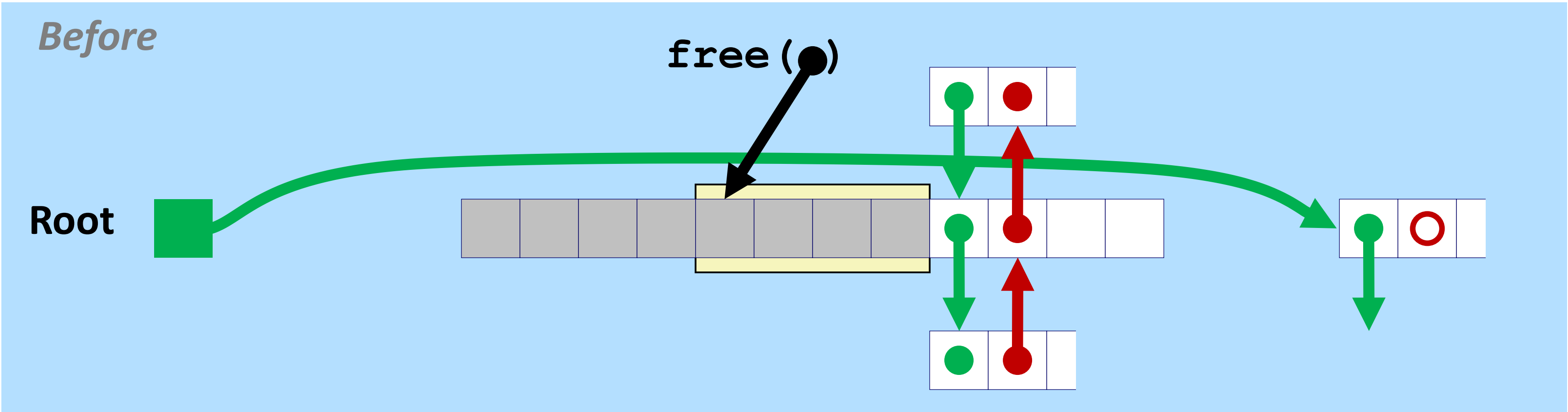
Freeing With a LIFO Policy (Case 2)



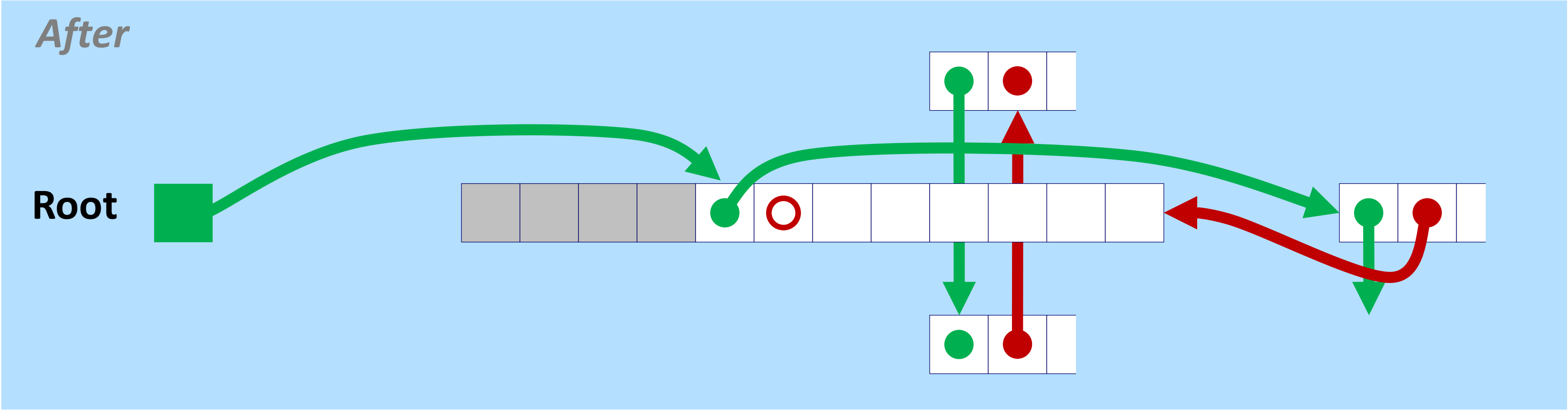
- Splice out predecessor block, coalesce both memory blocks, and insert the new block at the root of the list



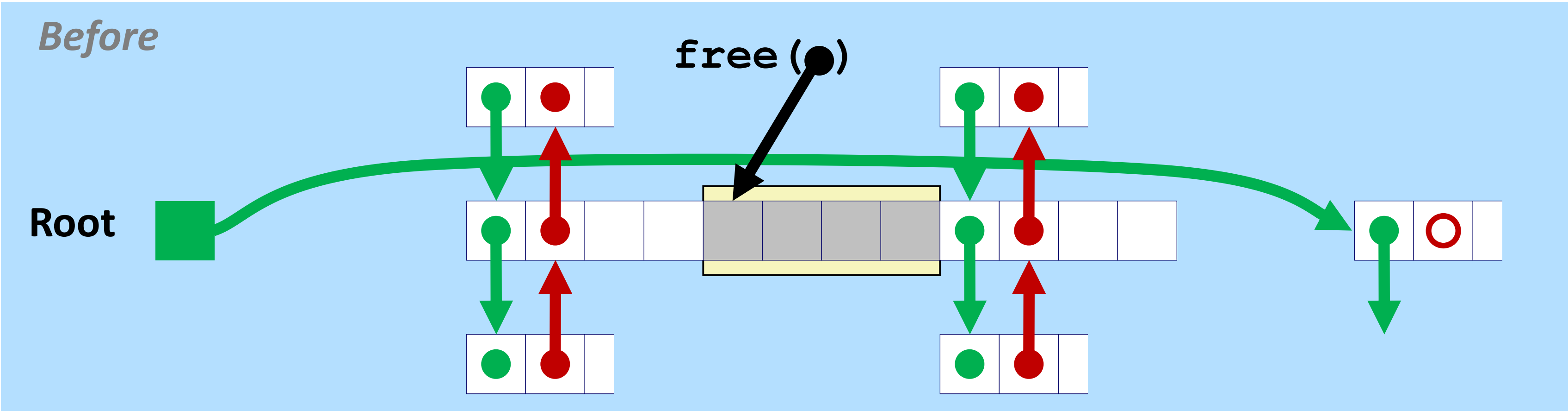
Freeing With a LIFO Policy (Case 3)



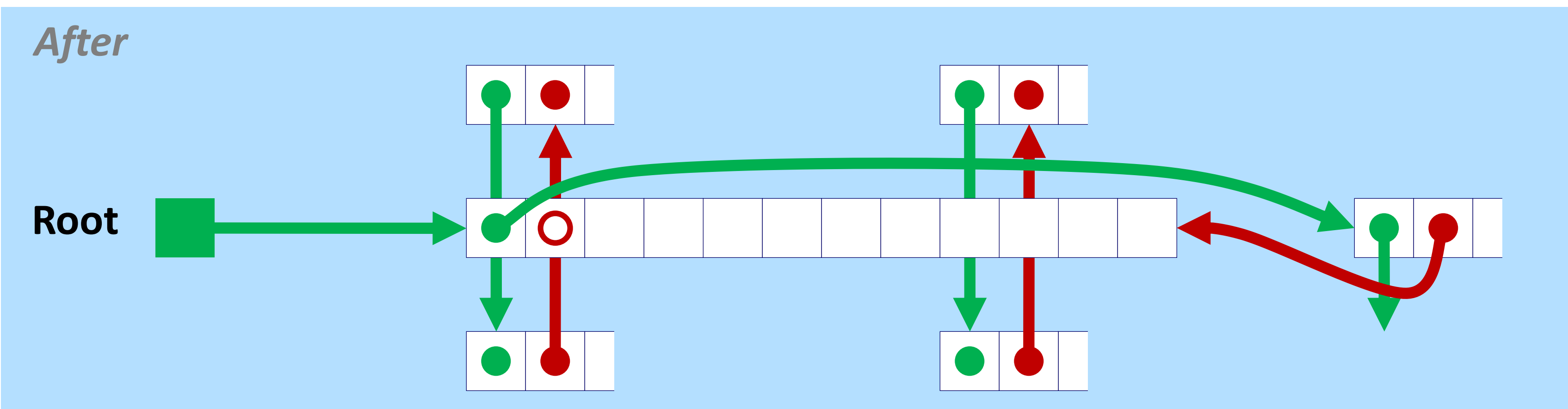
- Splice out successor block, coalesce both memory blocks and insert the new block at the root of the list



Freeing With a LIFO Policy (Case 4)



- Splice out predecessor and successor blocks, coalesce all 3 memory blocks and insert the new block at the root of the list



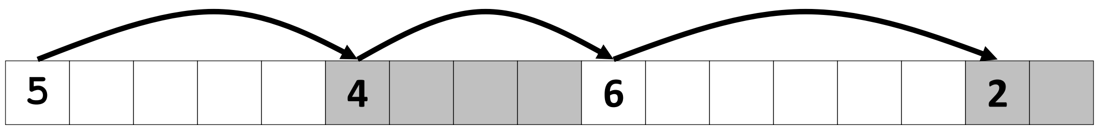
Explicit List Summary

- 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?

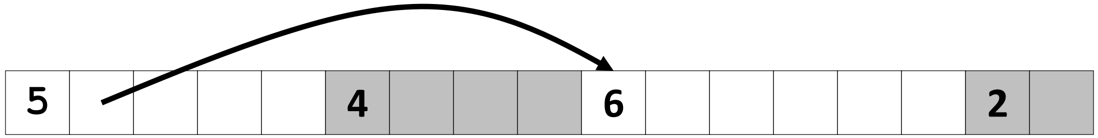
- Most common use of linked lists is in conjunction with segregated free lists
  - Keep multiple linked lists of different size classes, or possibly for different types of objects

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 b lock, and the length used as a key

Dynamic Memory Allocation - Advanced Concepts

- **Dynamic memory allocation**
  - Implicit free lists
  - Explicit free lists
  - **Segregated free lists**
- Garbage collection
- Memory-related perils and pitfalls

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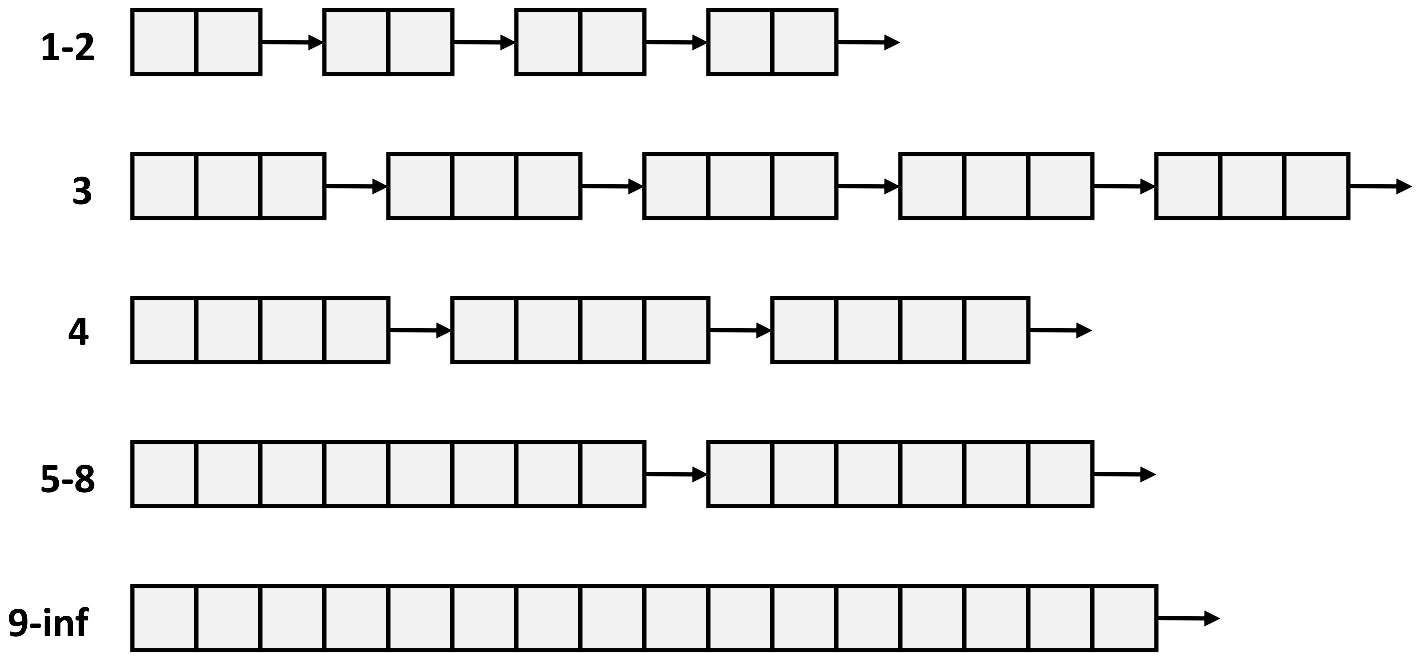
Segregated List (Seglist) Allocators

- Each size class of blocks has its own free list



- Often have separate classes for each small size
- For larger sizes: One class for each two-power size

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.

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.

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 on eTL

Dynamic Memory Allocation - Advanced Concepts

- Dynamic memory allocation
  - Implicit free lists
  - Explicit free lists
  - Segregated free lists
- **Garbage collection**
- Memory-related perils and pitfalls

Implicit Memory Management: 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, Oberon

- Variants (“conservative” garbage collectors) exist for C and C++
  - However, cannot necessarily 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

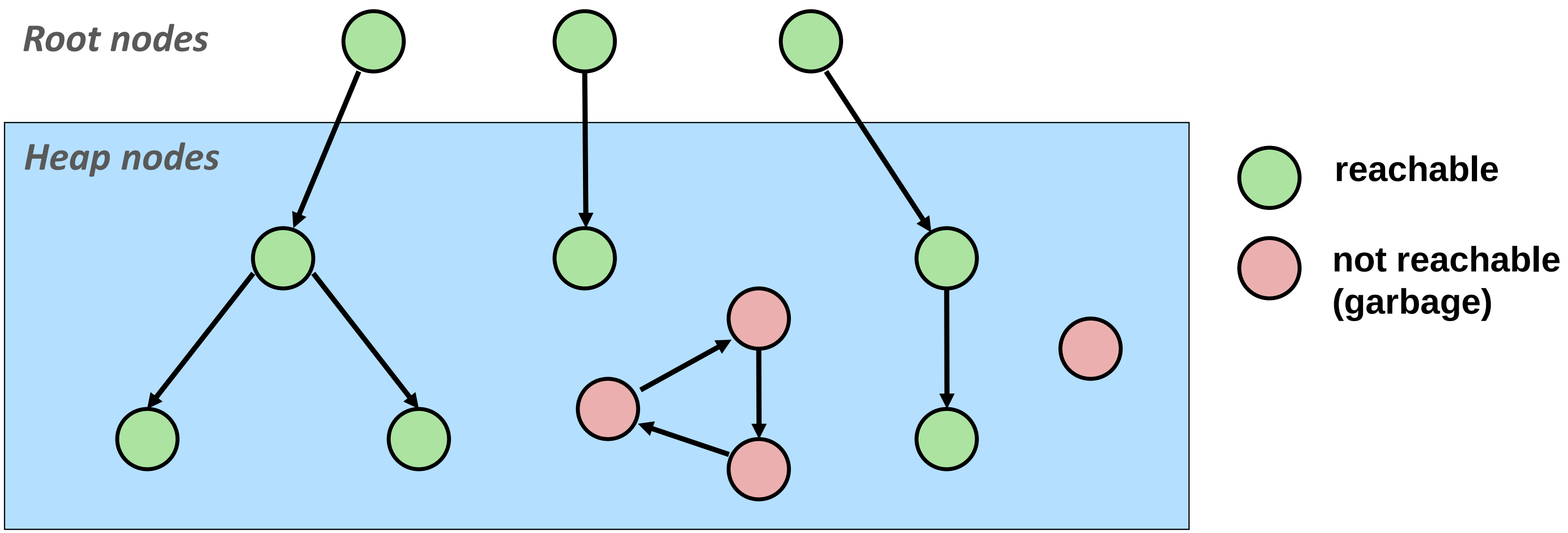
- Must make certain assumptions about pointers
  - Memory manager can distinguish pointers from non-pointers
  - All pointers point to the start of a block
  - Cannot hide pointers
    (e.g., by coercing them to an int, and then back again)

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
- Copying collection (Minsky, 1963)
  - Moves blocks
- Generational Collectors (Lieberman and Hewitt, 1983)
  - Collection based on lifetimes
    - Most allocations become garbage very soon
    - So focus reclamation work on zones of memory recently allocated
- For more information:
  Jones and Lin, "Garbage Collection: Algorithms for Automatic Dynamic Memory", John Wiley & Sons, 1996.

Memory as a Graph

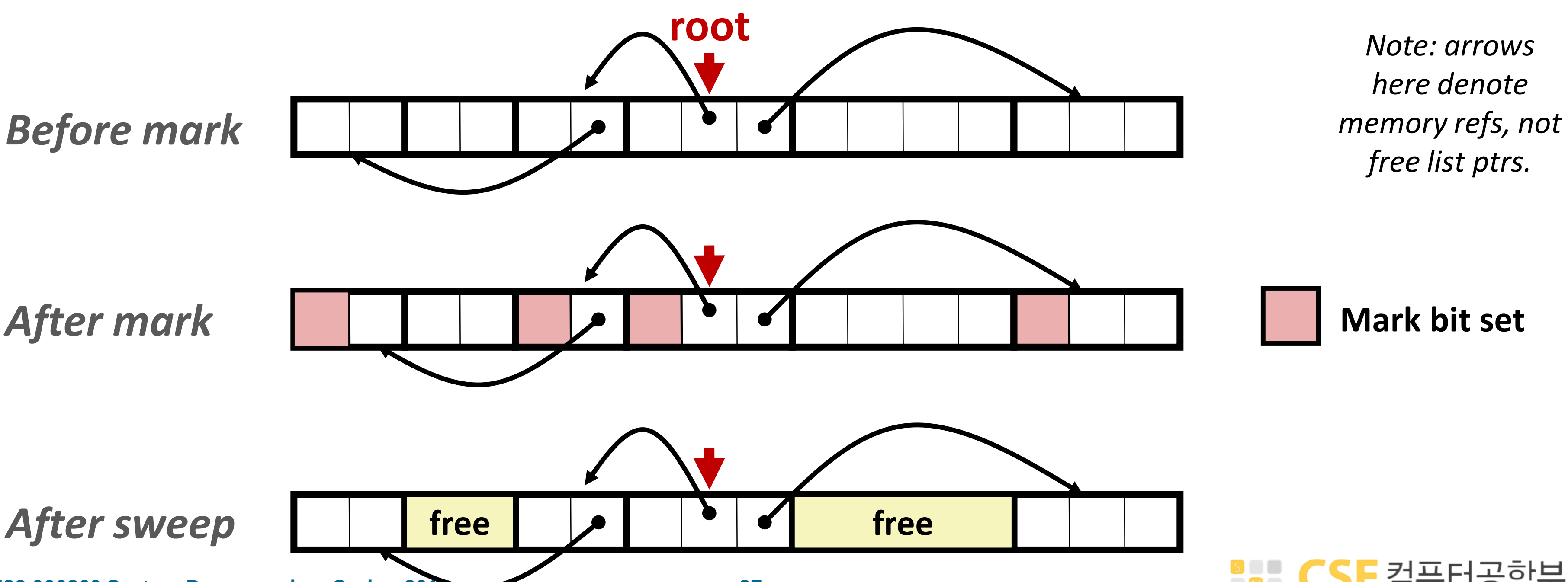
- We view memory as a directed graph
  - Each block is a node in the graph
  - Each pointer is an edge in the graph
  - Locations not in the heap that contain pointers into the heap are called root nodes (e.g. registers, locations on the stack, global variables)



A block is *reachable* if there is a path from any root to that node. Non-reachable blocks are *garbage* (no (legal) access possible anymore 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 each reachable block
  - Sweep: Scan all blocks and free blocks that are not marked



Assumptions For a Simple Implementation

- Application
  - `new(n)`: returns pointer to new block with all locations cleared
  - `read(b,i)`: read location i of block b into register
  - `write(b,i,v)`: write v into location i of block b

- Each block will have a header word
  - addressed as b[-1], for a block b
  - Used for different purposes in different collectors

- Instructions used by the Garbage Collector
  - `is_ptr(p)`: determines whether p is a pointer
  - `length(b)`: returns the length of block b, not including the header
  - `get_roots()`: returns all the roots

Mark and Sweep (cont.)

Mark using depth-first traversal of the memory graph

```
ptr mark(ptr p) {
   if (!is_ptr(p)) return;          // do nothing if not pointer
   if (markBitSet(p)) return;       // check if already marked
   setMarkBit(p);                   // set the mark bit
   for (i=0; i < length(p); i++)    // call mark on all words
     mark(p[i]);                    //   in the block
   return;
}
```

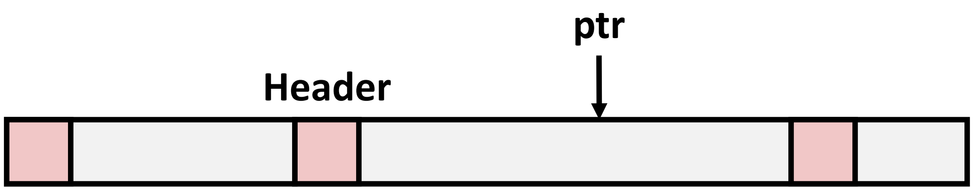
Sweep using lengths to find next block

```
ptr sweep(ptr p, ptr end) {
   while (p < end) {
      if markBitSet(p)
         clearMarkBit();
      else if (allocateBitSet(p))
         free(p);
      p = nextBlock(p);
}
```

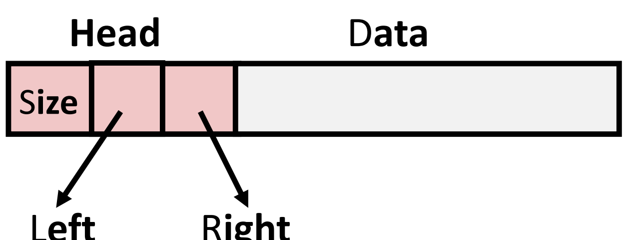
- Instructions used by the Garbage Collector
  - `is_ptr(p)`: determines whether p is a pointer
  - `length(b)`: returns the length of block b, not including the header
  - `get_roots()`: returns all the roots

Conservative Mark & Sweep in C

- A "conservative garbage collector" for C programs
  - is_ptr() determines if a word is a pointer by checking if it points to an allocated block of memory
  - But, in C pointers can point to the middle of a block



- So how to find the beginning of the block?
  - Can use a balanced binary tree to keep track of all allocated blocks (key is start-of-block)
  - Balanced-tree pointers can be stored in header (use two additional words)



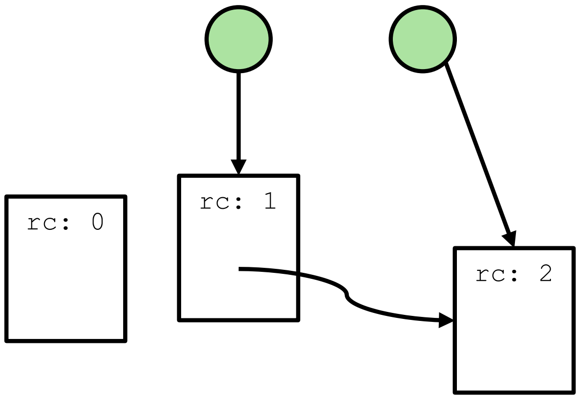
Left: smaller addresses
Right: larger addresses

Mark & Sweep

- Discussion
  - no overhead on pointer manipulation
  - no problems with circular data structures
  - start/stop algorithm: non-interruptible, global memory traversal necessary during which no other process can run

Reference Counting

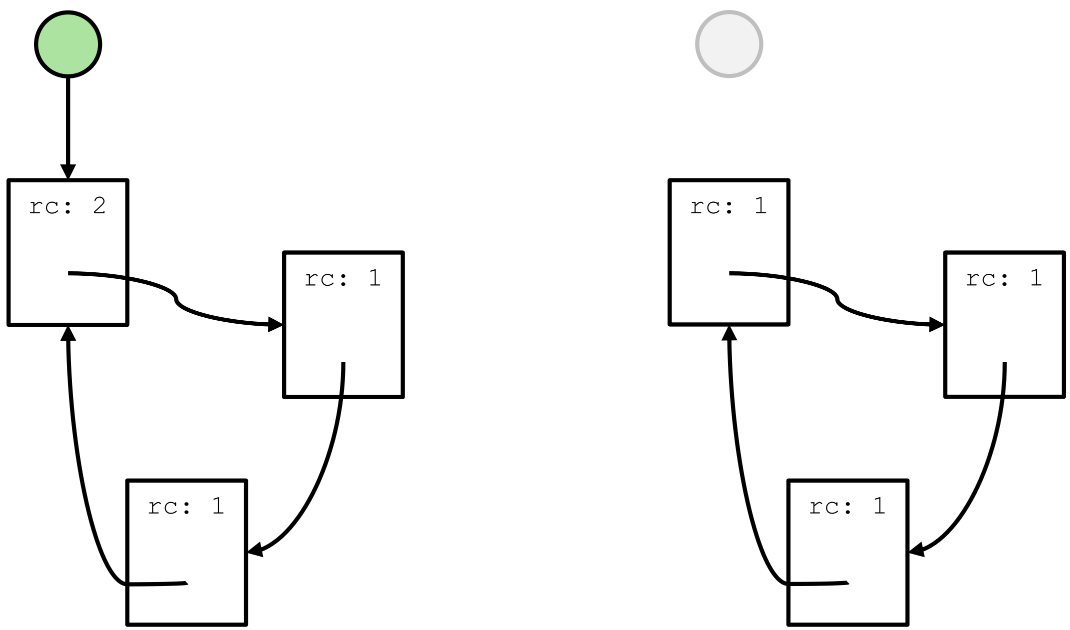
- Each memory block has an additional *reference count* field counting the number of references to this block:



- Invariant: reference count is always correct
  - allocation: simple
  - assignments: compiler

Reference Counting

- Discussion
  - garbage collection cost distributed, but relatively high
  - immediate knowledge when a block is garbage
  - cannot reclaim cyclic data structures



Copying Algorithm

- Heap divided into two semi-spaces
  - current data
  - obsolete data

- When running out of memory
  - roles of the spaces reversed
  - GC traverses reachable set and copies each reachable block from the (now) obsolete data space into the current data space
    - automatic compaction

Copying Algorithm

- Discussion
  - simplified & efficient heap management
    - no allocated/free block lists necessary, just an “end of allocated space pointer”.
    - no internal fragmentation
    - eliminates external fragmentation on each GC
  - effectively usable memory space halved
    - with virtual memory, do we need to back the spaces with physical memory?
  - GC needs to update pointer references

Exact Garbage Collection

- Treating every word in allocated blocks as a potential pointer is
  - slow
  - inexact

- Modern languages include information about data structures in the binary, so that the GC knows exactly
  - what registers contain pointers
  - for each data structure (on the stack, in the heap) where the pointers are

Dynamic Memory Allocation - Advanced Concepts

- Dynamic memory allocation
  - Implicit free lists
  - Explicit free lists
  - Segregated free lists
- Garbage collection
- **Memory-related perils and pitfalls**

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

Dereferencing Bad Pointers

- The classic scanf bug

```
int val;

...

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

- 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

- Misunderstanding pointer arithmetic

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

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

   return p;
}
```

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);
}
```

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 (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

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
- Garbage collection (Boehm-Weiser Conservative GC)
  - Let the system free blocks instead of the programmer.